PROVENANCE, WEATHERING, AND TECHNOLOGY OF SELECTED ARCHAEOLOGICAL BASALTS AND ANDESITES

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Basalt and andesite have been used consistently in human history as stone media for grinding tools, for architectural elements, and as material for monumental sculpture. This study examines some selected archaeological basalt or andesite use with several aims.

One primary aim is to examine problems of determination of provenance of selected Inca andesite contexts in Peru, Neolithic and Canaanite basalt contexts in the Levant, and an Olmec basalt context in Mexico where these contexts may compare or contrast in mineralogy, technology, or other areas.

Another major aim has been to attempt characterisation of archaeological weathering of basalt and andesite as it is similar to or differs from geological weathering. This is the first appraisal of this problem which has both made application of prior studies of geological weathering and has also made use of comparative analysis of archaeological contexts beyond the regional level, using the same cultural contexts mentioned above. Another important original addition to a study of archaeological weathering of basalt and andesite (if not stone in general) is an appraisal of stoneworking as it may accelerate weathering. A tentative dating application is also suggested.

A third important focus of this study regards questions of technology and uses of basalt and andesite. A formulation of one method of enquiry into human criteria of selection for stone is provided for the first time as a basis of approach to technology. Availability, workability, durability, and aesthetic appeal are some potential criteria of selection suggested in this study. The study also provides a global overview of some common uses of basalt and andesite with a survey of the known technology of stoneworking applicable to the selected contexts.

Other original contributions include assembly and experiments with a portable field laboratory for optical petrology in remote archaeological contexts (and pioneering a thin section mounting medium for stone) and appraising the above cultural contexts for suggesting authentication techniques of stone artefacts. Instrumental techniques used in this study include petrography, scanning electron microscopy with energy-dispersive X ray spectroscopy, and electron probe microanalysis.
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PREFACE

In 1984 as a graduate student in Athens, Greece, I was introduced to the potential of optical petrology at the British School of Archaeology in Athens, where research at the Fitch Laboratory integrated material analyses and archaeology. This potential was further clarified in Israel in 1985 when attention was given to the geological components of coursework in historical geography and the role of geomorphology in influencing historical demography.

This led to the research project that is the subject of this thesis wherein several questions on the provenance and weathering of stone, particularly volcanic stone, were considered in a variety of archaeological contexts around the world. Two questions of significance repeatedly suggesting themselves were the following: (1) Is it objectively possible to determine the geological source of stone used for a monument? (2) Is it possible to use stone weathering as an archaeological chronometer? My preexisting relative familiarity with basalt and andesite both from geological training and archaeological experience made these rocks the most favourable materials to study in greater detail in the light of these two questions. Another question which grew out of this study was 3) Why did cultures use certain stones when others were often equally or more available? That is, assuming some identification of different stone properties and qualities from culture to culture but without assuming these cultures possessed anything resembling a developed geological awareness, were any criteria of stone choice
operating even on an experiential basis?

Given the lack of any coordinated scientific archaeological research into basalt and andesite monuments worldwide, I was impressed with the opportunity and need to examine the questions. Given the extent of geological variation within a single basalt or andesite flow, not to mention the wide mineralogical range of these materials worldwide, and given the technology needed to examine them, my initial responses to the above questions were mostly optimistic but also ambivalent as to the likely success of the research project.

To fieldwork in Greece in 1984, 1985, and 1987 and in Israel in 1985 was added fieldwork in California 1986–88, as well as in Peru and Italy in 1988 and Mexico in 1989. A prototype field laboratory was assembled to cope with petrographic analysis in remote loci. Research and consultation at U.S. Geological Survey in Menlo Park, California, has both provided analytical capabilities and shown the original questions to be complex.

In general this thesis has several major parts. The first section covers geological and historical understanding of basalt and volcanic material (Chapters 1-2). The second section reviews the literature concerning stone provenance studies and presents and reviews innovative field analysis as well as analytical tools for field study of geological material (Chapters 3-4). The third section investigates the provenance and potential criteria of choosing and using selected archaeological basalts and andesites (Chapters 5-7). The fourth section reviews the literature of basalt and andesite weathering and presents new information on the weathering of selected archaeological basalts and andesites.
(Chapters 8-10). The remaining chapter of this thesis presents conclusions and potential future applications of the present research, including the dating of basalt and andesite monuments and artefacts and artefact authentication and stone conservation as these also relate to basalt and andesite (Chapter 11).

Specific chapters deal with the following topics: Chapter 1, geologic occurrence and variations in basalt and andesite, and rationales for the selection of particular sites in this study; Chapter 2, historical references to basalt and andesite, known global archaeological basalt and andesite contexts, and potential criteria which may have been used in antiquity which resulted in the selection of certain stone materials, basalt and andesite among others, as opposed to other types of rock, along with selected discussions on the appropriate stone technologies; Chapter 3, a literature review of prior methods used for provenance studies; Chapter 4, optical petrology in the field with portable equipment; Chapter 5, new provenance determinations made (with the calibration or modification of older provenance studies) in selected Inca contexts in the Cuzco province of Peru, and potential Inca criteria of andesite stone selection; Chapter 6, a review of provenance studies and new research on the provenance determination of a major Olmec context in Mexico along with a possible reconstruction of stone selection criteria in Olmec stone technology; Chapter 7, a new study of provenance and technology of selected Canaanite and related contexts in the Levant; Chapter 8, a review of basalt and andesite weathering research; Chapter 9, a new formulation of stoneworking as an
NECESSARY LIMITATIONS OF RESEARCH

The necessary limitation of research to basalt and andesite to the exclusion of other volcanic stones (obsidian, rhyolite, dacite, latite, etc.) and even other silicates is scientifically defensible on several grounds, not the least of which is the dearth of prior archaeological study of basalt and andesite and the abundance of this material in archaeological contexts throughout the world.

The choice of certain contexts over others has been carefully thought out to focus on and/or isolate particular variables. Both cultural and chronological range have been determinants in the selection for detailed study of sites where basalt and andesite occur. As mentioned, details of rationales for the selection of particular archaeological sites are found in Chapter 1.

It has also been necessary to limit the research in order to obtain useful results within the constraints of time and funding. Naturally, it is a future goal of research beyond the thesis to attempt a comprehensive global analysis of archaeological basalts and andesites.

ACKNOWLEDGEMENTS

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work with patience and constant valuable assistance at the Institute of Archaeology, University College, University of London; Dr. Terry Keith, Asst. Branch Chief of Igneous and Geothermal Processes, U.S. Geological Survey, Menlo Park, California, my supervisor there who provided resources and encouragement; Dr. Michael Clynne, also of U.S. Geological Survey, Menlo Park, Petrographer and Vulcanologist, who assisted with many petrographic interpretations; Professor Anthony Snodgrass, Classical Archaeology, Cambridge University, who was originally instrumental in my direction toward archaeological science; Valerie Jones, Mineralogy Dept., British Museum of Natural History, who gave me access to a vast collection of worldwide geological samples for study; Dr. Merle Greene Robertson, Pre-Columbian Art Research Institute, San Francisco, who much encouraged my Mesoamerican fieldwork; and to the academic staff members at the Institute of Archaeology who helped in questions of cultural and regional contexts, including Dr. Warwick Bray (Latin America), Dr. Peter Parr (Western Asia), Mr. Peter Dorrell, and Dr. Ian Glover (Southeast Asia). Most of all, I am grateful to my wife and children who encouraged and endured.
Chapter One

THE OCCURRENCE OF BASALT AND ANDESITE

1.1 Geological Nomenclature

Definitions

The geological focus of this research is on basaltic and andesitic rocks as they are found in archaeological contexts. Geologic definitions of basalt and andesite are thus provided here. The definitions of Thorpe, Le Maitre, and Gill in particular will be incorporated in various sections within the following discussion. The basalts and andesites falling within the focus of this study are all "igneous extrusive intermediate rocks" (Thorpe and Brown, 1985; Le Maitre, 1976, 1989). These terms will be briefly defined in successive paragraphs. The following definitions of basalt and andesite refer to manner of deposition, texture, colour and general mineralogy.

Basalt is volcanic lava which is usually fine-grained, i.e. has mean grain size < 1 mm (Thorpe and Brown, 1985:32); is melanocratic, i.e. "rocks rich in dark-coloured minerals" (Le Maitre, 1989:90) or mafic, i.e. has a relatively high percentage of ferromagnesian minerals such as olivine or pyroxene, among others, (Williams and Mc Birney, 1979); and contains up to 52 wt % of SiO (Nockolds et al., 1982); therefore classed geochemically as basic (Thorpe and Brown, 1985:31). Most basalts studied in this research also have the textural features of groundmass, i.e. an extremely fine crystalline "matrix" (Thorpe and Brown, 1985:32) and phenocrysts, i.e. individual minerals such as the mafic or ferromagnesian minerals which crystallize somewhat freely in the magma and can be easily greater than 1 mm (Thorpe and Brown,
1985:32) and are thus *porphyritic*, i.e. "containing phenocrysts in a finer-grained groundmass" (Le Maitre, 1989:107).

The major phenocrysts of basalts in general and the basalts studied here are plagioclase feldspar, pyroxene, and olivine (Le Maitre, 1989:50). Basalts are by far the most abundant *extrusive*, i.e. surface-deposited as lava (Grout, 1940:28) igneous rocks; the total surface earth area covered by basalt is greater than all other extrusive igneous rocks combined (Read and Watson, 1973; Bell and Wright, 1985). Figure 1.1 below shows basalt and andesite placed in a QAPF schematic diagram.

Andesite is also volcanic lava which is usually fine-grained (Bell and Wright, p. 92) is *mesocratic*, i.e. usually light-grey to dark-grey in colour due to 52-65 wt % SiO which classifies it geochemically as intermediate (Thorpe and Brown, 1985:31). Andesites also nearly always have the textural features of groundmass and phenocrysts. The major phenocrysts are plagioclase feldspar, pyroxene, and hornblende, with minor phenocrysts usually being biotite and olivine, though not at the same time (Nockolds et al, 1978:96). Accessory minerals include apatite and magnetite. Andesites are the second most common extrusive igneous rocks after basalts (Read and Watson, 1973:424; Bell and Wright, 1985:94). The terms "igneous extrusive intermediate" are further defined in the following paragraphs.

By *igneous* it is meant that in its petrogenesis the rock is formed in a magmatic (or molten) state below the earth's surface (Williams and McBirney, 1979: 19-34; Turcotte, 1987: 69-74; Thorpe and Brown, 1985:1). Igneous rocks such as granite or diorite are formed far below the earth's surface and are termed *plutonic* igneous rocks. They are formed by cooling from the molten state
Classification and nomenclature of volcanic rocks according to modal mineral content using QAPF diagram. Corners of the double triangle are Q = quartz, A = alkali feldspar, P = plagioclase and F = feldspathoid.

(from Le Maitre, 1989:23)
and after cooling can be exposed on the earth's surface by such
geologic forces as tectonic uplifting and/or subsequent erosion
(Ryan, 1987:259-79). Intrusive (or plutonic) is the opposite term
of extrusive not only in that the cooling of the rock takes place
below the surface but also is therefore at a much slower rate,
causing larger-grained crystallization. The textural feature of
individual grain size in intrusive rocks can be 1-5 mm (medium)
or > 5 mm (large) depending mostly on rate of cooling (Thorpe and

By extrusive, then, it is meant that the nature of geologic
deposition is by volcanic action, including eruption from cinder
cones, stratovolcanoes, and shield volcanoes, with common surface
features such as visible lava flows (Williams and Mc Birney,
1979:71-77; Wright and Swanson, 1987:231; Read and Watson, 1973:
364). As a textural feature, many extrusive rocks may show two
distinct generations of crystallization. The first generation
of crystallization for porphyritic rocks - which andesites
usually are (Gill, 1981:168) (and all of the basalts considered
in the present study are) that is, they have the texture of
large phenocrysts in a groundmass (Gill, 1981:168; Thorpe and
Brown, 1985:32) - is one with early-formed large phenocrysts
(whose crystallization began in the magma where cooling was slow)
(Thorpe and Brown, 1985:32) and of low variation with relative
thermal stability - although zoning in plagioclase feldspar
phenocrysts reflects small variations in calcic to sodic
concentrations most likely caused by crystallization conditions
such as temperature change, magmatic mixing and hydration (Gill,
The second phase, usually the groundmass matrix, has later-formed, much smaller crystals reflecting a faster cooling rate at or near the surface. Thus, in contrast to intrusive igneous rocks such as granite or diorite, the solidification of extrusive igneous rocks such as basalt or andesite occurs relatively near the earth’s surface.

By intermediate it is meant that the composition is more or less mid-range between the basic rocks with a mafic character, i.e. high concentration of ferromagnesian minerals (rocks such as meymechite – actually ultrabasic – or tholeiitic basalt) and the acid rocks with pronounced silicity, i.e. high concentration of silica which is often found as quartz (rocks such as rhyolite). Geochemical classifications based on silica content define intermediate as being between 52-65 wt % SiO (Thorpe and Brown, 1985: 31). Usually the term intermediate refers mainly to andesite, but since andesitic basalts or basaltic andesites found in this study are around or just outside the low end of this range (at around 50-54 wt % SiO) an intermediate category is extended here for the purpose of this study.

Basalts and andesites in this study have some common mineralogical features to be discussed shortly. Extrusive rocks of a magmatic nature also often share markedly-common visible textural of groundmass and phenocrysts despite derivation from different deposit locations and plate tectonic origins worldwide. It is usual for the groundmass to be made up of the same minerals as accrete into phenocrysts under certain conditions of temperature and composition. As mentioned, the basalts and andesites in this study have the features of porphyritic texture with both groundmass and phenocrysts.
Because of some common features in mineralogy and texture, a certain amount of overlapping is to be expected at the boundary between basalt and andesite. This andesitic-basalt to basaltic-andesite range on the extrusive intermediate continuum has been called the "basalt–andesite dilemma" (Wilkinson, 1986:34) and will be explored in some detail in the following sections. This is an important consideration due to the fact that many of the archaeological samples in the present study fall in this range, as has been stated elsewhere.

1.2 Geological Variables of Basalt and Andesite

1.2.1 The Need for Clarity

While the term andesite has a history of over a century and a half of use (von Buch, 1836), it has often been subsumed within the geological category of basalt. Such an overlapping or subcategorization has not been made any easier by the lack of agreement between geologists as to more precise boundaries of common definition on chemical and textural grounds.

Recently there has been growing scientific concord regarding the boundary between basalt and andesite. This boundary depends on the composition of the plagioclase feldspar in the rock (as determined by the albite to anorthite range from CIPW normative standards), the percentage of silica (generally expressed in terms of whether the molten rock is undersaturated, saturated or oversaturated with silica), and ratios between potassium, sodium, and aluminium oxides (Wilkinson, 1986). Major subdivisions of extrusive rocks championed by Wilkinson and others (Chayes, 1966; Le Maitre, 1968 & 1989; Irvine and Baragar, 1971; Miyashiro,
1978; Ewart, 1982) have adopted new definitions for the basalt : andesite boundary. The TAS (total alkaline silica) classification sets the basalt : basaltic andesite boundary at 52 wt % SiO and the basaltic andesite : andesite boundary at 57 wt % SiO (Le Maitre, 1984 & 1989). It has been maintained that silica percentage as a critical parameter has some disadvantage for it to be given priority independent of other mineral criteria (Wilkinson, 1986:36), although Le Maitre has subsequently qualified his results in that additional calculations such as the CIPW norm should also be used in conjunction with TAS, along with other procedures (Le Maitre, 1989:25-27).

However, in critical evaluation, it may still be important to recognize that any such boundary is arbitrary in that a natural continuum may not always conform to human distinctions on the one hand and may necessitate further calibration as new material is integrated on the other hand. Furthermore, Wilkinson notes that his new "proposed classification makes no provision for basaltic andesite...mainly because of inconsistent usage over the years and/or initially imprecise definitions" (Wilkinson, 1986:31). Attempts to divide clearly the close mineralogic identities of andesitic basalt and basaltic andesite are in acknowledgement of the "basalt andesite dilemma" (Wilkinson, 1986:34). Many archaeological examples in this study belong to this overlapping category.

With this caveat notwithstanding, it must be recognized that mineral and textural range of individual basalts alone is enormous, not to mention andesite range as well. Some of these mineralogical, textural, and tectonic variables follow.
One of the most important variables in definition is mineralogical composition of basalts or andesites. The mineralogy will reflect certain conditions of petrogenesis and may also reflect a particular tectonic plate location (Gill, 1981, esp. Chapter 1, pp. 39, 189, and Appendices; Thorpe and Brown, 1985:3; and Figure 1.5 (p. 19) as developed shortly in the present chapter).

Some minerals appear normally only in basalt, some only in andesite, and some in both. For example, olivine is often present as a phenocryst product of mafic crystallization (particularly in the Great Rift in the Levant and also in Mexican basalts under discussion later regarding selected archaeological material of the present study). Although it is a ferromagnesian mineral, olivine as a phenocryst in these basalts can be either a primary (dominant) phenocryst as in Levant basalt or a secondary or even tertiary phenocryst, outnumbered by both plagioclase feldspar and pyroxene as in the Tuxtla basalts of Mexico), particularly in a rock on which contemporary petrographers disagree as to its identification either as a basalt or as a basaltic andesite, (Coe and Diehl, 1980), highlighting Wilkinson’s point regarding the inconsistent or imprecise definitions. Part of the problem in identification may be due to the reluctance of some geologists to accept as andesite a material with frequent olivine phenocrysts, although it is often maintained that the basaltic andesites may contain olivines (Read and Watson, 1973:423; Thorpe and Brown, 1985:67 & ff; Le Maitre, 1989:50). Clearly the latest studies in nomenclature allow olivine in basaltic andesite. Figure 1.2 below
provides some clarification on nomenclature used for porphyritic lavas in terms of possible phenocryst phases and combinations.

Figure 1.2 MAJOR PHENOCRYST PHASES IN PORPHYRITIC LAVAS

<table>
<thead>
<tr>
<th></th>
<th>Basalt</th>
<th>Basaltic Andesite</th>
<th>Andesite</th>
<th>Dacite</th>
<th>Rhyolite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plagioclase</td>
<td>**</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>Olivine</td>
<td>**</td>
<td>**</td>
<td>*</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Pyroxene</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>*</td>
<td>--</td>
</tr>
<tr>
<td>Hornblende</td>
<td>*</td>
<td>*</td>
<td>**</td>
<td>**</td>
<td>*</td>
</tr>
<tr>
<td>Biotite</td>
<td>--</td>
<td>--</td>
<td>*</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>Alkali Feldspar</td>
<td></td>
<td></td>
<td>*</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>Quartz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe-Ti Oxide</td>
<td>**</td>
<td>**</td>
<td>*</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

*** most often present    ** frequently present
* rarely present        -- absent or rare

(from Thorpe and Brown, 1985: 67)

It is also true that andesites pass into basalt by increasing anorthite (calcic) content of the plagioclase feldspar (Read and Watson, 1973:423).

Some basalt names reflecting mineral differences are tholeiitic basalt, picritic basalt, alkali olivine basalt, ankaramite basalt, trachybasalt (not in current favour), absarokite basalt, shoshonite basalt, and andesitic basalt (Mackenzie, Donaldson, Guilford, 1982). Some names like picrite, melilite or basanite are not used by all geologists for subcategories of basalt while some names listed above are suggested as having overlapping subcategories. It is primarily basalts with SiO wt % between 46-51% (only one, Hazor archaeological basalt, below this at 44.5% SiO )
which are found in the present study.

Some andesite names reflecting mineral differences are pyroxene andesite, biotite hornblende andesite, boninite (high magnesia andesite), dacitic andesite, trachyandesite (not in current favour), calc-alkali andesite, tholeiitic andesite, feldspathoidal andesite, and basaltic andesite (Mackenzie, Donaldson, Guilford, 1982:101). Again, some of these names or types are overlapping subcategories.

While these lists cover most of the common basalt and andesite names as distinct rock types, some are often used imprecisely or are synonymous with others also in this list (Wilson, 1986:34). Naturally, because the present study deals mostly with material on the basalt-andesite boundary, most of the names or types mentioned above are not germane to this discussion.

It is important to note that although Le Maitre states that the term andesite-basalt "for rocks intermediate in composition between andesite and basalt" is obsolete (Le Maitre, 1989:46), he recognizes the term basaltic andesite for volcanic rock having the expected feldspar composition of an andesite with the ferromagnesian olivine expected in basalt (Le Maitre, 1989:50).

The mineralogical variations present in the material examined in the present study will be fully discussed in Chapters 5 - 7. These discussions will take into account prior identification of the material which may be either dated or made according to different definitions for basalt and andesite, although updated where possible.

1.2.3 Textural Variables

The above description of mineralogical variables suggests such differences will also be manifested texturally. It is to be
expected that a given mineral type will not necessarily display identical textures in different deposits. Size and percentage of phenocrystals will also reflect petrogenesis: magmatic conditions can favor crystallization of many small phenocrysts or fewer large ones of one mineral while not affecting other minerals so markedly. In magmatic evolution the reaction series which comprise the order in which minerals crystallize (Ryan, 1987; Turcote, 1987; Read and Watson, 1973:404) will determine texture as, for example, different minerals precipitate out of the magma according to reaction series (Bowen, 1956), starting with basic magma (up to 52% wt SiO), then intermediate magma (up to 57 wt % SiO), and finally into acid magma (more than 57 wt % SiO). Figure 1.3 below exemplifies the main reaction series applicable to basalt and andesite.

Figure 1.3 MINERAL REACTION SERIES

A) mafic minerals  B) plagioclase-feldspar minerals

olivine  anorthite
enstatite  bytownite
diopside  labradorite
hornblende  andesine
biotite  oligoclase
orthoclase
muscovite
quartz

The olivine and the anorthite begin to crystallize at higher temperatures and lower temperature crystallization forms such
minerals as biotite and albite (Read and Watson, 1973:404-07).

Textural features of basalts and andesites can vary greatly. Some of these features which can be optically determined include the following as shown by Table 1.1 below.

Table 1.1 COMMON TEXTURAL FEATURES IN BASALT AND ANDESITE

1. Grain size: fine-grained to medium-grained (mean < 1 mm) (mean < 5 mm) (although some phenocrysts can be > 5 mm)

2. Porphyritic: contrast between large phenocrysts and groundmass matrix
   or Homogenous: no contrast (or indeterminate)

3. Volume: in Ratios of Phenocrysts to Groundmass

4. Crystal Fabric and Habit: Shape of crystals in geometric arrangements
   (euhedral: bounded by complete and perfect faces)
   (subhedral: bounded incompletely by faces)
   (anohedral: lacking crystal faces)

5. Glomerocrysts: clusters of joined phenocrysts

6. Vesicles: cavities (gas) or amygdaloidal (secondary crystallization)

An example of textural variation which evidences the diversity of petrogenetic conditions follows. One of the most common mineral combinations found in andesite provides a description of it as an augite (pyroxene) andesite. Although the nearly ubiquitous plagioclase feldspar is the dominant phenocryst in augite andesite, its presence is assumed here in the name augite andesite. In bulk chemical composition three augite andesites may be nearly identical, yet the size and distribution of phenocrysts may be very dissimilar.
For example, pyroxene andesites from Santorini, California, and Peru in archaeological use may have a wide range in elemental composition in regard to spectroscopic analyses, e.g. the wt % of SiO ranges from 54.5 - 62.7; the wt % of CaO ranges from 4.5 - 7.9; the wt % of AlO ranges from 14.2 - 23.9; the wt % of FeO ranges from 1.7 - 7.2; the wt % of KO ranges from 1.1 - 4.0; the wt % of NaO ranges from 2.0 - 5.0. Yet, while the Santorini andesite is from an island archipelago and the California and Peruvian andesites are from western continental orogenic margins, the Santorini island arc andesite very closely resembles the orogenic California andesite in thin section (Plates 1.1 & 1.2) in polarised light and as texturally determined by optical petrology. In fact the California orogenic andesite bears little resemblance using the same textural comparisons to the orogenic Peruvian andesite. As can be seen in the photographs, the elementally-different Santorini and California andesites have markedly similar texture in groundmass volume, phenocryst volume, size and distribution, whereas the Peruvian andesite has markedly different texture with lower phenocryst volume, size and distribution. Furthermore, this Peruvian andesite (from Pisaq on the Rio Vilcanota, Cuzco province) is significantly different mineralogically and texturally from other Peruvian biotite and hornblende andesites (from Rumiqolqa and Huaccoto) within a 35 mile radius.

Many other examples of textural variation even within one local volcanic suite, e.g. the Hauran-Golan olivine basalt depositions in the Levant (as examined in some detail in Chapter 6), may have very different textural features (see Plates 6.3 to 6.8) although chemical analyses may show them to be elementally
Plates 1.1 and 1.2

(Plate 1.1 [above]) SANTORINI PYROXENE ANDESITE: Note similarity in texture, e.g. plagioclase feldspar, pyroxene, groundmass and overall volume, to (Plate 1.2 [below] OLOMPALI PYROXENE ANDESITE. The only clear difference is the OLOMPALI groundmass microcrysts.

Scale (for both photographs) 0.4 mm =  | ------------

14
similar (see Table 7.6) with "flows of similar chemical type" (Thorpe-Williams et al., 1990b:11). Such variations in textural constitutions of andesites and basalts must be expected, i.e. more the rule rather than the exception. In these circumstances the role of optical differentiation using microscopic analysis, as will be discussed in Chapters 3 & 4, may be important for suggested determination of stone sources. This will be presented more fully in successive chapters.

As can be inferred from the above Figure 1.3 and Table 1.1, likely mineral and textural features used to distinguish basalt from andesite would be that because andesite usually crystallizes at a slightly lower temperature than basalt (Read and Watson, 1973:406), basalt would typically contain more olivine than would andesite (if indeed any olivine is present except in basaltic andesite) and basalt would also be unlikely to contain biotite, which the more acid andesites might contain (Read and Watson, 1973: 423). Tholeiitic basalts, however, could contain little or no olivine (Read and Watson, 1973:408; Le Maitre, 1989:121-22). No tholeiitic basalts are included in archaeological samples and analyses of the present study, thus tholeiitic basalt will not be a focus of this research.

Another mineral and textural feature which could be useful in distinctions between basalt and andesite is the nature of the plagioclase feldspar: basalt would be more likely to have the basic plagioclases such as anorthite, bytownite, and most usually labradorite (Read and Watson, 1973:408) whereas the acid plagioclases such as albite would be very unlikely; andesite on the other hand would be more likely to have the intermediate plagioclases, most often andesine (or have more acid plagioclase
than do basalts) (Read and Watson, 1973:422). As stated elsewhere in the present study, "andesites pass into basalts by increase in the anorthite content of the plagioclase" (Read and Watson, 1973:423).

A solely textural feature often used to distinguish basalt from andesite is the zoning of plagioclase feldspar phenocrysts. While some zoning is possible in basalts, in particular normal zoning with more calcic plagioclase in the phenocryst cores, common oscillatory zoning found in andesite is very unusual in basalt (Read and Watson, 1973:423), probably due again to the fact that basalt crystallizes at higher temperature than does andesite, therefore the "albitization" of andesite plagioclase is possibly alternating in lower, less stable temperature-disturbed zoning (Read and Watson, 1973:423) or as a result of environment (such as hydration) and diffusion rate-controlled compositional gradients (Gill, 1981:171). However, again, the members on the margins of the basalt to andesite continuum, e.g. andesitic basalt and basaltic andesite, may not possess strictly typical textural features of either basalt or andesite.

1.2.4 Tectonic Variable

Another important consideration in an introductory chapter on geological nomenclature and the nature of basalt and andesite is the plate tectonic setting in which these rocks occur, whether on a continental margin, a mid-oceanic ridge, an orogenic (mountain-forming) chain, or an island arc. The basalts and andesites under consideration in the selected archaeological settings present study derive from lava flows of various kinds in asso-
ciation with continental tectonic activity usually in orogenic, i.e. mountain-forming, contexts (as distinguished from mid-ocean ridge basalts, also in association with tectonic activity but not in association with continental margins or island arcs). Figure 1.4 shows global distribution of volcanic rock in plate tectonic settings both near to and distant from plate margins. The work of Gill and Thorpe shows orogenic (or continental mountain-building) volcanism and island archipelago volcanism to have distinct tectonic origins and thus to give rise to some rocks of distinct mineral constitutions although others are of similar constitution (Gill, 1981; Thorpe, 1985). Figure 1.5 demonstrates some of the probable relationships between plate tectonic setting and igneous classification.

As will be seen in subsequent chapters, the separate regional discussions of basalt and andesite characterisations will include some mention of plate tectonics and elemental tendencies, as in the following characteristics of South American volcanic suites. Plate tectonic origins are shown to be relevant distinctions for characterisation of Andean volcanics, for example, in the Eastern Cordillera as suggested by Thorpe for the SVZ (South Volcanic Zone) and CVZ (Central Volcanic Zone):

"The geochemical characteristics of the SVZ lavas correspond to island-arc volcanic rocks while those of CVZ lavas are enriched in K, Rb, Th and U in comparison with such lavas and approach the overall composition of the continental crust...The CVZ basaltic andesites may be derived from mantle containing subduction zone components." (Thorpe, 1982 Ch.1: "Plate Tectonic Setting and Andean Magmatism."

As will be seen in Chapter 5, high K percentage is seen in chemical analyses of Rumiqolqa and Huaccoto andesites. Prior studies also suggest biotite and hornblende mineralogy in both plutonic and extrusive Andean material (Pitcher, 1984:154-55).
Figure 1.5 below also presents an overall picture of tectonic setting relative to basalt and andesite.

Figure 1.5 IGNEOUS PLATE TECTONIC SETTING

<table>
<thead>
<tr>
<th>Plate Margin</th>
<th>Within Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constructive</td>
<td>Destructive</td>
</tr>
<tr>
<td>Margin</td>
<td>Ocean Basin</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Extrusive</td>
<td>Basalt</td>
</tr>
<tr>
<td>Intrusive</td>
<td>Gabbro</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(from Thorpe and Brown, 1985:3)

In keeping with diversity of volcanic material and the variable of mineralogy (as discussed in prior detail), Harmon and Barreiro suggest:

"Destructive plate margin magmagenesis is one of the most intensely studied and widely debated topics in the earth sciences at present. Calc-alkaline volcanic and plutonic rocks in orogenic settings exhibit such a diversity of composition and character that the subducted oceanic lithosphere,
the overlying 'enriched' lithospheric mantle and the lower continental crust all have been advocated recently as the primary source region for island-arc and continental margin basaltic to andesitic magmas." (Harmon and Barreiro, 1984:1)

Also, MORB basalts (mid-oceanic ridge basalts) can be distinguished from the mostly continental margin or orogenic basalts on clear mineral grounds, MORB basalts most often being more mafic (Norry and Fitton, 1987). With high concentrations of olivine or pyroxene minerals to the possible near exclusion of other minerals like feldspars, MORB basalts can be quite basic (Read and Watson, 1973:430).

In summary, the different tectonic environments may favor different varieties of extrusive rock. Oceanic regions with thin oceanic crusts will have predominantly olivine basalts, e.g. as the large shield volcanoes of the Hawaiian islands (Read and Watson, 1973:409). Stable continental areas will have plateau regions with tholeiitic basalts, e.g. as in the Deccan Traps of southern India (Sen, 1986:627-28). Orogenic belts on continental margins and some island arcs over subduction zones adjacent to continents will have andesites, e.g. Javanese Andesites in Southeast Asia - Oceania or Aegean (Thera) andesites in Greek islands (Puchelt and Hoefs, 1971:318-21; Gill, 1981:207, 336). In many regions such as where plate margins are proximal, as is the case in the Mexican Volcanic Belt (including the Tuxtla Mtns.) on the narrow isthmus edge of the eastern face of the North American continent and also in the Levant where a rift valley separates Eurasian and African plates, olivine or alkaline basalt is expected (Read and Watson, 1973:623; Freund et al., 1965:37; Hasenaka and Carmichael, 1987:241 & ff).
1.2.5 Variations in Weathering and Age

Another variable which is more problematic in field identification than in petrography is the age and weathering stage of the rock, either geological or archaeological. Fresh andesite is likely to be dark grey to light grey in colour (the dark colour may also often be attributed to glass content), whereas the same andesite can be externally weathered with pinkish oxides of mafic minerals. Other weathered andesite colours can include pale grey, beige, mauve, and pale green. Furthermore, mineral colour may be greatly affected by factors like variable hydrothermal alteration in the same deposit, as can be found at Rumigolqa, Peru, where vertical stratigraphy is not as important as proximity to hydrothermal vents which have altered some of the dark grey andesite to a red hue without affecting other material in this deposit. This local hydrothermal activity can also change chemical composition while retaining the optical pseudomorphs of the original minerals. This is not to suggest that age is not a significant weathering factor but that other variables may be also at work.

The age of a deposit itself may be responsible for the state of an andesite. Andesites of a great age may be so altered chemically as to be andesite in name only, having reached maximum alteration and perhaps with it a temporary equilibrium until further conditions favour additional alteration, e.g. albite may be replaced by chlorite which may be more stable in a certain environment than the albite. However, even though time may be the greatest single factor over millennia (Colman and Pierce, 1981), for geological weathering (as discussed in Chapter 8 later), it is unlikely that it would ever be the only weathering factor.
Another factor which may affect weathering is climate. Studies on differences between tropical and temperate andesites suggest macroclimate can greatly affect weathering rates of certain minerals within basalt and andesite (Colman and Pierce, 1981:8-9) and silicates in general (Winkler, 1975). Other environmental factors potentially affecting the geological weathering of basalt and andesite have been identified as biological organisms (vegetation like algae and lichens), topography (altitude as well as terrain) and microclimate (Colman and Pierce, 1981:9). It has been determined that the actual rate of weathering is somewhat faster for basalt than for andesite (Colman and Pierce, 1981:10). On a mafic to felsic scale, the more mafic the basalt, the faster the weathering (Colman and Pierce, 1981:10). In the case of the andesitic basalts and basaltic andesites, this rate difference is less marked. The weathering of extrusive rocks will be more fully explored in Chapter 7.

1.2.6 Summary of Variability

Sections 1.2.1 - 1.2.5 illustrate that study of basalt and andesite must account for a wide range of geological conditions and circumstances. Some implications of variations are immediately apparent: while variations in basalt and andesite will facilitate determination of the provenance of individual geological materials, this same factor of variation will be likely to hinder the extrapolation of weathering patterns from one site to another, particularly complicated by such variation in environment.

Any archaeological investigation which does not take account of these variables at the outset will be at great risk of
poorly assessing either large or small scale differences between individual basalts or andesites.

1.3 *Rationales Used for Archaeological Selection in the Present Study*

The present study of volcanic material has been selective for certain archaeological basalts and andesites which share some common features. The attempt has been to choose archaeological contexts where at least one feature can be compared (whether in the proximity of geological material, environmental conditions, site and stoneworking chronology, or stoneworking methods) to the other selected sites or contexts. Naturally, it was not expected that all the contexts would match perfectly, in which case the two most important features were arbitrarily selected to be the mineralogical proximity and the site chronology (where a wide range of chronological use could provide comparative data), in keeping with the research of Colman and Pierce that the two most important weathering factors were time and parent mineralogy (Colman and Pierce, 1981). The following paragraphs detail the selection criteria.

One criterion used in selecting the sites to be studied was the mineralogical constitution of basalt or andesite. Wherever possible, geological material close to a basaltic andesite "boundary" has been chosen. The rationale for this is that expected phenocryst minerals should include basic to intermediate plagioclase (e.g. bytownite, labradorite, andesine) and mafic minerals such as olivine and pyroxene (Le Maitre, 1989:50). Thus it would be theoretically possible to also examine material which was outside the basaltic andesite boundary but also had either a
common mafic or plagioclase mineral for potential weathering comparisons (see Figure 1.2) in a felsic groundmass.

Another criterion used in site selection was that they should be broadly similar in their environment or climate. Where possible, sites similar in Mean Annual Precipitation (MAP) and Mean Annual Temperature (MAT) were chosen, although this aim was not fully realized except in Inca contexts in Peru. Common relative humidity overall (as in the tropics) or in seasonal variations was a climatic subfactor in the total environmental picture. The assumptions applied to all sites was that current climatic conditions are similar to those that have pertained over the last few millenia, or that any significant past climatic variation will have had similar effects on the sites studied.

While several contexts are from temperate Mediterranean climates and others are from high altitude or tropical climates, in most cases considerable similarity can be found in MAP and MAT. On the other hand, it was also considered desirable to have some contexts reflect a wide range climatic range where possible but have similar chronology in order to assess factors other than time in the weathering of archaeological stone.

Another criterion for site selection was the requirement that the samples removed from rock surfaces needed to be quite large in order that the full thickness of any weathering features might be preserved (not necessarily the same as the quantity of samples required for representative sampling on each site). In each case large objects such as architectural members (or in some cases sculptural objects) were chosen so that weathering indices could be potentially observable. This would be problematic if the objects were small artifacts because smaller objects would too
often possess an insufficient thickness for observing a complete weathering profile from worked surface to fresh core. It was also necessary in studies of stone provenance (as well as weathering studies) to obtain a large number of samples for representative sampling (to be taken up in Chapter 4).

A secondary selection criterion used in selecting sites for this research was that the most probable kind of stoneworking technology used to shape the basalt or andesite, in most cases battering the stone with hammerstones made of materials such as quartzite or dolerite, should be similar at the different sites. The rationale for this is quite simple in that similar stone compression will be a resultant feature of similar techniques of stoneworking. As can be seen, this criterion applies not to provenance study but to weathering analysis. If the extent of weathering of material could be evidenced to be independent of variations in stoneworking technique and solely dependent on another feature such as time (all other variables being equal), it could suggest a reliable dating technique in stone weathering.

A final criterion for the selection of archaeological material for study was that it should display wide chronological range. Archaeological material of similar age from different sites is also valuable for assessing the effects of variables other than time on the weathering process in that if material were of comparable age but dissimilar in weathering, the difference could be attributed to mineralogical, environmental or other variables. In some cases this contemporaneity was desirable (as an experimental control factor where all other variables were equal), but for this project site selection mostly
reflected a wide spread of ages to determine if time could contribute to significant weathering differences. The range in chronology of selected cultures is from circa 8500 B.C. (Jericho) to A.D. 1450 (Inca contexts).

Thus these selection criteria are the factors which determined the location of fieldwork. For a summary of these selection criteria, see Table 1.2 below in which each archaeological locus thus chosen can be seen in relation to the others.

<table>
<thead>
<tr>
<th>Culture</th>
<th>Mineralogy</th>
<th>Environment</th>
<th>Use</th>
<th>Stoneworking</th>
<th>Chronology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inca</td>
<td>hornblende</td>
<td>mountain</td>
<td>ashlar</td>
<td>battering (probable)</td>
<td>15th c. A.D.</td>
</tr>
<tr>
<td></td>
<td>andesite</td>
<td>tropical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>biotite</td>
<td>andesite</td>
<td>mountain</td>
<td>ashlar</td>
<td>battering (probable)</td>
<td>15th c. A.D.</td>
</tr>
<tr>
<td></td>
<td>pyroxene</td>
<td>mountain</td>
<td>ashlar</td>
<td>battering (probable)</td>
<td>15th c. A.D.</td>
</tr>
<tr>
<td></td>
<td>andesite</td>
<td>tropical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Olmec</td>
<td>pyroxene-olivine</td>
<td>lowland</td>
<td>sculpture</td>
<td>battering (probable)</td>
<td>10th c. B.C.</td>
</tr>
<tr>
<td></td>
<td>basalt</td>
<td>tropical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canaanite</td>
<td>olivine</td>
<td>Mediterranean or semiarid</td>
<td>tool sculpture (probable)</td>
<td>8th mill. B.C. and 15th c. to 10th c. B.C.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>basalt</td>
<td>temperate</td>
<td>ashlar</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Archaeological material was studied at two other contexts, however, sampling was not permissible or possible on the archaeological material itself. In these cases the analyses were strictly confined to geological material, and these last two contexts will only enter into geological discussions.
Table 1.2b  ARCHAEOLOGICAL CONTEXT SELECTION CRITERIA

<table>
<thead>
<tr>
<th>Mineralogy</th>
<th>Environment</th>
<th>Use</th>
<th>Stoneworking</th>
<th>Chronology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Culture</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycladic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pyroxene</td>
<td>Mediterranean</td>
<td>ashlar</td>
<td>unknown</td>
<td>15th c. B.C.</td>
</tr>
<tr>
<td>andesite</td>
<td>or semiarid</td>
<td>temperate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amerind</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pyroxene</td>
<td>Mediterranean</td>
<td>sculpture</td>
<td>unknown</td>
<td>unknown</td>
</tr>
<tr>
<td>andesite</td>
<td>or semiarid</td>
<td>tool</td>
<td></td>
<td>temperate</td>
</tr>
</tbody>
</table>

In discussion of the above general table, several clarifying points are noted: 1) in describing environment the first word given (e.g. mountain, lowland or Mediterranean) is in reference to local environment or altitude) whereas second word given is in reference to latitude and or dominant climatic factor based on MAP and MAT (e.g. tropical, temperate, semiarid); 2) in method of stoneworking, hammerstones in these contexts provide evidence; 3) the Olmec material has been described elsewhere on occasion as andesitic basalt (Coe and Diehl, 1980); 4) some similarity in mineralogy or lithology can be seen in that pyroxene and olivine respectively are seen as the primary phenocrysts after plagioclase feldspar; and 5) the Amerind material from Olompali, Marin, California, has been assumed to be Pre-Penutian in culture or date of petroglyphs, circa 3000 B.P. (Parkman, 1986, pers. comm.). but chronology and stoneworking in this context have yet to be established. This Amerind material is unfortunately heavily covered with lichen (which affects weathering rates, as noted in Chapter 8) and is culturally protected so that sampling is prohibited on archaeological material. As such this Amerind context, along with the Cycladic context at the Akrotiri of Santorini (Greece) in the Aegean must wait to be examined.
further outside the present study for further weathering data. It will also not be included in questions of provenance in the present study because the andesite petroglyphs at Olompali are in their own native rock emplacements, i.e. boulders in original deposition on Burdell Mountain, where geological source is unquestioned at the present (Parkman, 1986, pers. comm.).

As suggested earlier, it was not always possible to find archaeological contexts which conformed exactly to the above criteria. In some cases, one criterion would be sacrificed if other factors were as required. Since both provenance and weathering data were assessed for Olmec, Canaanite, Neolithic and Inca contexts, the above criteria and conditions were chosen where others not specified here might be ideal on an individual basis were only these unspecified criteria to be pursued separately. The chapters which follow on provenance and weathering explain each archaeological and cultural locus in more detail.

1.4 Conclusions

In summary, the geological nature of basalt and andesite as defined in the literature especially by Le Maitre in 1989 suggests that much of the debate over the arbitrariness of nomenclature will give way to chemical definitions, particularly total alkali silica (TAS) and related systematic expression of all the features rather than being defined by colour or just mafic content. Also important to this thesis is the boundary between basaltic andesite and andesite (Le Maitre, 1989:28, 40). The variables mentioned in sections 1.1 and 1.2 are reminders that not all basalt or andesite is identical, i.e. that any such manmade continuum will probably always be modified.
Chapter Two

REVIEW OF HISTORICAL USE OF BASALT AND ANDESITE
AND POTENTIAL CRITERIA FOR STONE SELECTION

2.1 Ancient Historical References to Basalt or Andesite

2.1.1 Old World References: Known and Potential

The use of basalt in antiquity has been known even by such historians as Pliny the Elder, as the first attestation of the word basalt comes from his Historia Naturalis, XXXVI 58, 147, even though it can be argued that his use of the word as a stone medium extends to meanings beyond definitions for volcanic stone. However, Pliny’s systematic efforts suggest an incipient scientific and historical appreciation for this material.

It is to be expected as has been suggested with Classical antiquity (Moore, 1834) Pliny’s Latin basalt and the Greek words basanos ("touchstone") and basanites (from which the current geological name for a type of basalt derives) and also noted for ancient Mesopotamia with a variety of lexical terms (Stol, 1978) that practitioners and manuals of ancient stone technology would have terms for stone which could encompass basalt but would in all likelihood overlap with other dark stones entirely unvolcanic in origin or physical characteristics beyond colour. This is also well established for Egyptian lexicography of stone in the word bhn which could encompass a wide range from basalt to greywacke (Lucas and Harris, 1962; A.J. Spencer, 1990, pers. comm.). It is also the case for Assyrian lexicography with the words adbar as well as kasurru and šallamtu probably referring to basalt but also overlapping with other stone or, as in the case of the other cultures noted above, not mineralogically identifying all basalts by our terms (Campbell Thompson, 1936; Stol, 1978). A word
possibly related to the Egyptian bhn is found in classical or biblical Hebrew: bht, tentatively identified as a porphyry or a stone alternatingly black and pearly white (or with an ochre red) if its descriptive appearance in Esther 1:6 is reliable or can be translated: bht uss udr ushrt as "baḥat and ochre and white and black" (Brown, Driver, and Briggs, 1979:96, 204, 695, 1007, 1059).

Any incipient geological awareness of basalt and andesite (which until the mid-19th c. was subsumed within the basalt range with the word "andesite" coined at that time) is not suggested for ancient technology based on anything beyond observation, but it must be expected that certain characteristics beyond colour (i.e. hardness and maybe even durability) would have been noted experientially by ancient masons in quarrying or looking for new quarries as those of prior generations were exhausted. With these caveats, Table 2.1 below contains some of the above terms used since antiquity for basalt and andesite.

Table 2.1 POSSIBLE ANCIENT TERMS FOR BASALT AND ANDESITE
MATERIAL IN OLD WORLD CONTEXTS

<table>
<thead>
<tr>
<th>Term</th>
<th>Culture/Language</th>
<th>Literary Reference/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. gul-gul</td>
<td>Sumerian</td>
<td>Stol, 1979: 89 &amp; ff</td>
</tr>
<tr>
<td>2. lasqum</td>
<td>Akkadian</td>
<td>Stol, 1979: 86</td>
</tr>
<tr>
<td>3. adbar(u)</td>
<td>Sumerian</td>
<td>Campbell Thompson, 1936: 160 &amp; ff</td>
</tr>
<tr>
<td></td>
<td>Akkadian</td>
<td>Campbell Thompson, 1936: 160 &amp; ff</td>
</tr>
<tr>
<td></td>
<td>Old Babylonian</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Assyrian</td>
<td></td>
</tr>
<tr>
<td>4. walledamtu</td>
<td>Akkadian</td>
<td>Campbell Thompson, 1936: 160 &amp; ff</td>
</tr>
<tr>
<td></td>
<td>Old Babylonian</td>
<td>Campbell Thompson, 1936: 160 &amp; ff</td>
</tr>
<tr>
<td></td>
<td>Assyrian</td>
<td></td>
</tr>
<tr>
<td>5. kasurru</td>
<td>Akkadian</td>
<td>(from the city Gasur) Campbell Thompson, 1936: 160 &amp; ff</td>
</tr>
<tr>
<td></td>
<td>Old Babylonian</td>
<td>Campbell Thompson, 1936: 160 &amp; ff</td>
</tr>
<tr>
<td></td>
<td>Assyrian</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Word</td>
<td>Language</td>
</tr>
<tr>
<td>---</td>
<td>--------</td>
<td>----------</td>
</tr>
<tr>
<td>6.</td>
<td>simurr</td>
<td>Old Babylonian</td>
</tr>
<tr>
<td>7.</td>
<td>behen</td>
<td>Egyptian</td>
</tr>
<tr>
<td>8.</td>
<td>kunkunuzzi</td>
<td>Hittite</td>
</tr>
<tr>
<td>10.</td>
<td>rehajim (?)</td>
<td>Hebrew</td>
</tr>
<tr>
<td>11.</td>
<td>pelah tahtit (?)</td>
<td>Hebrew</td>
</tr>
<tr>
<td>12.</td>
<td>Lydia lithos</td>
<td>Greek</td>
</tr>
<tr>
<td>13.</td>
<td>basanos</td>
<td>Greek</td>
</tr>
<tr>
<td>14.</td>
<td>basanites</td>
<td>Greek</td>
</tr>
<tr>
<td>15.</td>
<td>lithos mylias</td>
<td>Greek</td>
</tr>
<tr>
<td>16.</td>
<td>pyrimachos</td>
<td>Greek</td>
</tr>
<tr>
<td>17.</td>
<td>basalt</td>
<td>Latin</td>
</tr>
<tr>
<td>18.</td>
<td>hamma</td>
<td>Arabic</td>
</tr>
</tbody>
</table>

Some discussion of the above list is necessary to clarify any possible misinterpretations. First, this list is not comprehensive for Old World antiquity. Second, it may list only some of the most common words. Third, several qualifications must be noted. One is that pyrimachos could also as easily mean "fire-resistant" as "fire-fighting" or even like flint, "fire-starting" or having fire associations, as pyrites. Also, none of the Hebrew words are well-attested and two (#10 & #11) are only suggestions given the near ubiquity of basalt in the Levant used in millstone.
associations (Stol, 1979:83). However, in the word bahat both phonetic and semantic connections with "porphyry" to the Egyptian behen could be significant.

One observation drawn from the numerous ancient Near Eastern possible words for basalt suggests an abundance of basalt in the area: this can be evidenced easily by major volcanic flows in the Caucasus, Taurus, Zagros, Jebel Druze, Hauran-Golan-Jordan Valley Rift Zone, and many others from which ancient peoples could take material for artefacts (see Figure 1.4). Although some discussion in Chapter 7 will centre on the Anatolian (Caucasus-Taurus) use by the Hittites (and a brief mention of the volume of Assyrian use), Chapter 7 will examine in some detail the Jordan-Great Rift Valley major basalt abundance.

Also, as mentioned earlier in this chapter, the geologist von Buch created the word "andesite" in 1836 for the volcanic rock found mainly in the Andes mountains of South America, a lava with a generally lighter hue than the basalt under which it had been subsumed until the mid-19 c. (von Buch, 1836). The comments of Le Maitre are most appropriate to the distinctions between basalt and andesite as presently defined (Le Maitre, 1989), summarised earlier in Chapter 1 of the present study.

2.1.2 New World References: Known and Potential

Although they are not mentioned on the above table, New World words for basalt or andesite must also have existed where these stones were used in distinction to other available stone. Rumi, a current Quechua generic word for "stone" (Cordero, 1989:98) may be reflected in some component of a relict Inca word for andesite
specifically. Unfortunately, it is too nonspecific when it could apply to other stones as well at the Inca andesite quarries of Rumiqolqa, Peru, although its association there has been known for centuries (Protzen, 1986). Nonetheless in Junin Quechua and in Ecuadorian Quichua certain word stems can be extrapolated into the appropriate Quechua compounds for grey and black stone. With a slight palatalization of the "r" phoneme (a common linguistic exchange of "r" for "l"), lumi is the Junin word for "stone" and uqi and yana are the terms for "grey" and "black" respectively (Cerron-Palomino, 1976; Cordero, 1989:125, 129). Thus, yanalumi could mean "black stone" and uqilumi could mean "grey stone" in the Junin dialect of Quechua in the volcanic (andesite) mountainous province all around Huaraz, Peru, with yanarumi and uqirumi meaning the same things in the Cuzco Quechua or Quichua dialect (Cordero, 1989:98, 125, 129). This is not unfeasible considering numerous current Quechua toponyms (place-names) which are likewise attested in the Colonial texts as then Inca toponyms for the same places, many of which can be seen on current Peruvian and Ecuadorian maps and often refer to ancient Andean quarries. What would be most helpful in this case would be for Quechua dialects to also convey the idea of vulcanism. One such Quichua word compound is ninata shitag urcu (Cordero, 1989:301) which can be translated as "fire-throwing mountain." How original to the Inca this compound might be is unknown, since multiple compounds have some history as neologisms (i.e. "new words") in language as a whole. Nonetheless, recent vulcanism can thereby be asserted as thus witnessed by native Andean observers. Unfortunately, any application to a specific Inca stone medium or Inca historicity of the term cannot at the
present time be suggested.

Olmec terms will likely be impossible to reconstruct, but Aztec terms could be possibly reconstructed considering the many Aztec basalt sculptures, the accessible Aztec-Spanish chronicles, and the current Nahuatl language. One such possible term could be tetl, which probably best means just "stone." In view of the fact that the most abundant stone available to the Aztecs was basalt, living as they did in the Cordillera Volcanica of highland Mexico, the word tetl alone may suffice (Simeon, 1855). However, over 400 words in Simeon alone have tetla- as a root for many compounds. If nothing else, it shows the following possibilities: 1) how pervasive the word is; 2) or how important certain properties of stone were in the Aztec culture; or 3) how the word lends itself to a rich spectrum of idiomatic expressions across a wide range of activity (Baquedano, 1990, pers. comm.). Other terms which suggest the Aztecs made textural and density distinctions include tezontle for "pumice," tepetlatl possibly for "mountain rock" and tetlacuiloliztli for "stone sculpture" (Simeon, 1855), although these may also be relative terms.

In the Polynesian culture of Easter Island, words exist in the Rapa Nui (Easter Island) language and Marquesas Islands for basaltic material, particularly hanehane for the red basalt scoria used in the monumental sculptures, and ke'etu (or keetu) in the Marquesas Islands for the same idea. Another such word is toki in the Rapa Nui language for the basalt picks used to work the hanehane. Several other related terms in Rapa Nui include punga for polishing stone, very likely a pumice, and paenga for worked stone in general.
These are only a few possibilities which, more than anything else, incline this researcher to suggest that some awareness has existed among different cultures (some in contact with each other but many having independent observations) for a pre-scientific appraisal of stone properties in general and basalt and andesite specifically. It is hoped this brief discussion may suggest paths of future study as well as generate a more accurate catalogue after continued research. Table 2.2 below lists the possible New World terms in summary form.

Table 2.2 POSSIBLE NEW WORLD HISTORICAL TERMS FOR BASALT AND ANDESITE

<table>
<thead>
<tr>
<th>Term</th>
<th>Language/Culture</th>
<th>Meaning</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. rumi</td>
<td>Quechua (C) -Inca?</td>
<td>&quot;stone&quot;</td>
<td>(Protzen, 1988, pers. comm.)</td>
</tr>
<tr>
<td>2. lumi</td>
<td>Quechua (J)</td>
<td>&quot;stone&quot;</td>
<td>(Cerron-Palomino, 1976, p. 80)</td>
</tr>
<tr>
<td>3. yanarumi</td>
<td>Quechua (C)</td>
<td>&quot;black stone&quot;</td>
<td>(Czwarno, 1990, pers. comm.)</td>
</tr>
<tr>
<td>4. uqirumi</td>
<td>Quechua (C)</td>
<td>&quot;grey stone&quot;</td>
<td>(Czwarno, 1990, pers. comm.)</td>
</tr>
<tr>
<td>5. yanalumi</td>
<td>Quechua (J)</td>
<td>&quot;black stone&quot;</td>
<td>(Czwarno, 1990, pers. comm.)</td>
</tr>
<tr>
<td>6. uqilumi</td>
<td>Quechua (J)</td>
<td>&quot;grey stone&quot;</td>
<td>(Czwarno, 1990, pers. comm.)</td>
</tr>
<tr>
<td>7. tetl</td>
<td>Nahuatl -- Aztec ?</td>
<td>&quot;stone&quot;</td>
<td>(Simeon, 1855, p. 520)</td>
</tr>
<tr>
<td>8. tepetlatl</td>
<td>Nahuatl</td>
<td>&quot;mountain stone&quot;</td>
<td>(Simeon, 1855, p. 496)</td>
</tr>
<tr>
<td>9. tezontle</td>
<td>Nahuatl</td>
<td>&quot;pumice&quot;</td>
<td>(Baquedano, 1990, pers. comm.)</td>
</tr>
<tr>
<td>10. tetlacuiololiztli</td>
<td>Nahuatl</td>
<td>&quot;stone sculpture&quot;</td>
<td>(Simeon, 1855, p. 522)</td>
</tr>
<tr>
<td>11. hanehane</td>
<td>Rapa Nui</td>
<td>&quot;statue stone&quot; ?</td>
<td>*</td>
</tr>
<tr>
<td>12. ke'etu</td>
<td>Marquesas</td>
<td>&quot;statue stone&quot; ?</td>
<td>*</td>
</tr>
<tr>
<td>13. toki</td>
<td>Rapa Nui</td>
<td>&quot;basalt pick&quot;</td>
<td>*</td>
</tr>
<tr>
<td>14. punga</td>
<td>Rapa Nui</td>
<td>&quot;polishing stone&quot;</td>
<td>*</td>
</tr>
<tr>
<td>15. paenga</td>
<td>Rapa Nui</td>
<td>&quot;worked stone&quot;</td>
<td>*</td>
</tr>
</tbody>
</table>

C = Cuzco dialect; J = Junin dialect

* Note: terms 11 - 15 all derive from the "Glossary," Journal of New World Archaeology 19 pp. 63-64.
These are only a few of the Old and New world terms which are more or less connected with basalt and andesite. Doubtless, both philology and ethnography will add to and/or subtract from the historical listings suggested in this preliminary synthesis.

2.2 Examples of Archaeological Use of Basalt and Andesite

2.2.1 General Properties and Global Distribution

While volcanic material has been used for millenia, its use appears limited to a certain range of human activity. Because of its usually coarse-grained texture and roughness (often due to gas-induced vesicularity), its hardness (between 5-6 on an approximated Mohs scale), and its usual dark colour, volcanic material is often not suitable for certain high detail use if other stone is available, particularly for artistic expression in such uses for sculptural or epigraphic media. There are exceptions, however, in that some cultures, notably Olmec and Hittite, have chosen basalt or andesite for sculpture when other stone was readily accessible. This suggests criteria other than workability.

Obsidian or volcanic glass is another highly-prized volcanic material. Its glassy nature allows it to fracture in splintery conchoidal fragments of an acicular shape with extremely sharp edges. For this reason obsidian flakes were sought for millenia, obviously not for sculptural reasons but for its ideal properties in making points and arrowheads or similar hunting and cutting functions whose sharpness would often make it a better material than flints or cherts except that it was also more brittle. The
seminal and still valuable pioneering work on ancient obsidian trade around the Mediterranean (Cann, Dixon, and Renfrew, 1969) with Melian, Liparian, and Turkish obsidian sources among others, shows how valuable and how widespread obsidian exchange was to cultures as early as the Mesolithic period. Other studies could also be cited of obsidian trade in both Old and New Worlds, among them the well-established Mesoamerican obsidian network operating as early as 4000 B.C. (Wilkerson, 1981; Moholy-Nagy and Nelson, 1987; Parry, 1987).

Because of the worldwide distribution of vulcanism, particularly in contexts of plate tectonic activity as discussed earlier in Ch. 1 (see Figures 1.4 & 1.5), it should be expected that archaeological use of basalt and andesite will be found relatively close to abundant flows. Figure 2.1 depicts major global archaeological distribution of cultures which have used volcanic material as discussed in the following paragraphs, with numbers provided on the global map to be linked with a map key.

2.2.2 Use of Basalt and Andesite in Tools

Prolific literature exists showing that volcanic material was widely used for millstones (Runnels, 1981) or querns (Peacock, 1980), pestles (Dorrell, 1983) and similar grinding tools (Childe 1943; Roder, 1953; Crawford and Roder, 1955; Moritz, 1958; Stol, 1978; van Tilburg, 1986; Thorpe and Williams-Thorpe, 1988). Volcanic stone has also been used for axes since the Neolithic in various loci: (1) Scandinavia (Olausson, 1983); and (2) Britain (Shotton, 1969); to name a few examples.
Figure 2.1

GLOBAL DISTRIBUTION OF ARCHAEOLOGICAL BASALT AND ANDESITE

(SEE TEXT FOR EXPLANATION OF NUMBERS AS CULTURAL CONTEXTS)

AREAS OF PAST AND PRESENT VULCANISM

3000 miles
GLOBAL DISTRIBUTION OF ARCHAEOLOGICAL BASALT AND ANDESITE

(See text for explanation of numbers as cultural contexts)
Cultures having used basalt and andesite for grinding tools would be too numerous to list. However, noting some of the above researchers, Runnels has studied (3) Aegean distribution and Doumas has comments on Santorini material (Doumas, 1983); Peacock has studied a wide range from (4) Roman and Mediterranean querns to (5) Gallo-Romanic and (6) Teutonic millstones; Dorrell has catalogued (7) Neolithic and Bronze Age Levant tools, Stol has discussed ancient Near Eastern millstones in (8) Sumer, Babylon and Assyria, Thorpe and Williams-Thorpe have studied a wide range of millstones or querns from the Roman, (9) Sardinian, (10) Cypriot, contexts to Asia Minor and the ancient Near Eastern (11) Levant; and van Tilburg has noted Pacific Islanders' tools from the (12) Marquesas and Easter Island.

Due mostly to physical properties of roughness and hardness as well as durability (some of which must have been known in earliest antiquity by experience), basalt and andesite are ideal as grinding material because they will pulverize organic material such as grains without significant compression or abrasion loss of the stone over time.

2.2.3 Use of Basalt and Andesite as Pavingstones

Another ideal use for flow-banded volcanic material which has a preferential alignment of its texture due to flow in a semi-molten state (or successively very shallow flows) and thus a tendency to fracture into flat slabs is as road or paving stone. A few cultures which have thus utilized basalt include (13) Roman (Moore, 1834; Hibbert, 1985) and (14) Colonial Spanish in Peru (Gregory, 1916), to name but a few.
2.2.4 Use of Basalt and Andesite in Architecture

Basalt and andesite have also been used frequently for architectural members and even sculpture either where cultures appear to prefer its aesthetic features, particularly dark colour, even when other stone is readily available.

While the following listing is not comprehensive, some of the cultural contexts in which basalt or andesite have been used for architectural members (often ashlars) ashlars include (15) Levant Neolithic Jordan (Betts, 1982), (16) Ghassoulian Chalcolithic (Epstein, 1985), (17) Canaanite (Yadin, 1958), (18) Cycladic (Puchelt and Hoefs, 1971; Marinatos, 1969-1976), (19) Sardinian Nuraghi (Gallin, 1987; Scheuer, 1990), (20) Roman Galilee (Yeivin, 1987), (21) Dacian (Condurachi and Daicoviciu, 1971:107; Radulescu, 1968), (22) Inca (Gasparini and Margolies, 1980; Protzen, 1986), (23) Aztec (Baquedano, 1984), (24) Tiwanaku (Pentland, 1837; Bandelier, 1910, 1911), (25) Wari (MacEwan, 1987 Hunt, 1990a), and (26) Polynesian (Van Tilburg, 1986).

2.2.5 Use of Basalt and Andesite for Sculpture or Religious Art

(Campbell Thompson, 1936; Stol, 1978; Reade, 1981), (34) Dacian (Condurachi and Daicoviciu, 1971:107), (35) Aztec (Baquedano, 1984; Baquedano and Orton, 1990), (36) San Agustin (Colombia) (Reichel-Dolmatoff, 1965), (37) Javanese Hindu and Buddhist (Winkler, 1975:155), and (38) Easter Island (Van Tilburg, 1986) cultures, among others.

2.2.6 Use of Basalt or Andesite for Petroglyphs

Related to sculptural use of basalt or andesite stone as an artistic medium, evidences of andesite for petroglyphic carvings can be found among (39) South African cultures (Willcox, 1984: 128); (40) North American Amerinds (Bard, 1976:21; Dorn and Whitley, 1984:319; and Parkman, 1986, pers. comm.) and among (41) Inca masons in Rumigolqa, Peru (Protzen, 1986:82), and in the Arabian Peninsula with (42) the Safaitic culture (Macdonald, 1991), to name a few examples.

It is vital for the sake of balance to note that while Figure 2.1 and the unprecedented lists of cultural uses above is only a preliminary register of global uses of basalt and andesite, it is by necessity limited in known African and Far East Asian contexts. This is because the selected contexts of the present study were drawn primarily from Old World and New World sites and the relevant literature. Doubtless this preliminary listing, which geographically reflects the research interests of this study, could be doubled or trebled by being more global. This, however, does not detract from what is a long-needed beginning in assessing global historical uses of basalt and andesite.

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2.3 Potential Stone Criteria for Selection

A theme which will recur throughout the present study is the question "Did ancient cultures have criteria for the selection of stone, and if so, can they be reconstructed?" This question does not presuppose that any one culture had a monopoly on the criteria (although certain cultures would have more appreciation for some of the criteria than other cultures), nor does it mean that any strictly-scientific geological principles formed the basis of understanding in what would be experientially-derived by observation or obtained via apprenticeships in traditions or even more or less crafts guilds in an incipient stone technology.

The potential criteria synthesised for the first time in this study are suggested as availability, workability, durability, and aesthetic appeal. A possible sub-criteria (only because it is more difficult to define and evidence in the opinion of this researcher) might be metaphysical properties associated by legend or other possibly religious sources. Brief definitions of these criteria are as follows.

2.3.1 Criterion of Availability

Availability could be defined here as a composite of both the relative abundance of a certain stone and access to it in terms of proximity to a given cultural occupation locus (e.g. the massive Yucatan limestone sediments on which Late Maya and Toltec complexes are found; these make up more than 95% of the Yucatan geology, conditioning for the most part the Late Maya and Toltec limestone architecture found all across the Yucatan).
However, it must be stated that availability is a relative term: access to a stone might be next to impossible by overland means and yet very accessible over water (e.g. Aswan granite via the Nile over a 600 km distance, albeit downstream). Furthermore, a distance one culture might consider prohibitive for available stone might be of little consequence to another culture.

2.3.2 Criterion of Workability

Workability is defined here as the ease or lack of resistance of a stone to modification as reflected in relative hardness and predictability of fracture. Regularity of fracture and softness (estimated 3-4 on a Mohs scale) of homogenous material like limestone, which is usually highly suited to carving and sculpture) can be contrasted with the platy or planar fracture of slate. This is corroborated by the dearth of sculpture or carving in slates, although this very feature of platy fracture also makes slate ideal for roofing. Limestone, on the other hand would be likely to be found in almost any comprehensive list of stones which have been worked through human prehistory and prehistory (Lal, 1978; Dorrell, 1983; Hunt, 1989). Another stone which can demonstrate an ease of carving or workability might be schist, as can be evidenced by the quantity of 2nd c. A.D. Gandharan Buddhist sculptures in this medium (Newman, 1988). Although it flakes considerably, schist fractures in one direction, thus allowing some predictability for the sculptor or stonemason. Conversely, stones often considered difficult to work include granitoid, quartz and quartzite rocks, mostly due to the relative hardness of quartz itself at 7 on the Mohs scale of mineral hardness. Nevertheless, many cultures from prehistory onward
have indeed used granites and quartzites for tools and sculptural media, as noted in prehistoric contexts for quartzite (Semenov, 1964), in Egyptian contexts for granites (Klemm and Klemm, 1981), and in Inca contexts for granitoid rocks (Protzen, 1985).

It must also be suggested here that different concepts and theoretical or experiential requisites of workability might exist with any ideal workability determinable among a range of stones greatly dependent on intended function, as mentioned for slate.

2.3.3 The Criterion of Durability

Durability is suggested as a complex of stone properties such as resistance to weathering and hardness. Resistance to weathering may be in many cases be related to solubility, for example, a stone’s capacity for dissolution in water or acids in aqueous solution. Sulfates like gypsum are very water soluble and carbonates like limestone can have surface calcium carbonate converted to calcium bicarbonate in the presence of carbonic acid which is a weak but natural phenomenon occurring in rain combined with carbon dioxide (Hunt, 1989). In some cases density of the crystallographic lattice may be factored into both durability and hardness. In other cases, as in some sandstones, quartz grains may themselves be very resistant to weathering but the cement which holds them together may be relatively soluble.

Some of the presuppositions which would be assumed here are that a culture would need to have sufficient time to gauge the relative durability of stone. Certainly a culture with such historical longevity as the Egyptian culture, spanning perhaps two millenia, ought to have sufficient time assessments. On the
other hand the aridity of an Egyptian environment would minimize some water-related weathering. Nevertheless, cultures would often be able to gauge relative weathering profiles of stone use of their antecedent or older neighboring cultures.

2.3.4 Criterion of Aesthetic Appeal

Aesthetic appeal is defined here as the value attached to one stone compared to another for various possible reasons. Some of these reasons might be colour, variegated banding, or inclusions in the stone. It is the opinion of this researcher that the Inca Pachacuti in Peru (c. 1438 A.D.) chose andesite partially for its dark grey to black hue which could lend dignity to an edifice as well as sparkle with tiny reflective hornblende (or mica) phenocrysts in a closeup view of several yards. The tiny flashes of reflection of the sun would be in contrast to the dark stone.

The sun itself was worshipped as the sun god Inti among the Inca, thus the presence of the god could, in the opinion of this researcher, be manifest as well within the stone, thus making it all the more desirable a building medium for Inca architecture, as it certainly was used with some regularity in and also outside the Rio Hautanay valley (Gregory, 1916). In any case, andesite was specifically chosen for stoneworking when it was not the most available stone around (granodiorite, sandstone and limestone are more prevalent and more proximal to Cuzco) with the nearest known andesite quarries at Huaccoto and Rumigolqa, 19 and 35 km distant respectively. Aesthetic appeal seems to play some importance in Pachacuti’s choice with the considerations noted above.

Marbles could be more readily cited as obvious candidates for the application of aesthetic appeal as an important criterion,
particularly with the Roman appetite for unusual coloured marbles (Ward-Perkins, 1972). Another possible stone chosen at least in part for aesthetic appeal was alabaster, certainly correlated with workability in ease of carving which allows it to be worked into relatively thin-walled vessels with beautiful translucence.

It is also possible that a culture might choose a stone in defiance as it were of all the anticipated obstacles ensuing from such choice or where aesthetic appeal made all other factors insignificant. In the Hadrianic period of Roman quarrying in the mid-2nd c. A.D. onward one such stone choice could be cited which was highly prized for almost two centuries, indeed being the most expensive quarried stone in Diocletian's Price Edict of 301 A.D. (Lauffer, 1971:341). This prohibitively-costly stone was known as imperial porphyry, worth 200 denarii per cubic foot (as compared to the nearby Mons Claudianus granite at 100 denarii per cubic foot). It was entirely under imperial control (hence the name "imperial") and was found exclusively on Mons Porphyrites in the eastern Egyptian desert between Qena on the Nile and the Red Sea. Quarries were almost inaccessible, up to 80 km away from any water and in one of the most inhospitable, extremely arid locations in the Roman provinces, where human life was dependent on constant supply routes. Not only that, but the maroon-red stone with small white laths of feldspar is extremely hard to quarry and carve (its granitoid minerals being around 7 on the Mohs scale). After transport across the arduous overland route to the Nile at least 50 miles distant, the stone would have to floated downriver to Alexandria and thence to Rome. Naturally, this stone was unique, enhanced by the all the difficulties which
would make it even more exotic than mere appearance allowed. Much prestige would therefore be attached to anyone who could afford it (after imperial permission was obtained) against all these very considerable obstacles. This is one of many such possible examples of deliberate stone choice for marked reasons, despite the difficulties in obtaining and working the stone (which would also add considerable value).

While each of the above partial definitions and examples are brief, detailed elaboration will be found along with applications in the actual archaeological contexts of the present research. In view of the preliminary nature of this discussion of potential stone criteria, it is acknowledged that these ideas will need to be greatly amplified in subsequent research.

Some presuppositions of highest importance must also be noted at this point. Differences in qualities and working properties of various stone would have to be recognizable (and possibly even accommodated in ancient lexicons). Another qualifier is that no single criteria would be likely to be the only factor in stone selection; it is more likely that an interplay of several be decisive for stone selection. For example, in the noted case of Late Maya and Toltec use of limestone, it is probably not only the availability of the limestone but also its workability: its relative softness enabled it to be carved into the unparalleled exquisite sculptural relief of hieroglyphic art (one might ask which came first or which influenced which: the stone selection influenced by the hieroglyphic tradition or the hieroglyphic tradition developing by the available workable medium?). The same interrelated criteria might be claimed for the abundant sandstone of the Maya site Yaxchilan in the Usumacinta basin of Guatemala,
also well-suited for hieroglyphic art due to its fine-grained homogeneity and relative softness which make it so easily-worked.

2.3.5 Sub-Criterion of Metaphysical Appeal

A sub-category of stone criteria could be suggested as perceived \textit{metaphysical} properties, that is, not derived from any empirical or experiential intrinsic understanding of the stone but from some extrinsic ideas such as religious influences. This could be the most difficult criterion to establish unless it were specifically mentioned within a cultural record. There appear to this researcher some possible Olmec metaphysical identifications of volcanic stone with other known Olmec underworld contexts. Some of the possible connections are as follows. First, basalt is the most extensively-used sculptural medium in Olmec sites for colossal heads and other figures (Stirling, 1946, de la Fuente, 1973). Second, Olmec stone sources for this basalt can be found throughout the Tuxtla mountains whose volcanic peaks are always visible from Olmec sites (Coe and Diehl, 1980; and by observation of this researcher). Third, Olmec mounds at the sites have been tentatively identified as replicating the volcanic peaks (Bernal-Garcia, 1989). If, in keeping with the underworld mythology of the Olmecs (as suggested to this researcher by F. Kent Reilly, University of Texas-Austin, at the Seventh Palenque Congress in Mexico in 1989), the Olmecs could have had a reverence for volcanic stone for the following rationales in the opinion of this researcher: 1) the Olmec sites surround the volcanic Tuxtla Mtns. and Lake Catemaco (which may be a huge relict caldera with a 10 km diameter) in the center of this range but Olmec sites are
not found (to date) within these same mountains, suggesting either a healthy fear of volcanic activity and/or a resulting sacredness of this perhaps original Olmec heartland in these mountains; 2) observation could show this volcanic stone in a molten state to derive literally from the underworld, and the Olmec appear to be sufficiently close to witness just such contemporary eruptions and lava flows (which may have driven them out of the Tuxtlas in the first place); 3) if underworld power could be attributed to rulers, priests, etc. from this fiery liquid (or pyroclastic bombs) which after a molten "birth" could miraculously harden on cooling into workable stone, then it would be a powerful stone acquisition to be harnessed and monopolized by the Olmec hierarchy. These are admittedly speculative ideas, but they will unfortunately perhaps never be confirmable.

Another possible metaphysical association has already been suggested earlier in the Inca use of volcanic stone with the mica or hornblende phenocrysts as reflections of the sun-god Inti. It is perhaps best to consider the metaphysical criterion to be subsumed within the aesthetic category since it will be difficult at best to confirm any such "metaphysical" properties.

While a final possible metaphysical association may belong in another category, there is also the question of tradition: could a culture continue to use a stone because stoneworkers often follow the example of their teachers? Familiarity with a stone in a stonemason's training could well be a criterion for continued use (although it may not suggest why this stone was selected in the first place). However, the possibly metaphysical association with tradition is that a culture may derive some security in the knowledge of continuity, i.e. that as their ancestors worked such
and such stone, and as they continue that tradition, so they might expect that their descendants will also continue to use this stone. Thus in some way, the participants in a culture may hope that their culture will survive based on passing down these traditions; that preservation of just such traditions may even be perceived as guaranteeing their cultural longevity.

Although there is no intentional prioritizing order implied in the above sequence of potential stone selection criteria (availability, workability, durability, aesthetics, metaphysics). it is the opinion of this researcher that the least sophisticated users of stone, i.e. with the lowest relative stone technology, may well have a similar order of priority operating; conversely more sophisticated users of stone might have a reverse order of priority with aesthetic appeal as a foremost criterion. It is also important to note that this articulation of stone criteria extends beyond the primary focus of volcanic stone.

2.3.6 Interplay of Several Criteria in Stone Selection

Several primary arguments and some secondary evidences suggest that such an interplay of criteria existed in certain ancient cultures: 1) the exclusive use of one stone for limited functions and not others attests deliberate choice; 2) the above discussion in section 2.1 on historical terms presupposes an observational distinction and probably evidences an incipient recognition of basalt or andesite for unique qualities; 3) the choice of one stone not readily available when other stones were available and were in fact even more workable suggests markedly deliberate criteria of selection, particularly true for aesthetic
appeal or durability as high priority criteria. The following subsections amplify each of these arguments.

2.3.7 Evidence of Exclusive Function

First, the exclusive use of some stone for certain functions evidences stone recognition by observation of some experimental properties. The fact that the microcrystalline silicate flint and other quartz family members like quartzite and the volcanic glass obsidian are almost universally used for tool functions, and especially blades and points, is indicative that this can only be a result of experimental knowledge of conchoidal fracture and relative hardness (around 7 on a Mohs scale approximation). Perhaps the foremost discussion on overwhelming silicate function (flint, chert, obsidian, and quartzite) in the technology of tool industries is found in the work of Semenov (Semenov, 1964:33-37), although there is a prolific current literature on flint working (Orton, 1980; Roberts, 1985; Vaughan, 1985; and numerous articles by Newcomer and others in Lithic Technology, to name a few). This is not to say that other stones weren't used as well for the same function but rather that mainly these stones were used for such tasks. It is unlikely that archaeological research will turn up many friable sandstone points and blades in an area where flint or chert abound or where obsidian networks operated. Here, the criteria suggested are durability and workability even where flint, chert, or especially obsidian (Cann, Dixon, and Renfrew, 1969) were not easily available and including availability in such places as Paleolithic and later Britain where flint was and is abundant.

This argument could be enlarged by citing the universal
function of basalt and andesite as grinding tools, again evidence for observation and recognition of stone properties of roughness and hardness for use in querns, millstones, mortars, metates, and related uses (Peacock, 1980 and 1989; Lowe, 1981; Runnels, 1981; Runnels and Murray, 1983; Dorrell, 1983; Williams-Thorpe, 1988; and Williams-Thorpe and Thorpe, 1988, among others). Additional andesite grinding tools have been observed by this researcher from unrelated contexts in diverse cultures such as Levant Neolithic, Cycladic Aegean, Philistine, Canaanite, Israelite, Olmec, and Javanese. In many of these cases the distribution of basalt and andesite exceeded distances of 100 km to the nearest volcanic sources. Suggested criteria involved here are durability and workability and sometimes availability.

2.3.8 Distinctions of Historical Vocabulary

Second, the historical vocabulary evidences stone recognition even if on the non-scientific level of stoneworking experience. Certainly any reconstruction of any such selection criteria on the part of ancient masons across many cultures can only be suggested where a body of ancient literature exists to verify or deny such hypotheses. This will be most deducible in societies which have literary systems, such as Bronze Age Egypt in the 3rd and 2nd millenia B.C. or the Mesopotamian societies in the 3rd to 1st millenia B.C., and the Classical Greek and Roman cultures in the 1st millenia B.C. and A.D. as well as the Aztec culture in the 2nd millenium A.D.

The fact that many of the above Old and New World words given above in section 2.1 are specifically attested for what would
today be definable as basalt or andesite by the most knowledgable geological assessments (Le Maitre, 1989), confirms that unique names identified stones. Campbell Thompson notes Assyrian words (based on Akkadian sources) for at least 25 different stone names (or mineral categories), of which the likely terms for volcanic stone are only 3 or 4 (Campbell Thompson, 1936); this is further highlighted by Stol who notes synonymy between the word for a stone which is identifiable as basalt and the term "lower millstone" in several ancient Mesopotamian languages (Stol, 1979) reinforcing the argument stated in subsection 2.11. While the sophisticated Egyptian stone technology could in fact recognize stone types and repeat sculptures in the same stone again and again, it is also true that several terms exist which could refer either to basalt or dolerite (Lucas, 1934:64-65). Nonetheless, it is obvious that many Egyptian terms for different stones could not refer to volcanic stone. Some confusion might exist on the part of the scribe where distinctions would be perfectly clear on the part of the mason, therefore, even where literary evidence is possibly ambiguous, the actual repeated forms in one stone (as shown by multiple Egyptian basalt sculptures over three millenia) are strong evidence for at least a stone tradition if not also an experiential working knowledge of one stone in contrast to other stones, particularly if these other stones were also worked. It seems inconceivable that a skilled mason or even a studio of mason’s apprentices would not be able to distinguish on the basis of colour, hardness, and fracture alone the clear contrasts between alabaster, diorite, basalt, and granite in 3rd millenium B.C. Egypt.

A hypothetical working knowledge (or even terminology) could
set apart these stones as shown in Table 2.3 below without using any exclusively geological descriptions. In the opinion of this researcher, Egyptian categories could work somewhat thusly.

Table 2.3  HYPOTHETICAL STONE PROPERTIES IN ANCIENT EGYPT

<table>
<thead>
<tr>
<th>Stone</th>
<th>Colour</th>
<th>Other Qualities</th>
<th>Hardness (Relative)</th>
<th>(Criteria)</th>
</tr>
</thead>
<tbody>
<tr>
<td>alabaster</td>
<td>white</td>
<td>lustrous, translucent</td>
<td>soft</td>
<td>(aesthetics, workability)</td>
</tr>
<tr>
<td>diorite</td>
<td>dk. green</td>
<td>lg. white flecks</td>
<td>harder</td>
<td>(aesthetics, workability)</td>
</tr>
<tr>
<td>basalt</td>
<td>dk. grey, black</td>
<td>tiny mirrored flecks</td>
<td>harder</td>
<td>(aesthetics, workability)</td>
</tr>
<tr>
<td>granite</td>
<td>1 white</td>
<td>black flecks</td>
<td>hardest</td>
<td>(aesthetics, durability)</td>
</tr>
<tr>
<td></td>
<td>2 red</td>
<td>black flecks</td>
<td>hardest</td>
<td>(aesthetics, durability)</td>
</tr>
</tbody>
</table>

With a replacement of such terms as "fleck" with mafic or felsic phenocryst and a relative Mohs scale of hardness for alabaster at 3, diorite at 5, basalt at 6, and granites at 7, the above stones can be easily described in simple geologic terms. As stated in section 2.1, behen describes basalt (although possibly mica schist and slate as well, but their horizontally flake-fractured cleavage would be obviously different to experienced masons), with additional words for other stones in the Egyptian lexicon supporting such a hypothetical catalogue.

2.3.9 Evidence of Low Availability

When a stoneworking context calls for a stone not readily available, that is, not obtainable on a local scale, use of an "exotic" (non-local) stone offers evidence that convenience alone
is not a factor but rather that certain non-local stones may be prized for specific properties not inherent in the local stones. The range of distance for what may be considered local depends on such identifiable features as transport means, topography, size and quantity of stone material at the source combined with the volume of stone needed, work force, and others. It must be considered that although otherwise desirable stone may be quite local and ideal in every feature, the relative volume of material needed may far exceed the known volume of available stone, thus where continuity of material is an expectation, another perhaps slightly less suitable stone which has a greater quantity could be selected instead. Examples of some of these low availability contexts are as follows.

Melian obsidian can be found distributed over a 750 sq mi. radius of the Eastern Mediterranean from its Aegean source as early as the Neolithic even when other obsidian sources exist in closer proximity (Cann, Renfrew, and Dixon, 1969). Basalt for querns can be traced all over Europe and the Mediterranean, to be specific, Auvergne basalts in France, Sardinian basalts, and German basalts can be found in Roman England (even when basalts can be found in Wales and the Lake District) used as donkey mills and grindstone capacities (Peacock, 1980). In some instances the question of contemporary working may or may not be a factor; there may not be a knowledge of an equivalent local stone. Nevertheless, the French, German, and Sardinian basalt sources were worked at various Roman times and some chronologic overlap of quarries must have existed. In another example, Rumigolqa andesite is further from the Cuzco placement contexts than is the far closer Huaccotto andesite or the immediately-available
granodiorite of El Rodadero just above Cuzco (Gregory, 1916; Gasparini and Margolies, 1980; Hunt, 1990a). Aswan granite from the Upper Nile used in Lower Nile (Memphis-Giza-Hierapolis) loci is yet another example of unavailable stone brought a great distance, in this case at least 500 km, although it should be noted what superior transport the Nile river provided (Ward-Perkins, 1972). These are just a few of perhaps scores of examples to illustrate this point.

When other selection criteria have superseded the factor of availability, whether for properties of workability, durability, aesthetics, metaphysics, or some other possible criterion, it is more than mere coincidence that the stone selected is the product of deliberate, perhaps experiential, choice. Of all the factors suggested thus far in the present discussion, the evidence of certain stone brought over a distance (and over other stone sources through which its transport passed) is the strongest possible evidence of stone selection criteria.

2.4 Conclusions

In summary, while the question of criteria for stone selection needs further examination, the current discussion is without precedent in attempting to systematize potential stone criteria. Naturally, the preliminary nature of this discussion cannot hope to exhaust such a rich, albeit speculative, topic.

The potential stone criteria for selection as discussed here suggests that future analyses of stone use may be able to reconstruct such selection criteria as availability, workability, durability, and aesthetics (with possible metaphysically-
conditioned choices as well). These suggested criteria will be assessed repeatedly in the present study in following chapters on specific cultural contexts.

Furthermore, the historic identification of volcanic stone in various cultural references over a period greater than 4,000 yrs. and various words possibly used to describe basalt or andesite in the vocabulary of ancient cultures (as discussed in section 1.4) constitutes a new topic, preliminary for the present but intended to be comprehensively catalogued in the future. It reinforces the suggested stone selection criteria and is itself corroborated by the (also preliminary) listing of global uses for basalt and andesite which could easily double or treble with continued catalogueing of past uses in Africa and Asia as well as in the central or peripheral contexts found through this study, whose archaeological selection processes were described in Chapter 1.
Chapter Three

REVIEW OF METHODS USED TO DETERMINE PROVENANCE

3.1 Review of Prior Archaeological Provenance Methods

To demonstrate its validity scientific archaeology requires quantitative techniques. These have often been borrowed from the physical sciences. The application of physical sciences to archaeology is termed archaeometry (Leute, 1987; Aitken, 1989). The following excerpt from Leute provides an appropriate definition of archaeometry.

"'Archaeometry' is a synthetic term indicating that 'ancient' things or phenomena related to them are to be 'measured' or quantified. The need for such quantitative treatment is obvious if one imagines the questions asked by those historians who have to appraise the material remnants of the past...The experienced archaeologist...utilizes not only his knowledge of history but also his knowledge of technology." (Leute, 1987:1)

Leute discusses the pivotal roles of physics and chemistry in elucidating quantitative problems of archaeometry. Even though the role of petrology with optical microscopy for mineralogic identification is briefly discussed by Leute in his text on archaeometry (Leute, 1987:119 & ff) the nature of petrographic identification is rightly perceived as qualitative rather than quantitative. The role of petrography will be discussed in some detail in this chapter.

One common archaeological problem which usually requires several archaeometric applications is the determination of source (or provenance) of archaeological material, using such methods as elemental analysis and discriminant clusters of major and trace elements. These are semiquantitative or quantitative as opposed to qualitative analyses. However, in both quantitative and
qualitative analyses asking the right questions of the material and accurate interpretation of the data are equally important for determination provenance (Griffiths, pers. comm., 1989).

The scientific determination of provenance depends greatly on the type of archaeological material under consideration. Finding the source of lithic material used by man must involve geology (Rapp and Gifford, 1982). Numerous methods exist which have been successfully used to determine the geological provenance of archaeological material made of stone. Particular applications of some of these methods to volcanic stone will be noted in the following sections.

3.1.1 Literature Review on Stone Provenance

The following statement from a seminal publication on the problem of source analysis may suffice as a partial introductory definition of provenance determination:

"The basic problem...is one of identifying the source of material found in excavations by comparing its properties with those of materials known to come from a particular place. The procedure of distinguishing sources from one another may be termed characterization. At least three factors bear on the solution of this problem: the degree to which the sources may be uniquely characterized by measurements of one or more parameters, the number of sources in a given region, and the area over which practical identification of material with source is to be attempted, and the extent to which material may have come from sources other than the nearest."

(Cann, Dixon, Renfrew, 1969:578-9)

These are the parameters of provenance analysis and remain valid after several ensuing decades of continuing investigation. Perhaps the element of characterisation is still both the most difficult as well as the most important in provenance research.

A brief sketch of microscopic analysis shows it to be perhaps the oldest available scientific method in application to stone.
While it cannot be associated with provenance, the analysis of material from Stonehenge by the eminent astronomer Halley was in fact microscopic and perhaps the first recorded application. It also attempted an understanding of the antiquity of the material by its general weathered condition (Stukeley, 1740). Certainly the work of Thomas which followed on Stonehenge was a direct provenance study which was successful in finding the source of some Stonehenge blue dolerite menhirs to be Carn Meini in the Prescelly Mountains of Carmarthenshire, Wales (Thomas, 1923). In the decades before and after Thomas, multiple investigative techniques and instrumental methods have been applied to the above parameters of provenance analysis in archaeology.

Specific applications of geological and geochemical science to archaeology can be found which have a bearing on this study. Some archaeometric techniques derived from geological studies, which are primarily qualitative in the earlier applications to archaeology, have been employed to study stone provenance include petrographic analysis (Dumour, 1865; Washington, 1898; Shotton, 1969; Peacock, 1980; Shipley and Graham, 1987; Newman, 1988; Stross et al., 1988), scanning electron microscopy (Riederer, 1985; Margolis, 1989), electron probe microanalysis (Hornblower, 1962; Margolis, 1989), X-ray fluorescence (Lee et al., 1982; Williams-Thorpe, 1988; Croudace and Williams-Thorpe, 1988), neutron activation analysis (Heizer et al., 1973; Allen et al., 1982; Stross et al., 1988), isotopic analysis (Craig and Craig, 1972; Herz et al., 1977; Herz and Wenner, 1978; Coleman and Walker, 1979; Herz, 1985; Herz and Waelkens, 1989); electron spin resonance spectroscopy (Lloyd et al., 1985; Griffiths and
Woodman, 1986); (Maniotis and Nikolaou, 1989); and X-ray diffraction (Margolis, 1989; Allen et al. 1982).

The above is by no means a comprehensive list. Rather, it is a small sample of relevant literature whose purpose here is to illustrate the variety of techniques used in attempting to determine the provenance of stone. In providing the above references to the literature, an attempt was made to cite the most relevant or most recent research.

In critical review it is notable that some of the above techniques have had restricted application to certain types of stone. Some may be more widely applied in the future whereas others such as optical petrography are restricted to minerals occurring in relatively large grains.

Neutron activation analysis (NAA) yields quantitative information from homogenous stone like quartzite (Heizer, Stross et al., 1973) but would be destructive of valuable optical features such as the texture and relatively diverse mineralogies of volcanic material. Nonetheless, NAA could still be useful if larger samples of the rocks as a whole or single minerals were to be studied. Isotopic analysis has had considerable archaeological application to marbles (Herz and Wenner, 1978; Herz, 1985; Herz and Waelkens, 1988) partially due to the relative homogeneity of these carbonates. Electron spin resonance (ESR) has been most associated with flint (for which petrography is generally unsuitable due to its fine-grained homogeneity). Electron spin resonance spectroscopy is also a technique which is applicable to thermal history (Griffiths, pers. comm., 1989) but would not be suitable for coarse-grained heterogenous volcanic material such as found in the present study. ESR might not be suitable for
andesite and basalt because of the possibility of overwhelming broad Fe signals and the complex mixture of signals from a polymineralic material (Griffiths, pers. comm., 1990). X-ray fluorescence (XRF) is suitable in semiquantitative analysis of volcanic stone with wavelength-dispersive spectroscopy (Croudace and Williams-Thorpe, 1988) as a secondary step after petrography but would in itself yield no textural detail. Although both XRF and electron probe microanalysis (EPMA) can have wavelength-dispersive spectroscopy features, EPMA offers optical capability which, while it may not match optical petrography, surpasses XRF in that capability. X-Ray diffraction can be highly quantitative but is often used as a terminal technique rather than an initial technique as it can yield no textural information. It is also a destructive testing technique although applicable to a variety of geological material (Margolis, 1989). Petrography on the other hand is highly useful as a starting point for most reasonably coarse-grained stone materials and yields much textural data. Furthermore, in some situations where a highly uniform chemical makeup is found throughout stone over a broad regional area such as in the Levant, petrography may provide a better signature than has been often surmised. Its role will be amplified greatly in the following sections.

Naturally, there is often debate as to the suitability of any one technique over another, greatly dependent on the research problems encountered, the questions to be answered which will vary from archaeological and geological situation to situation, and familiarity with archaeometric techniques available (Croudace and Williams-Thorpe, 1988; Griffiths, pers. comm., 1990). Thus, some of the above paragraph tends to generalisation of techniques
rather than characterisation of techniques.

Pioneers in the archaeological provenance of volcanic stone artefacts include J. Roder, D.P.S. Peacock, R.S. Thorpe, and O. Williams-Thorpe. Attention to their work partially referred to above has been vital to this research.

The potential accuracy of the archaeological provenancing of stone is greatly enhanced by the use of more than one of the above instrumental techniques in a planned sequence. While several of the applicable techniques have been briefly evaluated for applicability to stone provenance determinations, the discussions in this chapter focus on a sequence of techniques used in the present study which is restricted to igneous extrusive intermediate stone. This instrumental sequence used begins with petrography, continues with scanning electron microscopy, and culminates with electron probe microanalysis.

3.1.2 Combination of Techniques Used to Determine Provenance

Many studies of the provenance of archaeological stone involving several analytical techniques begin with petrography as the method most likely to yield qualitative data and general information as opposed to quantitative data. While petrography alone may be sufficient in some cases, the choice of analytical techniques depends greatly on the nature of the information needed. Table 3.1 below shows some appropriate paths used for determination of stone provenance as discussed in the literature. The following have been cited because the material is most often similar to the volcanic material analysed in the present study in most cases, or because the sequence of techniques is similar, or
both may be similar.

Table 3.1 PROVENANCE INSTRUMENTAL SEQUENCES

<table>
<thead>
<tr>
<th>Technique</th>
<th>Stone Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. OP</td>
<td>(andesite)</td>
</tr>
<tr>
<td>2. OP</td>
<td>(basalt, trachyandesite)</td>
</tr>
<tr>
<td>3. OP</td>
<td>(andesite)</td>
</tr>
<tr>
<td>4. OP</td>
<td>(latite porphyry)</td>
</tr>
<tr>
<td>5. OP + EPMA *</td>
<td>(talc-chlorite schists)</td>
</tr>
<tr>
<td>6. OP + XRF *</td>
<td>(basalt and trachyandesite)</td>
</tr>
<tr>
<td>7. OP + NAA</td>
<td>(quartzite)</td>
</tr>
<tr>
<td>8. OP + EPMA</td>
<td>(pumice)</td>
</tr>
<tr>
<td>9. OP + SEM w/ EDS + EPMA</td>
<td>(basalt and andesite)</td>
</tr>
<tr>
<td>10. OP + SEM + EPMA + XRF + IA + XRD</td>
<td>(marble)</td>
</tr>
</tbody>
</table>

Abbreviations used:

**OP** = Optical Petrology (Petrography)

**EPMA** = Electron Probe Microanalysis

**SEM** = Scanning Electron Microscopy

**EDS** = Energy-Dispersive X-Ray Spectroscopy (as add-on to SEM)

**NAA** = Neutron Activation Analysis

**XRF** = X-Ray Fluorescence *

**XRD** = X-Ray Diffraction

**IA** = Isotopic Analysis

* signifies additional quantitative analysis by energy-dispersive or wavelength-dispersive spectroscopy

References:
Some discussion of the above table is necessary here. It should again be noted that most of the above studies employing an established sequence of techniques have analysed volcanic archaeological material, i.e. basalt or andesite in nos. 1, 2, 3, 6 or volcanic latite, no. 4, (not counting the present study) and 8 analysing volcanic pumice. Furthermore, also as suggested, some precedent has been set for similar analytical sequence, beginning with OP and continuing with semiquantitative analyses. Thus these prior analyses of volcanic materials serve as ideally-comparable research in several ways to the present study. It should also be noted that success in determining provenance is possible using spectroscopic elemental analyses, i.e. in nos. 5, 6, 8, 10 (not counting the present study), so setting some precedents for the present study. Both these observations should evidence the provenance rationales followed here as reasonable in that they follow known successful sequences to some degree.

The innovative research value of the experimental sequence followed in the present study is that it has been chosen after careful consideration of the advantages and disadvantages of prior instrumental sequences. It was the most practical in light of instrumental techniques available to the author. Furthermore, the experimental sequence followed here did not involve excessive specimen preparation time, especially with the innovations detailed in the following chapter on a new mounting medium for optical petrography in a fixed or portable laboratory. As a detail to be enlarged on in Chapter Four, one can actually prepare a sample as a thin section and proceed through examination by petrography, SEM, and EPMA using the same thin section (where carbon coating suffices for both SEM and EPMA).
Identification of textural features is thus increased. Furthermore, it has an added advantage of utilizing some optical analysis throughout the analytical sequence, starting with optical petrography, then SEM with EDS, then EPMA. Even though optical resolution is greatly minimized with SEM and further reduced with EPMA, the increase of semiquantitative elemental analysis is seen as a much-needed compensation. In the case of some EPMA, like the nine detector instrument at U.S. Geological Survey, Menlo Park, California, multiple analyses capabilities are more desirable than high resolution optical capabilities. However, textural detail in analysis is still possible for opportunity to isolate individual features such as the identical phenocrysts or areas of groundmass in basalt or andesite from instrument to instrument in this sequence which allows some optical analysis throughout.

Moreover, especially innovative in the transition from field to fixed laboratory work is the employment for what appears to be the first time in archaeological research a portable field laboratory for optical petrology. Allowing portable polarizing microscopy in the field, with ability to begin characterisation of minerals at the outset, the present instrumental sequence has resolved some of the problems of field sampling and analysis. In Chapter 4 this will be discussed in more detail.

3.2 Special Role of Optical Petrology

3.2.1 Petrography of Stone in General

Petrography was used as a starting point in all the stone provenance studies mentioned above in Table 3.1 and many others not enumerated here. The contribution of petrography (or optical
petrography to archaeology has been established for at least a century, beginning with the study of the provenance of prehistoric European stone axes (Dumour, 1865) and continuing with the studies of marble provenance (Washington, 1898) and other subsequent studies up to the present (Melson and van Beek, 1983; Newman, 1988). With its scientific analysis of stone in thin section for mineralogical and textural features, the role of archaeological petrography in the latter half of the twentieth century has not diminished but rather increased with a greater application to ceramics (Matson, 1963; Shephard, 1968; Peacock, 1968, 1970; Freestone et al., 1982; and Schneider, 1989; Ellis and Alexianu, 1991; Whitbread, 1991). "Petrography has...been used to propose alternative provenances for particular classes of amphorae, e.g. certain Zenon jars" (Whitbread, 1991:294). As should be expected, petrography "remains a pre-eminent technique of many provenance studies" (Rapp and Gifford, 1982:49).

The following characteristics briefly evidence the important role of petrography: (1) petrography is not limited to any type of stone but can be applied to nearly any stone; (2) thin section preparation is relatively simple (requiring minimal instrumentation); (3) training in the interpretation of thin sections is provided in most geological education courses; (4) thin section analysis is especially useful for gaining a general picture of texture and serves to identify the minerals present when they are in the form of large grains; and (5) textural analysis of size, volume, and percentage of grains can readily be effected in a semi-quantitative manner with a little experience.
Other factors which will be discussed shortly make petrography particularly useful for volcanic stone.

3.2.2 Limitations of Petrography

Even though petrography in the absence of computer-assisted textural analysis is qualitative rather than quantitative, it is often sufficient for provenance determination if the geological source and archaeological material are equally unique and distinctive. However, the comment of Williams-Thorpe and Thorpe is significant here: "More recent studies indicate possible ambiguities in sourcing millstones by petrological study alone and point to the importance of confirming provenance by chemical analysis." (Williams-Thorpe and Thorpe, 1988). Although this comment refers to European millstone provenance rather than archaeological provenance determinations in general, it is nonetheless germane especially as volcanic material is also the subject of both this study and the study referred to above.

Some observations are included at this point. The present study has integrated other archaeometric techniques from the outset, e.g. SEM with EDS and EPMA. Also, both in the number of potential European sources and in the not uncommon occurrence of transport distances of several hundred kilometres, the provenance problem faced by the above experienced researchers (Williams-Thorpe and Thorpe, 1988) is much more difficult than in most of the archaeological provenance questions undertaken in the present study. When far fewer potential sources occur over a wider regional area as appears to be the case in the Cuzco Andean area of Peru and in the Tuxtla Mountains of Mexico, the issue of potential ambiguity appears to be less problematic. Also, these
two (Cuzco and Tuxtlas) mountainous cultural sites prevented too broad a distribution of material beyond a maximum of 100 km as opposed to the Mediterranean and European distribution of many potential stone sources in the research of Williams-Thorpe and Thorpe. Even in the case of marine access to the Tuxtlas peninsula from the Gulf of Mexico, all known Olmec sites are just as close to sources by overland transport as potential marine transport. The ambiguity problem in the present study will surface mostly in Chapter 7 (Levant potential source distribution and provenance).

Even with these qualifiers, the present study is not any less needed. In most of the archaeological contexts addressed here, the scientific determination of provenance has never been attempted before. Also, the advantages offered by a portable field laboratory make petrological provenance study much easier as well as rendering representative sampling more secure. These last two points will be taken up later. The development of a portable field laboratory is discussed in Chapter 4; archaeological loci and new provenance determinations are found in Chapters 5-7.

3.2.3 Petrography of Volcanic Stone

The particular appropriateness of petrography to the study of volcanic stone is now explored. Unlike many rocks, the basalts and andesites of the present study are relatively heterogenous. Whereas marble and limestone, for example, are made up of essentially one mineral (calcium carbonate CaCO₃) and therefore mineralogically quite homogenous, the volcanic stone studied here is suited to petrographic study due to its polynoramic constitution and textural features. As stated in Chapter 1,
andesites are usually porphyritic (Gill, 1981:168), i.e. have large phenocrysts in contrast to fine-grained groundmass (Thorpe and Brown, 1985:32), as are basaltic andesites and many basalts which may be highly mafic. Furthermore, major minerals may occur as phenocrysts (e.g. feldspar, pyroxene, olivine, hornblende, and biotite) and more than one type of phenocryst maybe present in a given rock, thus offering many potential compositional and textural parameters for use in distinguishing material of different provenance. Since these basalts and andesites also have such varied groundmass textures and structures (Nockolds et al., 1978:97), these can provide further bases for textural "signatures" to distinguish one source from another. Additional accessory minerals such as apatite, ilmenite, zircon, or others can further refine the degree of characterization attainable by optical petrographic analysis.

While chemical analyses will be likely to further refine or confirm initial petrographic analysis, it is unlikely that petrography will be superceded in the near future as the most important initial provenance tool for this range of volcanic stone, which has sufficiently large grain sizes to be amenable to identification by petrographic analysis.

As shown earlier from Table 3.1, the following representative studies have used petrography as a base or starting point: for andesite, basalt and related volcanics (Shotton, 1969; Peacock, 1980; Runnels and Murray, 1983); for pumice (Melson and van Beek, 1983); for latite and quartz porphyry (Shipley and Graham, 1987); and for basalt and trachyandesite (Williams-Thorpe and Thorpe, 1988), and in some cases have relied almost entirely upon petrography for successful determination of provenance.
3.3 Role of Scanning Electron Microscopy

Scanning electron microscopy (SEM) has been applied to many archaeological problems over the past three decades. Its capabilities for showing minute detail on non-planar or uneven surfaces of material are excellent, and it is capable of extremely high magnification (up to 100,000 x) far beyond the range of normal light microscopy which reaches its usual practical limits at 1,000 x. Its use in petrological studies is well summarized by the text Electron Microscopy in Mineralogy (Wenk, 1976), which provides a wealth of experimental and analytical data for the petrological researcher. The optical mineral identifications and crystal habits which its micrographs provide can be of great help along with practical guidelines for obtaining optimum analytical results.

As an analytical tool SEM is particularly useful for graphic examination of crystal substances which have accreted on surfaces and also for textural and mineralogical depiction of diverse archaeological material (Riederer, 1985). Many changes in the microstructure of materials are most readily observed by scanning electron microscopy. Whether by secondary electron back-scattered electron or X-ray imaging, SEM analysis of material is an excellent analytical follow-up to optical petrography, particularly when the additional resolution can focus on textural features already identified petrographically as suitable for further analysis, e.g. phenocrysts or groundmass, especially with the enormous range of magnification for detail with the highest potential for resolution. Add to this the Link System EDS
analysis and the potential for elemental identification offers much semiquantitative capability (particularly in the dot-scan mode) while retaining optical information not provided by normal low magnification petrographic microscopy.

Scanning electron microscopy provides an image of a surface and information on the distribution of elements upon the surface, a feature that non-scanning analytical techniques cannot directly offer. In addition, both polaroid and other photographic features offer permanent recording of analytical information.

In conjunction with the other SEM capabilities, the Link System Energy-Dispersive Spectroscopy (EDS) which regularly complements SEM units offers semi-quantitative elemental analyses as stated above, enhancing the SEM's optical usefulness. With the options of different elemental sample standards, a wide range of materials can be examined depending on the research aims.

Although SEM with EDS analysis is not ideal for organic material with a high percentage of carbon (or anything lower in atomic number), the usefulness of SEM with EDS for stone analysis is well-attested. Recent examples of the study of archaeological materials using SEM include glass (Tite and Bimson, 1989), ceramics (Schneider, 1989), and stone (Dorn and Oberlander, 1982; Margolis, 1989). The above studies utilized optical resolution capabilities of SEM and some (e.g. Margolis) involved semiquantitative EDS as part of the SEM analyses. For volcanic stone with distinctive textural features which could record subtle chemical changes, e.g. zoned plagioclase phenocrysts or iddingsite-rimmed olivine phenocrysts, SEM with EDS offers satisfactory visual and compositional information in planned instrumental sequences which begin with petrography. When the same samples are examined in
thin section by optical petrography and by SEM with EDS, the potential for analytical accuracy is optimized.

3.4 Role of Electron Probe Microanalysis

Electron probes have been used with increasing sophistication over several decades with "spectrochemical analysis of X-ray spectra" (Keil, 1967). While its imaging resolution is not as good as with SEM, its analytical capabilities can be more quantitative, "favour[ing] high quality chemical analysis rather than the emphasis on relief and observational flexibility of the SEM" (Freestone, 1982:99). Excellent summaries of electron probe applications to archaeological material can be found in archaeometric studies (Pernicka and Malissa, 1976; Courtois and Velde, 1981) dealing with ceramics and stone-like substances. As stated earlier, EPMA is an ideal second analytical stage after petrography, suggested by several prior studies (including Melson and van Beek, 1983; Newman, 1988; and Margolis, 1989).

Multiple spectrometers on newer EPMA instruments facilitate the rapid acquisition of quantitative results, offering as many as nine different detectors for a wide range of elemental analyses. Electron probe microanalysis continues to be a primary geological research tool for detailed studies, and is frequently used for silicates and volcanic material in particular (Clynne, 1990, pers. comm.).

Aside from reduced optical imaging compared to SEM, a primary contrast of EPMA and SEM with EDS is the increased spectroscopic sensitivity of X-ray detection of EPMA, allowing more quantitative results. However, as has been previously stated, sufficient
optical resolution enables the recognition of features already identified by petrographic and SEM examination.

Additionally, as previously stated, another asset of EPMA is that sample preparation for both SEM and EPMA utilizes carbon coating, which can result in time-economical transfers from one instrumental analytical session to another.

3.5 Analytical Sequence Employed in the Present Study of Stone Provenience

Several features of the analytical sequence employed in the present study are not novel. These have been found effective in other provenance studies using the instrumental sequences reviewed above. Other features such as the portable field laboratory for optical petrology are unique. The present discussion of the sequence of analytical techniques used in an attempt to determine provenance will describe in some detail the steps used in this research. An attempt will be made to summarize at the conclusion of this section with emphasis on the techniques newly employed or newly articulated in the provenance study presented here.

3.5.1 Procedures for Determining Provenance

It is the experience of this researcher that few published accounts of provenance studies discuss the steps which need to be taken prior to undertaking fieldwork. Many assumptions have been encountered in the literature regarding familiarity or training to be possessed by researchers. This is unrealistic due to the fact that researchers could approach provenance studies from a wide range of research disciplines, some of which would not be
likely to be as familiar with the physical sciences as others, e.g. archaeology, cultural anthropology, history, or art history to name a few, where even the basic questions or assumptions may need to be articulated rather than gained solely through experience. In thinking through the initial questions to be asked in discussing the securing of appropriate archaeological samples, the literature to date appears to be lacking in that it too often jumps into specific procedures of analysis rather than general aims and approaches to provenance determination. One notable exception to this is found in the literature where no prior experience or understanding of provenance determination methods is assumed (Rapp and Gifford, 1982 esp. pp. 45-53).

The following sections on specific procedures include aspects that are being articulated here for the first time and consideration of some rarely discussed assumptions. The steps taken in the present research were: Phase 1, Initial Questions and Emphases; Phase 2, Field Literature and Cartographic Resources; Phase 3, Obtaining Archaeological Material; Phase 4, Laboratory Analysis; Phase 5, Fieldwork; Phase 6, Laboratory Analysis (using the same instrumental sequences described in Phase 4). Hypotheses based on analyses are often necessarily tested and retested with different samples to eliminate variables which might show such hypotheses to be of limited applicability.

Phase 1: Initial Questions and Emphases

One possible avenue of approach with appropriate variations is derived from the initial question "Where did this artefact come from?" (Rapp and Gifford, 1982). That is, one may start with the archaeological material itself. This approach demands some
access to the archaeological material and some familiarity with the relevant literature. Such a beginning is likely to be the most common experience for archaeologists whose focus is on certain cultures within a given region and time frame. With clearly archaeological emphasis, this has been one route followed by this researcher.

Another possible avenue of approach with appropriate variations is derived from the initial question "In how many archaeological contexts can similar geological material be found?" In contrast to the above, one may have no archaeological material at hand. Such a beginning is not likely to be common for an archaeologist whose expertise is limited to one culture or time frame. It is quite likely, however, to be common for an archaeologist or geologist whose study is "monolithic", i.e. concentrating on one material only as it may have been employed across many cultures. With perhaps a geological emphasis, this has also been a route followed by this researcher whose major emphasis is centred on volcanic material. This process tends to be one with a broadening focus at first rather than a narrowing focus, especially if it is potentially global and not constrained by limitations of culture, time or space, e.g. in the present study an examination of very similar 2-pyroxene andesites from California (orogenic source) and Santorini (island archipelago source). Note Diagram 3.1 as it relates to these contrasting archaeological foci.
Diagram 3.1 CONTRASTS IN ARCHAEOLOGICAL FOCI

Traditional Model                   New Model

(1) Culture  (1) Material

(2) Time  (2) Space

(2) Use(s)  (2) Culture(s)

The arrows here signify the primary foci (1) of each specialist as they are qualified or shaped by the secondary foci (2) which also qualify or limit each other in some way.

The traditional model is that followed by archaeologists who specialize in one culture. They may attempt to integrate all aspects of that culture, e.g. architecture, material remains, technology, and in some cases even social, political, and religious aspects. A growing variant on this model is an emphasis on one type of material within that culture, e.g. Scythian metallurgy or Maya ceramics. Specialists then contribute to the total cultural picture.

The new model depicted here is that followed essentially by a material scientist specializing in one material. Fieldwork and laboratory work will not be limited to any one culture. For this research the cultures (considered within their time and space referents) are integrated with the total contexts of use and/or technology, perhaps even studied on a worldwide basis. While there may be resistance on the part of traditional archaeology to this potential, the material scientist will increasingly become part of mainstream archaeology.
Specific methods of determining provenance will depend greatly on the type of archaeological focus. To return to the initial questions asked (1: "Where does this artefact come from?" and 2: "In how many archaeological contexts can similar geological material be found?"), some combination of either of these emphases is feasible in that the second question easily follows the first. This may apply for a local analysis where the archaeological distribution of one geological material may be in multiple contexts (Williams-Thorpe and Thorpe, 1988). Or in the case of the present study, similar (but not identical source) material may be found over a wide region or even globally without any cultural connections between contexts. In either type of study, the discriminating process of elimination is then begun to distinguish the separate deposits and attempt to pinpoint the best geological candidate for the origin of a specific artefact.

Phase 2: Field Literature and Cartographic Resources

Whether adopting the first or second of the above procedures, one would consult relevant archaeological and geological studies in the literature to ascertain scientific contributions to these perhaps unasked or assumed questions from prior research. It is the experience of this researcher that archaeological reports prior to the last decade are often silent about any geological material from which their artefacts are made. It is equally true that most geological reports are silent about any archaeological material or significance to their work. The specific field literature used in the present study will be referenced region by region in the following chapter.

For the present study it was vital to first have a large-
scale (global) understanding of past volcanic activity. Prior basic geologic coursework fulfilled this basic need for this researcher, although refamiliarization with regional vulcanism worldwide was also necessary.

A comprehensive list of field literature and maps consulted in the past six years would be enormous, but the following excerpted examples provide some of the most useful references used for identifying potential fieldwork: Peru (Cobbing et al., 1981; Gableman, 1964; Gregory, 1916); Mexico (Hasenaka and Carmichael, 1987; Luhr and Prestegaard, 1989); Aegean Islands (Briqueu et al., 1986; Puchelt and Hoefs, 1971; Wyers and Barton, 1986); California (Howard, 1981); Levant-Near East (Barberi et al., 1980; Bonen et al., 1980); Italy (Bigazzi et al., 1986; Minissale and Duchi, 1988); Spain and Portugal (Amigo et al., 1984); Britain (Harris, 1977; Kokelaar, 1986) India (Mukherjee and Biwas, 1988; Newman, 1984; Sen, 1986). These geological studies were selected after it was determined that archaeological use of basalt or andesite was a high likelihood or already known.

Other areas surveyed but not reported in the present study include Turkey, Iraq, Iran, Egypt, Yemen, Romania, France, Germany, Ecuador, Colombia, Guatemala, Indonesia, Caribbean Islands, Iceland, Hawaiian Islands, and Easter Island. In the main these other areas also have quantities of volcanic rock, but not in a comparable quantity and quality of recorded contexts as have been selected for the present research.

Additional large-scale studies of global vulcanism have been major references for this study. These have been primarily descriptive for beginning research into correlating geological
and archaeological data (Williams and McBirney, 1979; Gill, 1981; and Thorpe, 1985).

Geological map resources regularly used for the present study include the following major map collections: U.S. Geological Survey Library Map Room, Menlo Park, California; Geology Department Cartography Room, University College London; and the Geological Association of London Geology Map Room of the D.M.S. Watson Science Library, University College London. Used in conjunction with the above are major topographic map collections including the following: University of California, Berkeley, Doe Library Map Room; and the Royal Geographical Society Map Room, London. Also, individual maps were purchased from U.S. Geological Survey, Menlo Park, California, California Department of Mines, San Francisco, California, and Pacific Travelers Supply, Santa Barbara, California. Whenever maps could not be purchased, photocopies were made and hand-coloured from originals for personal use in the field.

For either of the above emphases and/or approaches (i.e. archaeological or geological) to provenance studies, it would be expected that one should consult geological maps with small-scale detail throughout the preliminary process prior to fieldwork and continuing through fieldwork. Regional maps with 1:100,000 scale are inadequate guides to the task of selecting areas for detailed fieldwork. Certainly, during fieldwork both a topographic map and geological map with 1:25,000 scale are desirable, although it is not always possible to obtain these. Geologic maps can sometimes be obtained through national cartographic agencies but in many cases their availability is restricted by military or defence policy. In any case, familiarity with the maps prior to actual fieldwork is a prerequisite task.
Phase 3: Obtaining Archaeological Material

At this point it would be necessary for the material specialist to obtain archaeological samples of the relevant geological material, preferably including material from a variety of cultures. This step in the process can involve months of research whereas the culturally-based archaeologist is likely to have samples at hand or ready access to material. For example, this researcher suffered a delay of five months between initial determination of the fact that the Olmec culture used (Coe and Diehl, 1980) certain kinds of basaltic andesite and the obtaining of appropriate archaeological samples for preliminary study. In another example the gap between determination of the use of andesite by the Inca culture and obtaining samples was eight or more months. After the present researcher found a literary reference on Inca stoneworking of andesite, the British Museum of Natural History provided archaeological samples from an 1837 expedition collection (subsequent to this researcher's consultation of the British Museum of Natural History, Mineralogy Dept. Registers). It was necessary to return to another continent to request and obtain geological quarry samples from the author of the above reference on Inca technology (Protzen, 1986). From other corroborating sources it would appear this expenditure of time is very common, indeed normal for this type of research.

On another issue, sample collection can raise ethical considerations. Cultural patrimony, questions of authorization, and sampling permission must be tactfully and carefully respected. Of particular importance for continuing access to archaeological
material, protection of the reputation of the researcher is of great importance. Legitimate concerns and even rightful nationalist attitudes to the preservation of cultural property and the thwarting of illegal "archaeological" activity can easily stymy necessary and legitimate archaeological research as well. Naturally, obtaining appropriate permissions can again involve months of research time. This researcher spent months in and out of certain consulates (with consular officials dining in his home) before permission was granted to sample. Even then, the copious documentation (with seals and signatures) taken into one unnamed country could have even hindered controlled and legitimate sampling. Growing alienation between central officials and provincial administrators could actually negate official permission and permanently restrict subsequent research. Overall, this potential problem is generally complicated when sampling is to be undertaken in several regions and even more so when fieldwork is to be permissible in several countries. The above questions of sampling ethics are best discussed with other experienced researchers whose knowledge is current, and this must be assessed on a country-to-country (or region-to-region) basis. Specific sample collection procedures are discussed initially in this chapter and again in Chapter 4, particularly in light of representative sampling methods assisted by the portable field laboratory.

Phase 4: Laboratory Analysis

The next step would be essentially identical for either procedure. Laboratory analyses of the archaeological and geological material and the interpretation of results from both materials would be the culminating stages of research. This is often the
most time-consuming aspect of the research, involving the integration of the archaeometric applications and analyses discussed earlier (2.1) in the chapter. The steps in the present study are briefly outlined as follows: (1) assessment of samples in order to determine the best sequence of analyses; (2) preparation of necessary thin sections for petrographic analysis; (3) petrological analyses and interpretations; (4) photomicrography of thin sections; (5) preparation of samples for SEM with EDS (carbon coating, etc.); (5) SEM optical analyses; SEM photomicrographs; (7) X-ray energy spectroscopy (EDS) analyses (integrated with SEM micrographs); (8) SEM/EDS data interpretations; (9) EPMA sample preparation (which may involve new carbon coating if different preparations are needed rather than using the same preparations for SEM); (9) EPMA analyses; (10) EPMA data interpretation; (11) consultation of other literature or studies for comparisons; and (12) experimental conclusions.

To summarize Phase 4, upon which major experimental conclusions rest, petrography (optical petrology) is followed by SEM with EDS, followed by EPMA. This is an analytical sequence in which one moves from the general (larger scale detail using the polarizing light microscope) to the particular (smaller scale detail in SEM with EDS and EPMA) with increasing potential for quantitative analyses.

Petrographic examination was made either in a fixed laboratory or in the field using the portable laboratory designed and assembled by this researcher (Hunt and Griffiths, 1989). Field petrographic analyses were conducted in Peru, Mexico, California,
Fixed laboratory petrographic facilities utilized in this research include the Petrology Laboratory, Institute of Archaeology, London, and the Petrographic Laboratory, Trailer 11, Igneous and Geothermal Processes, U.S. Geological Survey, Menlo Park, California. Consultation in petrography has taken place in these facilities and those of University College London Geology Department, British Museum Research Laboratory, and British Museum of Natural History Mineralogy Department. Over 140 petrographic thin sections have been analysed from around 310 rock samples collected by this researcher and 203 additional specimens in private and public collections (including those of Professor J.P. Protzen and the thin section and rock samples of the British Museum of Natural History Mineralogy Department) studied in total.

The scanning electron microscope used in this research is a Hitachi S-570 model with secondary and backscatter detectors. The energy-dispersive X-ray spectroscopic (EDS) analysis on the SEM is a Link System 10/25 S model with a computer and analytical software. These instruments have been used in the SEM Laboratory of the Institute of Archaeology, London. Over 237 SEM micrographs and over 460 spectra have been obtained and analysed through SEM with EDS.

The electron microprobes used in this research are a Cambridge Instruments GeoScan II in the Microprobe Laboratory of University College London Geology Department, and a Cambridge Instruments 9 Detector Probe in the Probe Laboratory of U.S. Geological Survey, Menlo Park, California. Around 90 analyses were obtained and interpreted from these instruments.
Phase 5: Fieldwork

In many of the specific occasions of provenance research, particularly in the present study where little formal provenance analysis had been attempted with the material, fieldwork is required in many geographic loci. In fact, sampling itself demands the examination of both archaeological and geological sources in as many locations as is reasonable economically and temporally. For example, geological sampling necessitated for the tentative provenance determination of only part of the Tres Zapotes archaeological material took place over a 75 sq. km survey area and over a two week period in the Olmec heartland. Certainly it could be feasible that this geographical coverage and time spent might be ultimately insufficient in other circumstances. Because of the nature of fieldwork required on several continents, the planning and execution of fieldwork and the time spent per archaeological and geological context is even more demanding.

In the present study, fieldwork usually took place between the obtaining of archaeological material and its analyses and the obtaining of geological samples which actually constituted most of the fieldwork (except where archaeological sampling could not be done before fieldwork). This pattern of obtaining archaeological material and its analysis is prior to geological sampling is suggested as the ideal sequence of research in the experience of the present study. Where this sequence is not followed, the quality of planning and collecting appropriate representative samples (discussed in detail in Chapter 4) could be less ideal. The reasons should be clear: field samples may look fairly similar but prior laboratory analyses can heighten awareness and
clarify subtle distinctions; also, mineralogical analysis of the archaeological material by petrological analyses as well as some familiarity with literature on the local geological record of magmatic crystallization coupled with petrographic thin section analysis (Gill, 1981:168) may help to best identify beforehand the optimum topographic locus for detailed fieldwork. This is also important when the geologic source material and the archaeological material may not have been subjected to similar weathering situations, i.e. when an isolated outcrop of source rock has been far more exposed for millenia whereas the archaeological material may have been protected in an internal architectural feature for the same period of time and even subsequently sequestered in a museum environment. This will be dealt with in some detail in Chapters 8 to 10. Ultimately, knowledge of the material by prior petrological examination before the fieldwork should enhance the overall quality of provenance research.

The fieldwork undertaken in the present study was briefly mentioned in the Preface but will be described in more detail in Chapter 4 and each subsequent specific chapter on the individual contexts.

Phase 6: Laboratory Analysis

In essence this step would be mostly a repeat of Phase 4 but on geological material. Experimental procedures should require an identical sequence of analyses to be done. Because the volume of geological samples would generally be overwhelmingly greater than that of archaeological material, representative analyses would be correspondingly numerically greater. In terms of research time spent, it is likely that the greatest amount of time would be
used in these laboratory analyses and subsequent interpretation.

Provenance conclusions would follow these final laboratory analyses with the proviso that subsequent refinements in methods or instrumental techniques could later improve on accuracy or show the resulting provenance determinations to need updating. One of the primary goals of provenance research is the ultimate sharing of research by publication for purposes of information, clarification, and eliciting peer response.

3.6 Summary of Methods for Determining Provenance

Each of the specific contexts in which the provenance of artefacts has been investigated in the present study are given in Table 3.2 below. The individual discussions follow in Chapters 5 to 7.

Table 3.2 ARCHAEOLOGICAL PROVENANCE CONTEXTS

<table>
<thead>
<tr>
<th>Phase:</th>
<th>Inca</th>
<th>Olmec</th>
<th>Canaanite</th>
<th>Native American</th>
<th>Cycladic</th>
<th>Roman</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Literature</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2. Mapwork</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3. Archaeological Material Obtained</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Lab Analysis</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Fieldwork for Geological Material</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>6. Lab Analysis</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

In some cases above, fieldwork was simultaneously undertaken.
for both archaeological and geological material. As these were the first material study opportunities or provenance attempts in 1984 in Santorini, Greece, methods used and refined in the later fieldwork had the advantages of experience with double laboratory analyses, first of archaeological material and second of geological material (although in some cases additional archaeological material was obtained along with geological material in the fieldwork). Further archaeological material from the Levant was obtained long after fieldwork, in which case the geological analyses depended also on samples not necessarily collected by this researcher. Reference collections at the Institute of Archaeology, London, and the British Museum of Natural History, Mineralogy Dept., provided archaeological and geological samples respectively for some Levant provenance research. Archaeological material from Native American contexts had to be studied in situ where sampling was not permissible for the purpose of laboratory analysis. Further fieldwork in 1988 on geological sources for Roman stonework in the Alban Hills volcanic series and for Cycladic stonework at Akroteri, Santorini (Greece) in 1987 was also undertaken, but archaeological samples were either not permitted or obtained for analytical purposes. Thus these latter three contexts will only be discussed briefly in the present study of provenance and will be referenced in subsequent chapters where weathering information is presented.

In summary, the primary value of a discussion on provenance procedures, as used in the present study and detailed in this section, lies mostly in the experience of this researcher that prior archaeological provenance studies have not clarified some of these steps in their discussion of experimental procedures.
Further value is claimed for the double laboratory analysis process of both archaeological and geological material. The necessary fieldwork in between is claimed to be greatly enhanced by prior primary analysis for familiarization with the material. Furthermore, the use of geological map resources may be assumed by other provenance studies. The role of maps both before and on the field is vital to the success of provenance studies. Certainly the literature available through geological studies must be carefully assessed, but maps (either accompanying such studies or independent of them) can do much to suggest initial fieldwork investigation. In many cases, detailed chemical analyses of material from certain geological regions and deposits have not been made or are unavailable whereas geological maps can sometimes narrow research focus to the general geological material, after which chemical analyses can refine and confirm such loci. It is also to be noted that limitations will be confronted in the literature and map resources which are prepared for geological research without any planned intention of being used for provenance research. This is especially true where chemical analyses do not accompany geological discussions and maps, which, if they were available, would help greatly to isolate or eliminate inapplicable geological material in fieldwork undertaken for provenance research and which could be built on such data in more time and resource economical study of potential sources. Finally, the question of emphasis on archaeological or material analysis and training has not been discussed before. These elements are not to be taken for granted and are seen to be improvements of existing provenance methodologies.
4.1 Representative Sampling and Field Contextualization

Representative sampling and field contextualization are two constants which every archaeologist has to consider. Objectivity in determining the appropriate quantity of samples and careful attention to macro and microcontexts are requisites in any fieldwork. An improvement in these areas can greatly enhance the overall value of nearly any archaeological study. The following sections assess the importance of these constants.

4.1.1 Representative Sampling

First, a brief elaboration on representative sampling is germane. Appropriate questions must be asked repeatedly in the process of sampling. The archaeologist must make many qualitative choices regarding which material to sample in the face of competing or perhaps ambiguous candidates. Which is the best choice out of many? The archaeologist must also make quantitative choices as to the optimum number of samples. Should another reference sample be included between X and Y? Finally, although this should be determined at the outset, what are the sampling criteria? Such questions could be greatly aided by any tools which made distinctions between samples more clear as well as commonalities between geological and archaeological material. A set checklist of such questions must be established prior to collecting based on research priorities but may be modified upon arrival in the field should circumstances warrant such. One possible guideline which is based on this researcher's experience is provided below.
Table 4.1 REPRESENTATIVE SAMPLING CHECKLIST

A. Pre-Field General:

1. What are the field research priorities?
2. What are the sampling criteria?
3. How much time is available?
4. What optimum equipment/tools can be brought in?

B. Pre-Field Particular:

1. How detailed is the appropriate map?
2. What published information is available and applicable?
3. What legal/ethical sampling permissions are necessary?
4. What instrumental analytical techniques will be used?

C. Field General:

1. How large (in square metres) is the artefact/monument?
2. How large (in square metres) is the deposit/outcrop?
3. How large (in square metres) is the sampling area?
4. What estimated percentage of the total is being sampled?
5. What is the optimum specimen sampling size and number?
6. How many other candidate sampling areas exist?

D. Field Particular:

1. How many distinct colour and texture changes are visible within:
   a) artefact  
   b) sampling area  
   c) deposit?
2. What environmental microcontexts exist and how many?
3. How can one distinguish between geological and archaeological material?
4. Is the stoneworking method observable?
5. How much of the sample volume is being transported back?
6. What statistical sampling correlation is applicable?
7. Has field data been permanently recorded?
In discussion of the above possible checklist, it might be suggested that other questions not asked here may also be important. It is obvious that question C.5. on optimum number of samples basically asks the question "When does one have enough samples?" It should also be obvious that one can answer in the negative more easily than in the positive, e.g. 5 samples in a 50 sq. mi. area are almost certainly insufficient. It is also likely that any absolute priority of above sampling questions is not in any strict order although, for example, the same question as above (C.5.) cannot be answered until question D.1., "How many distinct colour and texture changes are visible?" is answered. Again, with question A.1. in mind, "What are the field research priorities?" it is likely that some questions are more applicable to one study and not another (e.g. weathering or provenance). It must be determined which questions are appropriate in the initial stages of research. The time spent answering these questions in the Pre-Field stage will greatly resolve questions at the Field stage. However, new questions may arise at the Field stage which could not be anticipated earlier. In any case excellent field notation, including photography, is necessary for the accuracy of any fieldwork (Thorpe and Brown, 1985:1, 7, 9-12). It should be noted that the above table and its questions are specifically derived from field experience which is most often found in quarry contexts.

However, one obvious problem associated with quarry contexts is the fact that quarrying subsequent to removal of any material for monuments or other artefacts under study may remove most or even all of the parent material. Such a complication is encountered more often with sedimentary and metamorphic material, as in
the case of Classical marble quarrying (Ward-Perkins, 1972), but can render true representative sampling virtually impossible. In such a case, one can only hope for a sufficient number of quarry fragments or if the material was dressed on site, enough debitage to allow further sampling.

Techniques for collecting strictly geological samples differ from those for collecting archaeological samples in several dimensions. Although some of the same procedures apply equally in terms of the above questions, the following distinctions apply.

First, the research focus of geologic sampling is on natural processes whereas the focus of archaeologic sampling is on the kind and degree of human modification. The presence of the human element is a given in the latter but must be absent in the former (in that for control purposes human modification is undesirable). In this case even geological material from a quarry context would have to be carefully assessed as to what amount of human modification would be present to render it archaeological. For example, a natural cliff face may have a quarry at its talus base. Determining which rock fragments are products of natural exfoliation or fracture and which are products of stoneworking is essential although possibly often very difficult to evidence, especially after considerable time has elapsed. A hammerstone blow would be likely to separate stone along natural fracture lines, but in many places along a worked stone the blows it has received will be directed away from natural fracture angles. Depending on the analysis to be performed and the particular study (e.g. provenance or weathering), a chip or fragment from the stone being worked is less likely to be considered archaeological if it can be equally
produced by a natural process (even though its production would have been by unnatural means). Obviously, this is far more important for weathering studies than provenance studies.

Second, for either study fresh geological material must be also sampled which is unweathered by either natural or unnatural processes (Thorpe and Brown, 1985:9). This is essential for several reasons. It must be evidenced that the sample is from an original context and an unworked surface of an unmoved stone (i.e. inseparable from "bedrock") can guarantee this. Although obtaining a sample of fresh core rock will be by necessity "unnatural," fresh surfaces do not have to constitute "working" if the fracture occurs along natural lines. For any comparison of material to be valid, it must be demonstrable that conditions are met which are as close as possible to original deposition.

These are some of the considerations which have been assessed in the representative sampling procedures followed in the present study, more or less applicable to each of the geological contexts encountered in this research. Other specific details will be covered in the subsequent chapters germane to certain sites.

4.1.2 Field Contextualization

Second, a brief discussion of field contextualization is needed. No geological study can be accurate without a proper perception of field relations: "Appreciation of field characteristics and field relationships of studied samples is essential." (Thorpe and Brown, 1985:1). Stoneworking contexts fall within the broad category of geological field relations, i.e. the interrelationships between the various micro and macrocontexts in a geological setting. The interrelationships between stone sample and
geologic deposition offer clear examples of this. When these interrelationships also reflect an archaeological setting, field relations can be extended to this additional meaning: stone monument from stone quarry. The tetrahedral diagram below (4.1) illustrates the suggested interrelationships.

Diagram 4.1 STONEWORKING CONTEXTS

Sample (Geological) Deposit

A — B

C — D

Monument (Archaeological) Quarry

By entering the human factor of stone modification into the natural picture, what was formerly only geologic has become more complex. Not only do the geologic elements (A - B) directly relate to each other and the same for the archaeological elements (C - D) but now it can be seen how field relations is expanded in the following statements (A - C; A - D; or A - BCD); B - C; B - D; or B - ACD) and so on.

Prior to the implementation of a portable field laboratory as experimentally used in this research, such an integrated approach to contextualizing field relations could be difficult to achieve due to time factors and fieldwork limitations for optical petrology.

That need exists for such implementation is in some part evidenced by the economic constraints on archaeological fieldwork. If significant time savings and more meaningful fieldwork both
accrue from such implementation, its use is easily justified.

Thus in terms of both representative sampling and field contextualization which are always vital to fieldwork, techniques or tools such as a portable field laboratory should be utilized when possible. The following discussion explores some of the advantages experienced in this research.

4.2 Advantages of a Portable Field Laboratory

The following discussion on specific advantages accruing from use of a portable field laboratory for optical petrology derives in part from excerpts of a published paper co-authored by this researcher, "Optical Petrology in the Field" World Archaeology 21.1 (Hunt and Griffiths, 1989). This paper will be referenced in numerous points in this chapter.

Where in prior fieldwork unaided eye or only hand lens examination of a field specimen have usually sufficed, (1) the field "microscope may reveal much that would be missed by eye and material may be re-examined, re-assessed, and re-sampled, with no time lag, in light of microscopic findings" (Hunt and Griffiths, 1989:165).

Specifically, improved field contextualization can make sampling more representative because thin section preparation in the field allows one (2) to eliminate unsuitable material on site, (3) correct and refine sampling hypotheses on site, and (4) sample elsewhere on the spot with increased mobility.

Furthermore, by providing immediate opportunity to reduce the gap between field observations about the sources and those observations made on the microscopic level, (5) the mineralogy of
material may be better understood on site where subsequent fixed laboratory observations would be unable to gauge such interrelationships because they could not be confirmed by direct observation without a return to the field or site (which may be impossible in certain rescue archaeology contexts). Field examination of thin sections "can be particularly important in critical situations where the excavation or field survey can be effected once and once only" (Hunt and Griffiths, 1989:165).

This "calibrating" capacity of a portable thin section laboratory suggests several other advantages. Economic benefits (7) are possible (offset by initial equipment outlay) if either less time is required in the fixed laboratory or such time as would be saved thusly is applied elsewhere. Also, practical demands (8) of both sample transport and storage are better met if less material has to be actually taken back to the fixed laboratory which might be thousands of miles distant. Experience shows that "despite careful recording of the field survey or excavation with notes and photographs, by the time microscopic examination is conducted it may be too late or too expensive to re-examine or re-sample [field] features which become of interest in the light of the new insights provided by microscopic examination" (Hunt and Griffiths, 1989:165).

Finally, if the actual production time of thin section preparation is reduced (9) due to time-saving features of the portable laboratory (compared to fixed laboratory production time), field time can be better used by either increasing the quantity of thin section preparations or by applying such field time elsewhere. In the experience of this researcher, average production time for preparation of thin sections in the field using the portable la-
laboratory rarely exceeds 45 minutes from sample extraction to finished microscope-ready slide.

For questions of representative sampling for a study of provenance, it is a valid working assumption that "the reliability of the provenance determination rests on the quality of the reference collection in its representation of the distribution and variety of the material" (Hunt and Griffiths, 1989:166). Thus, it follows from this that field "microscopic examination may alert [the researcher] to variety within the appropriate material which may indicate the need for more thorough sampling than might otherwise have been done" (Hunt and Griffiths, 1989:166). That this would be difficult for any other than a portable laboratory, especially in remote contexts, is readily apparent. Other advantages are expected to be observed in future experimentation as improvements are made on the original prototype assembled for this stone research.

The unique features of the prototype portable laboratory used in much of this researcher's fieldwork are discussed in the following section. In several of its methods of application and processes it will be seen as the first of its kind for archaeological (and in some cases geological) fieldwork.

4.3 Elements of a Portable Field Laboratory

The requirements of a portable field laboratory for optical petrology are for tools and equipment suitable for 1) mechanized stone cutting, 2) glass slide mounting and adhesion, 3) grinding and polishing and 4) polarized light microscopy (Hunt and Griffiths, 1989:167).
The above are basic requisites for petrographic examination but additional features are necessary which ensue from field conditions and its rigours which prohibit the transport and use of heavy, awkward equipment to remote areas. Therefore, a portable field laboratory must also be "self-contained and robust and preferably sufficiently light, compact and convenient to be carried and used by a single person" (Hunt and Griffiths, 1989:167).

4.3.1 Portable Mechanized Stone Cutting

Due to field conditions which required for economy of field time a self-powered tool to cut stone in thin (< 4 mm) slices, a portable (hand-held) tool was needed with a diamond saw blade and sufficient load velocity (> 3000 rpm). These requisites were arrived at after experimentation with various tools prior to field use. After a half-year of consultation and customizing, the experimental prototype tool used for fieldwork was an adapted Makita £3700DW Cordless Trimmer. It was adapted by lathing the arbor to fit a non-designated Makita £724950-8A Diamond Saw (a thin circular steel blade with diamond-impregnated rim) which was 8.65 cm in diameter and 1.7 mm thick. The blade was fitted with hexnuts, washers (steel and rubber) for detachability.

Mechanized grinding to reduce stone slices before and after slide mounting was provided by a silicon carbide grinding wheel, Mos (£C-80 MV) with a coarse 180 grit; a 7.65 cm diameter and 1 cm width. The grinding wheel was attached above the diamond saw blade, again with hexnuts and washers as is shown in Figure 4.1. Overall dimensions of the tool were 21.6 x 17.1 cm (8.5 x 6.7 in) and total weight with battery and attachments was 1.3 kg (2 lb, 14 oz), thus easily hand-held in operation (Plate 4.1).
PORTABLE MECHANISED CUTTING and GRINDING TOOL being used for preparing andesite thin section at Inca-Wari Gate, Huatanay Valley, Peru. (Figure 4.1 [below]) lists specifications of PORTABLE MECHANISED CUTTING and GRINDING TOOL PROTOTYPE.

Prototype Cutting and Grinding Tool (modified MAKITA Cordless Trimmer #3700DW with Diamond Saw Blade MAKITA #724950 8A and Grinding Wheel MOS # C 80 MV all assembled on arbor)

*World Archaeology* 21:1
(Hunt and Griffiths, 1989)
Power for the hand tool was provided by one rechargeable 7.2 volt nickel-cadmium battery (with spares) at 8000 rpm non-load velocity and at 3000-6000 rpm load velocity depending on the material. Depending on material, one battery charge lasted through several hours of use, thus extra charged batteries were desirable for remote use. Two different battery recharging units were used as well, one for AC (w/ step-down transformer for 240 volt mains) and one for DC (running off car or 4-wheel drive vehicle battery with cigarette lighter adaptor). These were Makita Fast-Chargers (£7010 for 110 volt; £7012 for 12 volt).

Water supply was also necessary for reducing drag friction in the cutting and grinding stages. This was provided by a small water pack (with ring attachment to the tool) and copper tap valve which delivered a variable feed of water. For stone cutting and grinding a constant feed of 5 ml per second was needed. The total water reservoir volume was 100 ml so refilling is necessary with some frequency depending on how long the tool is operating.

Thus the prototype tool meets all the stone cutting and grinding requisites of sufficient portability and power for field use and is ideal for remote sites. After much discussion with geologists and archaeologists it appears that this prototype tool is the first of its kind for field use and has been examined by numerous geologists and specialists in optical petrology. Because no prior discussion of such a tool has appeared in the literature other than the published article co-authored by this researcher in *World Archaeology* 21.1, 1989, any critical evaluation of this prototype will be in future discussions. However, concerns have been raised both by the present study and outside sources as to
the safety of the cutting tool as presently designed. Since the experimental modification is not to the specifications of the Makita company for which the original tool was designed, it is possible that potential damage to the tool or to its user could be serious. Possible safety risks include the disattachment of either diamond blade or grinding head during high velocity. Some possible risk of blinding or eye damage could also be projected by the high speed discharge of stone chips, powder, or grinding stone ejected from the rotating blade. For this reason, safety glasses are always to be worn (or other face and eye protection). Due to these concerns of potential safety hazards of the tool (as is), it is recommended that production of any working models from the original prototype described here should not be undertaken until such time as the Makita company, the present researcher or another entity engineers and tests a better model. Nonetheless, the present prototype has served well under experimental trial for several years without any visible loss of efficiency or any known damage to its parts or its user. Details of experimental use to date and archaeological loci follow later in this chapter in section 4.3.

4.3.2 Slide Mounting and Adhesion

As discussed previously in the published article, various adhesives which have been used in thin section preparation include Buehler's Epo-Kwik, Petropoxy 154, and Lakeside 70. Cold cure methods usually require the mixing of resin and hardening catalyst, as in the case of Epo-Kwik epoxy which is time-consuming both in the mixing time (up to 10 minutes) and curing time (up to 50 min at normal 21°C room temperatures). Heat cure methods obviously
require a hot plate or other heat source, as is the case with the Lakeside 70 cement. Some mounting agents like Petropoxy 154 require both mixing of resin and catalyst at 5:1 ratios with the necessary stirring and then heating to 150°C to decrease viscosity and bubbling. Additionally, Petropoxy 154 cures optimally after 24 hrs, and is therefore not intended for rapid preparation of thin sections (although moderate cure is achieved in 20 min).

Ease of handling and convenience of use in the above adhesive mounting media did not recommend them for field application. If at all possible, mixing ratios, heat applications, and messy or sticky processes with spatial bulk were avoided in the field.

Other features of mounting media could be discussed, such as refractive index, length of life (and discolouration), bonding strength, and coefficient of thermal expansion of the medium. The optimum refractive index of a slide adhesive should be around 1.53, which is the refractive index (R.I.) of the glass slide and SiO or quartz, around which R.I. much transmitted light petrography is standardized. Discolouration is usually caused by the additional absorption of ultraviolet light over a period of time and can be yellowish to dark amber. Bonding strength is usually achieved at full cure and can be measured either in p.s.i. or Shore D hardness. Coefficient of thermal expansion is the resulting contraction of the medium upon curing. Being stronger in its bond to itself with the glass than the internal bond of glass to itself, curing contraction can break the glass slide if too thick an application of adhesion is effected. A brief evaluation of the above common adhesives follows in Table 4.2 compared to a mounting medium pioneered in this research, Dymax Light-Weld 304.
Dymax Light-Weld 304 is an ultraviolet light-cured adhesive used in connecting fibre optics in industrial applications. Not only does it possess a uniquely-fast cure time of 10 minutes (or less, since manufacturer’s suggestion is less than 2 minutes) in ultraviolet light, but also requires not mixing or heat treatment for curing. It also has an R.I. of 1.53, is of medium viscosity and easy to handle (requiring only the amount needed per slide), has a high shear strength of 1000 psi, and has been tested for long-term discolouration for over 96 hours in intense illumination in an accelerated ageing device without significant yellowing.

The light source for curing the adhesive is battery-operated (5 C size batteries) with a low intensity 3 W/cm longwave UV light. As manufactured by Dymax, it is named Light-Welder PC-4. The size of the lamp was 16.5 x 8.9 x 3.0 cm (6.5 x 3.5 x 1.2 in) and its weight with batteries was 681 g (24 oz), thus is easily portable and convenient for use.

Light-Weld 304 has been used in both fixed lab and portable field lab for over three years by this researcher, with one 30 ml plastic vial supplying over 50 thin sections (and in some cases multiple consolidations). It has been used in temperate and tropical climates as well as at alpine altitudes of over 3500 m (where additional atmospheric UV enhanced curing) in temperature ranges from 10 to 30 °C (Plates 4.2 & 4.3).

Materials prepared for thin and polished section using Light-Weld 304 include a variety of stone types, ceramics, stuccoes and frescoes, although the majority of thin sections have been of basalt and andesite. Additional experimental details of fieldwork are provided later in this chapter in section 4.3.

Compared in personal petrographic experience with all other
(Plate 4.2 [above]) MOUNTING MEDIUM LIGHT WELD 304 being applied to glass slide, one drop per slide per thin section preparation. (Plate 4.2 [below] Ultraviolet light curing of LIGHT WELD 304 by battery-powered UV lamp for average 3 - 5 minutes.
mounting media in common usage mentioned above, the advantages of Light-Weld 304 even in the fixed laboratory suggests its use for thin section preparation, certainly most satisfactory for use in the field for time spent, convenience of handling, and transport, and it appears ideal for most stone adhesion needs. A comparison of mounting media can be seen in Table 4.2 below.

<table>
<thead>
<tr>
<th></th>
<th>Bushler’s Epo-Kwik</th>
<th>Lakeside 70</th>
<th>Petropoxy 154</th>
<th>Light-Weld 304</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curing Method</td>
<td>mix + cold</td>
<td>heat</td>
<td>mix + heat</td>
<td>UV light</td>
</tr>
<tr>
<td>Curing Time</td>
<td>30-50 m</td>
<td>20-40 m</td>
<td>20 m to 24 h</td>
<td>10 m</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>1.58</td>
<td>1.54</td>
<td>1.54</td>
<td>1.53</td>
</tr>
<tr>
<td>Hardness/Strength</td>
<td>80-85 Shore D</td>
<td>brittle</td>
<td>*</td>
<td>Shore D 1000 psi</td>
</tr>
<tr>
<td>Shelf Life</td>
<td>1 yr **</td>
<td>&gt; 5 yrs</td>
<td>1 yr</td>
<td>1 yr</td>
</tr>
<tr>
<td>Discolouration</td>
<td>low</td>
<td>high</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Viscosity</td>
<td>* (higher)</td>
<td>* (similar)</td>
<td>(higher)</td>
<td>(low)</td>
</tr>
</tbody>
</table>

Most of these figures were obtained through manufacturer’s published data; some obtained through personal laboratory use.

* Not available  ** Manufacturer suggests lower shelf life in higher sustained temperatures.

A critical evaluation of the other adhesives shows several disadvantages of each medium. Epo-Kwik has disadvantages of requiring ratio mixing (time-consuming) requiring separate contain-
ers (space-consuming), higher R.I., higher viscosity and cures in longer intervals (more time-consuming). Lakeside 70 has disadvantages of heat treatment (space-consuming), higher R.I., brittleness, discolouration and cures in longer intervals (more time-consuming). Petropoxy 154 has ratio mixing disadvantages (time-consuming) requiring separate containers (space-consuming), heat treatment (space-and-time-consuming), higher R.I., higher viscosity, and cures in longer intervals (more time-consuming). Additionally, the coefficients of thermal expansion as tested experimentally with each medium showed Light-Weld 304 to have the least amount of curing contraction. Also, Light-Weld 304 has a low toxicity (as a methacrylate) and uses methylated spirits as a solvent. Light-Weld 304 also made an ideal cover slip adhesive for subsequent photomicrography.

Upon consultation (again with numerous geologists and petrographers with both archaeological and geological experience) and discussions with Dymax chemists and suppliers, this use for Dymax Light-Weld 304 (or other UV-cured adhesives) constitutes a novel experimental application (C. Bachmann, 1989).

4.3.3 Thin Section Grinding and Polishing

This section has little to add of pioneering significance in field applications except for space-saving dimensions of glass plates (15 x 15 x 0.65 cm) custom-cut to this researcher’s specifications to fit the portable field laboratory carrying case. Smaller than typical petrographic glass plates (25 x 25 x 1 cm), they were fully satisfactory for rotational grinding and polishing with successively finer stages of carborundum grit powders (400, 600, 800, and 1000) and water slurries, with water washing
of the slide between each stage. As is standard for petrographic thin section preparation, the final polishing was to 30 microns. The carborundum grit powders were carried in plastic containers of 100 ml each, which would easily supply 50–100 thin sections; and water supply for grinding and polishing was provided by the water reservoir of the portable cutting tool and the drinking water supply of each field expedition (Plates 4.4 & 4.5).

The glass slides used by this researcher are in fact most often suitable for electron probe microanalysis chambers, being shorter (46 x 27 x 1.2 mm) as petrographic slides than the most commonly-used slides (usually 72 x 27 x 1.2 mm). While the space saved for transport ease (in a plastic slide box) was minimal, consideration of subsequent analysis of the same slides by both SEM and EPMA where the smaller detector chambers made such dimensions ideal showed the practicality of this choice in allowing the same slide to be easily used for all three techniques, with the proviso that a permanent cover slip was not applied until all analysis was thought to be complete.

4.3.4 Field Microscopy

Several petrographic (polarizing light) microscopes have been used experimentally on the field, "using sunlight or artificial light deflected by a substage mirror. The main drawbacks are the bulk and weight of the instrument" (Hunt and Griffiths, 1989:171) when microscope dimensions exceeded 12 in of height and 15 lb in weight (without carrying case which added 30% bulk and weight). One type used prior to finding the ideal field microscope was an older model American Optical Petrographic Scope (Plate 4.6).
(Plate 4.4 [above]) GRINDING and POLISHING THIN SECTION by adding carborundum powder, e.g. 400 grit, with water slurry to glass plate; (Plate 4.5 [below]) with hand-held GRINDING and POLISHING to 30 micron thickness. Approximate time of this stage 20-25 min.
(Plate 4.6 [above]) PETROGRAPHIC MICROSCOPE (American Optical) in field use was adequate but not ideal due to bulk and weight; (Plate 4.7 [below] SWIFT FIELD MICROSCOPE FM-31 was modified for petrographic purposes with polarizer/analyser and was very ideal.
A model designed or adapted for field use was sought for over two years which would be ideally portable and have its own light source powered by batteries. The best field scope to date was assembled by this researcher subsequent to the published article and is thus discussed here at some length.

A Swift FM-31 Pocket Microscope was obtained and converted to a simple petrographic instrument by the addition of customised filters. These were adapted and fitted to the eyepiece (as analyser) and near the light (as polarizer) on either side of the slide stage. These filters were housed in plastic which was tool-ed on a jeweler’s precision lathe specifically for this scope. The field microscope has three rotating objectives (4x, 10x, and 40x) whose magnifications were multiplied with the 10x eyepiece to provide at least the 40x and 100x magnifications standard to petrographic scopes (Plate 4.7).

The light source was provided by a Swift FMA-748 Illuminator, which was a portable add-on light source using a tungsten filament 2.2 volt lamp bulb powered by two 1.5 volt batteries of AA size and with a KB-4 blue filter for tungsten light.

The dimensions of the Swift scope in its compact carrying box are 16.5 x 11.1 x 5.1 cm (6.75 x 4.4 x 2 in) and dimensions of the Illuminator in its compact carrying case are 7.8 x 8.7 x 4.3 cm (3.2 x 3.5 x 1.25 in). Working dimensions of the total unit with added illuminator are the same for length and width at 16.5 x 5.1 cm but with a final height of 16 cm (6.4 in) (Plate 4.8). Although many of the microscope components are rubberized or of lightweight plastic construction, the density and robustness of the compact scope make it ideal as a field microscope which would be subject to field conditions. Its optics are fine Japanese len-
ses of high resolution, and its compact shape and appearance are unusual for a microscope. The total weight of the combined unit is less than 1.2 kg (2 lbs 10 oz), making it extremely portable.

As it is a working prototype, this scope will need refinement in several areas, some of which will be discussed later in this chapter in section 4.4 on anticipated modifications of the portable field laboratory. Nevertheless, having been tested on the field with satisfactory results, this appears to be the first petrographic application of a Swift FM-31 microscope as well as the first portable field microscope modified for polarized light.

4.4 Experimental Use and Archaeological Loci

The following field loci were venues for testing aspects of the portable laboratory beginning in late 1987 and continuing to 1990. Not all features were simultaneously tested because the portable laboratory was assembled over a two-year period.

For the experimental testing of features of the portable stonecutting tool, some of the experimental contexts include Cuzco and Piquillacta-Rumiqolqa, Peru; the Tuxtla Mtns. near Santiago Tuxtla, and Lake Catemaco, as well as outside Palenque, Mexico; near Lago Garda, Italy; Bronze Age settlements in the Sussex Weald, England; and San Mateo, San Francisco, and Contra Costa Counties of California, U.S.A.

For the experimental testing of features of Light-Weld 304 UV light-cured thin section mounting medium, some of the experimental contexts include Cuzco and Piquillacta-Rumiqolqa, Peru; the Tuxtla Mtns. near Santiago Tuxtla, and Lake Catemaco, as well as outside Palenque, Mexico; Bronze Age settlements in the Sussex Weald, England; and San Mateo, San Francisco, and Contra Costa Counties of California, U.S.A.
Weald, England; and San Mateo, San Francisco, and Contra Costa Counties, California, U.S.A.

For the experimental testing of features of the polarizing portable field microscope, some of the experimental contexts include the Tuxtla Mtns. near Santiago Tuxtla, as well as outside Palenque, Mexico; and San Mateo, San Francisco, and Contra Costa Counties, California, U.S.A. Additional thin section preparation features of the portable laboratory including grinding and polishing were also tested in the above field loci.

Of some interest is a discussion of the most remote field location in which the portable field lab was used. At the Wari site of Piquillacta, Peru, at 3500 m (11,000 ft) in the Andes, the field laboratory was used for thin section preparation and petrographic examination which evidenced the source of Wari basalt use in wall elements as the Rumiqolqa basalt flow a few kilometres distant. The water supply for thin section preparation was part of the drinking water supply carried in to the site. Acceleration of mounting medium curing was effected by additional UV light at this high altitude elevation, although thin section preparation time (which included photo documentation) was a little less than 1 hr per slide. The portable cutting tool had several hours of battery charge remaining after this with sufficient power in one battery for at least two more thin sections, with the spare battery fully charged as well. The entire portable field laboratory was carried by one person in rucksack and hand (Plate 4.9).

Subsequent to the fieldwork in Peru in 1988, fieldwork in Mexico in 1989 (with the new microscope) demonstrated that the entire portable field laboratory could be compactly assembled in one hand in an aluminium carrying case with handle. Dimensions of
(Plate 4.8 [above]) SWIFT FM-31 PORTABLE MICROSCOPE in compact carrying case; (Plate 4.9 [below]) assembled PORTABLE FIELD LABORATORY on location in Peru (with old bulky microscope). Total field laboratory, incl. SWIFT FM-31 MICROSCOPE, fits in blue box.
the total portable laboratory for transport are 38 x 25.5 x 11 cm
(15 x 10 x 4.5 in) and weight is 13.2 kg (26.4 lb).

The following fixed laboratory loci were venues for testing aspects of the portable laboratory beginning in mid 1987 and continuing to 1990. Again, not all features were simultaneously tested due to long-term assembling of components.

Facilities included in chronological order are the IGP Petrographic Laboratory, U.S. Geological Survey, Menlo Park, California; the Physical Science Laboratory, Simpson College, San Francisco, California; the Petrology Laboratory, Institute of Archaeology, University College, University of London; the Conservation Laboratory, Institute of Archaeology, University College, University of London; the Conservation Laboratory, Museum of London; and the British Museum Research Laboratory, London.

Additionally, aspects of the portable field laboratory were demonstrated to geologists and archaeologists at: the Museum of London (July, 1988); to the Director of the Fitch Laboratory, British School of Archaeology, Athens (Aug., 1988); Institute of Andean Studies Annual Conference, University of California, Berkeley, California (Jan., 1989); to the Director of the Pre-Columbian Art Research Institute, San Francisco, California (Feb., 1989); Septima Mesa Redonda Conference, Palenque, Mexico (June, 1989); Ceramic Technology Summer School, Institute of Archaeology, London (July, 1989); British Museum Research Laboratory, (Nov. 1989); and numerous others.

Experimental testings of other UV light-cured mounting media also provided by the Dymax Corp. (Torrington, Connecticut, U.S.A. 06790) were carried out by this researcher at the Petrography Laboratory, U.S. Geological Survey, Menlo Park, California, and by
this researcher and Dr. Dafydd Griffiths in Cuzco, Peru. Among others, Light-Weld 404, 504, and 21003 adhesives were tested for cure time, hardness, and discoluration along with Light-Weld 304. Light-Weld 304 was most satisfactory in all categories for petrographic purposes.

As noted via published paper (Hunt and Griffiths, 1989:169), several other polishing and grinding methods were experimentally used in addition to carborundum slurries. Under the supervision of Dr. Dafydd Griffiths, different grades of carborundum papers fixed by C-clamps on pine frames were tested in 1988. Also, in tests (again under the supervision of Dr. Griffiths) of polishing agents, ultra-fine grades (up to 1 micron polish) of carborundum-embedded plastic sheets were experimentally used (as in metallographic polishing, see Scott, 1986) for petrographic purposes in 1988. These were fixed on lightweight aluminium frame mounts made by Buehler, Ltd. It was determined at that time that carborundum slurries were more satisfactory for petrographic purposes due to tearing of the plastic sheets or the unavailability of coarser grades of polishing papers and plastics (down to 400 grit).

Some of the other microscopes tested for field use include American Optical Petrographic Microscope, Bausch and Lomb Petrographic B-1102 Microscope, and a partially-assembled microscope made from Zeiss optic parts. On each of these other microscopes, the optics were more than adequate but the weight and bulk (as described earlier in 4.2) made them unwieldy for good field use.

In the earlier description of the portable stonecutting tool in section 4.3, it was mentioned that a range of materials were tested for load speed drag friction on the adapted diamond saw.
Also as mentioned in the same section, it is conceivable that some applications of this experimentally-modified prototype could involve safety risks for both tool and operator. Anticipated improvements to the prototype tool are discussed in section 4.5. Experimental velocities of portable saw stonecutting were estimated for the following materials below in Table 4.3:

Table 4.3 ESTIMATED EXPERIMENTAL STONECUTTING VELOCITIES

<table>
<thead>
<tr>
<th>Material</th>
<th>Mohs Hardness (approx.)</th>
<th>RPM @ Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Low-fired ceramics:</td>
<td>2-3</td>
<td>6000 rpm</td>
</tr>
<tr>
<td>2) High-fired ceramics:</td>
<td>3-4</td>
<td>5200 rpm</td>
</tr>
<tr>
<td>3) Limestone:</td>
<td>3-4</td>
<td>5000 rpm</td>
</tr>
<tr>
<td>4) Marble:</td>
<td>4</td>
<td>4500 rpm</td>
</tr>
<tr>
<td>5) Basalt:</td>
<td>5-6</td>
<td>4200 rpm</td>
</tr>
<tr>
<td>6) Andesite:</td>
<td>5-6</td>
<td>4000 rpm</td>
</tr>
<tr>
<td>7) Granite:</td>
<td>6-7</td>
<td>3200 rpm</td>
</tr>
<tr>
<td>8) Quartz:</td>
<td>7</td>
<td>3000 rpm</td>
</tr>
</tbody>
</table>

Venue and/or source of material: 1) Neolithic pottery, Greece; low-fired pottery; Iron II Sussex ware, England; Maya mural lime stucco, Bonampak, Guatemala 2) Roman and Saxon pottery, England; 3) Maya limestone, Chiapas, Mexico; Garda limestone, Italy; 4) Carrara marble, Italy 5) Inca Basalt, Peru; Olmec Basalt, Mexico 6) Santorini andesite, Greece; Olompali andesite, California; Inca andesite, Peru 7) Rio Urubamba granite, Peru; 8) Lago Garda Quartz, Italy.

* The above rpm velocities can be validated with strobe-light sensors and pitch-derived soundings.

Also to be discussed is the experimental application of the Light-Weld 304 mounting medium in a wide range of petrographic contexts and on diverse materials. Again, these experimental applications were not made simultaneously or consecutively but as materials became available. The materials range from lime mortar,
which was very friable and had a tendency to cause bubbles in the mounting medium, to very hard quartzite. For some of the materials tested, Light-Weld 304 is not recommended. These will be noted in the discussion following Table 4.4.

Table 4.4 EXPERIMENTAL USE OF LIGHT-WELD 304

<table>
<thead>
<tr>
<th>Material</th>
<th>Source</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Maya lime stucco</td>
<td>Bonampak, Guatemala</td>
<td>friable; required consolidation with Light-Weld 304 before mounting.</td>
</tr>
<tr>
<td>2. Thai pottery</td>
<td>Ban Don Ta Phet, Thailand</td>
<td>inconsistent adhesion</td>
</tr>
<tr>
<td>3. Maya limestone</td>
<td>Chichen Itza, Yucatan, Mexico</td>
<td>friable, was adhered but with numerous bubbles.</td>
</tr>
<tr>
<td>4. Sussex Ware pottery</td>
<td>Sussex Weald, England</td>
<td>same as 3.</td>
</tr>
<tr>
<td>5. Neolithic pottery</td>
<td>Nicomedia, Greece</td>
<td>same as 3.</td>
</tr>
<tr>
<td>6. Minoan fresco</td>
<td>Knossos, Crete</td>
<td>same as 1.</td>
</tr>
<tr>
<td>9. Leucitic tuff (volcanic quarry)</td>
<td>Ariccia, Alber Hills, Lazio, Italy</td>
<td>same as 3.</td>
</tr>
<tr>
<td>12. &quot;Sperone&quot; basalt (volcanic quarry)</td>
<td>Rocca di Pappa, Alber Hills, Lazio, Italy</td>
<td>excellent adhesion; optically fine.</td>
</tr>
<tr>
<td>13. Leucite basalt</td>
<td>nr. Gabii, Lazio, Italy</td>
<td>same as 12.</td>
</tr>
<tr>
<td>Material</td>
<td>Source</td>
<td>Observation</td>
</tr>
<tr>
<td>------------------------------</td>
<td>-------------------------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>14. Leucite basalt</td>
<td>Monte Porzio, Alban Hills, Lazio, Italy</td>
<td>same as 12.</td>
</tr>
<tr>
<td>(volcanic quarry)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15. Olmec sculpture *</td>
<td>Tres Zapotes, Mexico</td>
<td>same as 12</td>
</tr>
<tr>
<td>(pyroxene basalt)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16. Canaanite temple *</td>
<td>Hazor, Israel</td>
<td>same as 12</td>
</tr>
<tr>
<td>(Huanan-Golan basalt)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17. Inca ashlar *</td>
<td>Rumiqolqa, Peru</td>
<td>same as 12</td>
</tr>
<tr>
<td>(basaltic andesite)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18. Colonial-Inca *</td>
<td>Cuzco, Peru</td>
<td>same as 12</td>
</tr>
<tr>
<td>ashlar (bas.and.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19. Inca quarry andesite *</td>
<td>Huaccotto, Peru</td>
<td>same as 12</td>
</tr>
<tr>
<td>20. Olompali andesite *</td>
<td>Marin, Calif., U.S.A.</td>
<td>same as 12</td>
</tr>
<tr>
<td>21. Santorini andesite *</td>
<td>Santorini, Greece</td>
<td>same as 12</td>
</tr>
<tr>
<td>22. Javanese sculpture</td>
<td>Borobudur, Java</td>
<td>same as 12</td>
</tr>
<tr>
<td>andesite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23. Rio Urubamba *</td>
<td>Ollanta, Peru</td>
<td>same as 12; somewhat more</td>
</tr>
<tr>
<td>granite</td>
<td></td>
<td>difficult to grind and polish.</td>
</tr>
<tr>
<td>24. granite</td>
<td>Florence, Italy</td>
<td>same as 23</td>
</tr>
<tr>
<td></td>
<td>paving stone</td>
<td></td>
</tr>
<tr>
<td>25. felsite</td>
<td>Roman quarry</td>
<td>same as 23</td>
</tr>
<tr>
<td>(imperial porphyry)</td>
<td>Jebhel Dokhan, Egypt</td>
<td></td>
</tr>
<tr>
<td>26. quartz</td>
<td>Lago Garda, Italy</td>
<td>optically fine; excellent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>adhesion; very difficult to</td>
</tr>
<tr>
<td></td>
<td></td>
<td>grind and polish.</td>
</tr>
<tr>
<td>27. quartzite *</td>
<td>Sussex bog</td>
<td>same as 26</td>
</tr>
<tr>
<td>(&quot;ironstone&quot;)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* indicates numerous thin section preparations made of this material (some in excess of 30 from same quarry).

Many other thin section preparations were made which are not mentioned here. A working interpretation of Table 4.4 intended here is to show that friability of material could create prob-
lems in bonding with medium, some of which problems could be re-
solved by consolidation with Light-Weld 304 by UV-light prior to
mounting on the glass slide. Also, it can be shown that, while
adhesion on the harder materials (e.g. granitic to quartzite) was
excellent, subsequent grinding and polishing was more difficult.
In terms of time per thin section preparation, these harder mate-
rials could take more than an hour to the finished (examination-
ready) stage, whereas the softer (hence easier to cut, grind, and
polish) materials (e.g. stucco, tuff, ceramic) would have taken
less time were it not for consolidations. One experimental con-
clusion with Light-Weld 304 and the portable field laboratory in
general is that basalt and andesite (medium hardness) were ideal
materials for thin section preparation, averaging 45-50 minutes
of time per thin section from stone extraction to finished stage.
Indeed, another experimental conclusion is that adhesion of stone
in general is expected to be satisfactory with Light-Weld 304.

Not all experimental use of Light-Weld 304 proved satis-
factory, although this researcher found it sufficient well
over 95% of the time in all applications. Other researchers from
the Institute of Archaeology, London, have attempted adhesion
with several types of low-fired ceramic wares (Peruvian, Thai,
and Egyptian) where Light-Weld 304 adhesion was inadequate. Due
to the hydrophilic character of low-fired ceramics (which often
resulted in inadequate removal of water except with heat) and
general porosity (which often resulted in Light-Weld 304 being
drawn up by capillary action away from bonding surface) of many
ceramics, it is recommended that use of Light-Weld 304 is better
applied for adhesion of stone to glass rather than ceramic to
4.5 **Anticipated Modification of Portable Field Laboratory**

Because of its prototype nature, modifications are expected on the portable field laboratory. While uses of the new mounting medium (Light-Weld 304) have been satisfactory, especially for stone, it is likely that further refinements can be made on UV-cured methacrylates used thusly, perhaps increasing bonding strength and decreasing an already-short cure time without sacrificing refractive index. It is also hoped that other UV-cured mounting media will be developed for ceramics. It is the opinion of this researcher that, at the present time, application of Light-Weld 304 is no better or worse in ceramic adhesion than other available mounting media (although others may not share in this opinion). However, this in no way limits its use for stone. Also, while the grinding and polishing properties of carborundum powders have been satisfactory for generations of petrographers and do yield excellent results, the experimental uses of other methods (as discussed in 4.3) such as carborundum-impregnated papers and plastics indicates that such could be improved for field use with their already-developed lightweight, non-bulky and relatively-convenient features (which are free of messy residues and use less water). On the other hand, some discussion of the portable stonecutting tool and portable microscope is necessary.

Evaluation of the portable cutting tool shows that it could be modified in various ways. The prototype has sufficient power and charging capacities, but increasing r.p.m. and battery life would both be welcome features. Also, having a doubling up of both saw blade and grinding wheel on the same end of an arbor
could be improved thusly. Mounting the motor drive in the center (as on standard fixed laboratory wheels) with saw blade and grinding wheel at opposite ends would be ideal in a 10000 rpm (non-load) motor which could take two batteries at a time and possess longer charging capacity. Such a design suggests that this improved stonecutting tool would have to be custom-manufactured. Also, the creation of a lightweight plastic folding plane could serve as a guiding saw table mounted with feet so that the portable table would be more stable and also free both hands for the material to be cut and ground.

Also, as presently used the prototype cutting tool needs to be improved for safety. A polyvinyl or vinyl acetate shield could be moulded specifically for eye protection. Furthermore, a wheel for grinding needs to be designed or obtained which will withstand friction at high r.p.m. without potential fragmentation (where combined friction and velocity could overcome the cohesion of the grinding wheel). This potential fragmentation has not yet been observed nor has any slight loss of grinding material from the wheel been observed during or after use, but since the current grinding wheels used on the prototype (180 grit silicon carbide, MOS = C 80MV; see Hunt and Griffiths, 1989:167-68) were experimentally adapted from uses for materials other than stone, it is a recommended improvement for efficiency as well as safety.

Evaluation of the portable field microscope shows that it has adequate optics and polarizing light features as a prototype, but that its staging for slide specimens could be vastly improved by fitting a rotating disc inside its current aperture if the light objective is also moved to the center of the stage apera-
ture. While the prototype microscope is adequate for diagnostic petrography, a better attachment for rotation of the analysing filter is also needed. At present it is loosely arranged under the light source and over the petrographic slide. This needs proper stabilising by being fixed to the illuminator, either by permanent means or by detachable clips such as short stage clips to hold this filter while the field microscope is in use. All of these proposed modifications have been amply discussed by this researcher and Dr. Dafydd Griffiths (from whom some of them originated) after fieldwork using the field scope designed and used by this researcher between 1988 and 1989.

These suggested modifications may be some time in the future as applications on a prototype which is certainly adequate at present for field optical petrology. Other improvements may be made on the prototype which are not foreseen by this researcher at the present time.

4.6 Summary

As shown in its potential for enhancing representative sampling and field contextualization with optical petrology in the field, the portable field laboratory assembled by this researcher is claimed to be the first of its kind, with several unique applications in the areas of thin section adhesive mounting medium and field petrographic microscope use.

Experimental use of it has been made in diverse global archaeological contexts. Temperate, tropical, and alpine settings have been explored as venues for its application as an analytical field tool.

Furthermore, although certain refinements are anticipated on
the prototype equipment for a portable field laboratory, the total unit assembled to date possesses a considerable number of features with tested time-economical, compact, robust, and portable advantages which significantly raise the potential of optical petrology in the field.
Chapter Five

INCA USE OF ANDESITE AND ITS PROVENANCE IN CUZCO PROVINCE, PERU

5.1 Introduction and Literature Review

The use of andesite and basalt as architectural ashlars by Inca stonemasons has been widely discussed throughout the literature (J. Rowe, 1946; Kendall, 1985; Vargas, 1970; Gasparini and Margolies, 1980; Protzen, 1985; Protzen 1986; and Agurto Calvo, 1987). Most of these archaeological or architectural studies are in agreement that the primary Inca quarrying centres in the Cuzco area are in the Rio Huatanay valley at Rumíqolqa and Huaccoto, both to the southeast of Cuzco (see Figure 5.1). Huaccoto is approximately 19 km from Cuzco at an elevation just below 4100 m (13,500 ft). Rumíqolqa is approximately 35 km distant at an elevation of 3330 m (11,000 ft).

Prior research on volcanic stone provenance determination of Inca contexts in the Cuzco province has been limited to early petrographic work (Gregory, 1916) which did not have archaeological study as a primary focus. While Gregory's geological services were supplied to the Bingham expedition of 1912 and following, his surveys of the Cuzco area still stand as a much-quoted model of initial scientific interest in Inca quarrying.

Geological investigations in the Cuzco province include those surveys with tectonic, petrogenetic, or metallogenic interests (Gregory, 1916; Kalafatovich, 1957; and Gabelman, 1964). Some of these investigations also cover the Anta plateau and the Rio Vilcanota-Urubamba watershed as far downstream as Machu Picchu but are notably incomplete or on a scale insufficiently detailed to be particularly helpful in provenance determination.
Figure 5.1  MAP OF CUZCO PROVINCE, PERU

SOURCES OF VOLCANIC (ANORBITITE) STONE
1. RUMIBOLQA
2. HUACCOTO
3. MT. ICHCHU BRECO
4. PISAQ (RIACHUELO KITIJAYU)

PERU
In addition to Rumiqolqa and Huaccoto, the other major extrusive deposition mentioned in these studies in the Rio Huatanay valley is found above the Huatanay valley plateau on the ridge of Mt. Ichchu-Orcco, between Huaccoto and Rumiqolqa, nearly 28 km distant from Cuzco. Although Mt. Ichchu-Orcco has been surveyed (Gregory, 1916:93 & ff) as part of south Cerro Pachatusan system, it has not yet been connected in the available literature with any Inca quarrying.

This may be due to its higher altitude at 4450 m (14,700 ft), a scoria texture "devoid of cleavage or flow structure" (Gregory, 1916:93) and its size of deposit (too small for extensive quarrying) in comparison to the nearer, lower, and larger quarries at Huaccoto which have ideal quarrying features (to be discussed shortly) (again see Figure 5.1).

Outside the tributary Rio Huatanay and in the watershed (into which it feeds) of the Rio Vilcanota-Urubamba can be found several other extrusive deposits. These known deposits are discussed in the following paragraphs.

Of note is the Pachatusan formation (north Cerro Pachatusan) on the Vilcanota side of the range between Cuzco and Pisac, discussed in several studies (summarized by Gabelman, 1964:22 & ff). It is approximately 10 km from Cuzco at an elevation near 4000 m (13,400 ft) but nearly inaccessible from the direction of Cuzco. While it may have served other sites as yet undetermined, the Pachatusan formation is extremely unlikely to have served Cuzco (due to lack of access) even though it would appear to be closer than either Huaccoto or Rumiqolqa. Another part of this formation might be found high above the Rio Vilcanota opposite Calca, although its elevation and mineralogy are unknown to this author.
(pers. comm. J.P. Protzen, 1988). It has not been suggested by a prior study that this geological deposit has ever been used for Inca quarrying (again see Figure 5.1).

Although most of the known extrusive deposits in the Cuzco province appear to be roughly in the triangle of the Huatanay-Vilcanota-Urubamba watershed convergence between Cuzco and Calca with intrusive granitic rock dominant downstream of the town of Urubamba, another volcanic deposit can be found outside this area above colonial Pisac at approximately 3310 m (10,920 ft) on the northeastern ridge over the Rio Vilcanota (again see Figure 5.1).

These extrusive deposits are the only ones known to date. Unfortunately, as mentioned previously, geological mapping of the Cuzco province is incomplete, therefore additional major deposits (and by extension potential quarries) of extrusive material may yet be found. The preliminary nature of this discussion is nonetheless accurate for the locales covered; as with other studies of provenance it is always much easier to determine where sources of material cannot be fixed than to pinpoint a firm source. Given the necessity of further scientific exploration of the rigorously steep Andean highland, it is expected that the present study will be superseded by future investigation. The following discussion examines each of the known Inca volcanic stone quarrying contexts in detail, noting where this study has provided new information.

5.2 Rumigolqa

5.2.1 Rumigolqa Quarries

Rumigolqa has been known as an Inca quarry for centuries through local tradition (Squier, 1877); indeed, its very name in
the Quechua is "stone storehouse." (rumi = "stone"; qolqa = storehouse). Being roughly a hundred meters below Cuzco in elevation, and downstream from it 35 km as stated earlier, the transport of stones to the Inca capital would have been difficult. Extant illustrations from the 16th c. chronicler Guaman Poma are to be considered fairly accurate in depicting Inca stone construction methods (Plate 5.1) and also in depicting Inca mode of transport as bringing worked stones up ramps which are still in evidence (Guaman Poma, [1616] 1956; Protzen, 1985: 164 & ff and 1986: 81 & ff; and this researcher’s experience in 1988), although Protzen’s cogent arguments against a mita workforce dragging the stones are to be taken seriously (Protzen, 1986: 88).

Protzen has the most reliable accounts of Inca stoneworking to date and has provided much personal assistance in the present research both in the fieldwork in Peru as well as in California. The primary quarry identified by Squier and Protzen is named the Llama Pit (Protzen, 1986: 82). At least 250 abandoned Inca ashlar blocks in various stages of stonedressing can be found there made from the andesite (Protzen, 1986: 83) (Plate 5.2).

To the naked eye, Rumiqolqa stone often exhibits conchoidal fracture. Although it is often flow-banded and sometimes glassy, the Rumiqolqa stone is generally a darker grey than the Huaccoto stone and is also generally slightly harder. The following discussion assesses Gregory’s early analysis and adds to it information from the analytical techniques not available in 1916.

Sampling at Rumiqolqa took place in 1988, with over 96 rock samples from and around the quarries, mostly from the most well-known Inca quarry, called the Llama Pit. Over half of the samples
(Plate 5.1 [above]) GUAMAN POMA, 1616 A.D., showing a perception of INCA CONSTRUCTION with stone ashlars; (Plate 5.2 [below]) View down into RUMIQOLQA QUARRY’S Llama Pit w/ abandoned Inca ashlars.
were either thin-sectioned for petrography or provided polished sections for SEM with EDS analysis.

5.2.2 Petrography of Rumiqolqa Material

The initial petrographic analysis made by Gregory in 1916 identified the Rumiqolqa quarry material as hypersthene basalt (Gregory, 1916:100). However, it should be categorized as hornblende andesite by present standards. The primary phenocrysts in the Rumiqolqa quarry material in order of total volume are plagioclase feldspar, basaltic hornblende, and biotite (see Plate 5.3). Very little pyroxene was found in any of the Rumiqolqa samples collected by this researcher (or the ones made available by J.P. Protzen) making up less than 1% of the total volume. However, there were found occasional xenoliths of apatite and opaque ilmenite.

Discussion of the plagioclase feldspar is as follows. Gregory identified the plagioclase as bytownite, which is unlikely as it is rarely found in basalt or andesite (especially unlikely to crystallize in a magma with biotite). Thus, it is more likely to be oligoclase or andesine (Keith, pers. comm., 1989). Plagioclase laths make up nearly 31% of the total volume, ranging 0.2-0.5 mm in length, are twinned according to the Carlsbad law, and are found in a moderately-aligned textural direction.

Gregory referred to the hornblende phenocrysts with "All the hornblende present is the brown variety common in basalts and is much corroded." (Gregory, 1916:100). It should be referred to as basaltic hornblende (or oxyhornblende) with a high relief, strong pleochroism, and typical amphibole 120 cleavage angles. Size of the hornblende phenocrysts averages around 0.8-1.2 mm in length.
As stated, this is the characteristic Rumigolqa phenocryst at approximately 16% of the volume. In some cases inclusions of pyroxene are found in the hornblende phenocrysts.

Biotite is also found in the Rumigolqa material, although with considerably less frequency than hornblende. The volume of biotite, with green to brown birefringence, is approximately 5% and the sizes of the laths average 0.7-1.2 mm in length.

As determined by petrographic analysis (and EDS), the texture of the typical Rumigolqa groundmass (although not with the same chemical averages) is made up of glass (also see Gregory, 1916: 100) and approximately the same mineral constituents as occur in the phenocrysts, with perhaps a few opaque grains of ilmenite or titannomagnetites. The volume of the groundmass is approximately 42% of the total volume. Also characteristic for Rumigolqa stone is the slight vesicularity of this lava. While not as porous as many andesites some vesicularity is nonetheless apparent at approximately 6% of the total volume.

This textural analysis is summarized in Table 5.2 with some discussion here. As stated, there is some preferential alignment indicated in the use of the term "hyalopilitic" by Gregory (1916:100), wherein the phenocrysts are parallel or subparallel with the overall alignment of the groundmass. Actually, this is apparent mostly for the hornblende and perhaps the biotite, not so much for the feldspars. This is probably due to the more elongate shape of the biotite and hornblende phenocrysts. Certainly in comparison to Huaccoto quarry material, texture of Rumigolqa material is relatively "felty" or random in direction in terms of both phenocrysts and groundmass.
The occurrence of Rumiqolqa quarry material in Inca archaeological contexts will be discussed after the section on the Huaccoto quarries and corresponding petrographic data. In the opinion of this researcher, it may yet be possible that Rumiqolqa quarries also contain a biotite andesite as yet unsampled and analysed by the present study. While such occurrence would make for easier provenance study (especially with biotite andesite use at Pikillaqta, 7 km from Rumiqolqa), it remains to be evidenced. Thus, since all material sampled and analysed to date belongs to the hornblende andesite category, this will be the assumed sole variety of andesite.

5.3 Huaccoto

5.3.1 Huaccoto Quarries

Huaccoto was known, according to Gregory and Protzen, as a quarry for centuries to colonial Peruvians, although sources (listed below) suggest it was most active in the later period after imperial Inca expansion under Pachacuti (mid-15th c.). It is Inca Pachacuti with whom the major Inca Rumiqolqa quarries are associated (Gregory, 1916:92) whereas Huaccoto is most closely associated with a Post-Conquest or Inca-Colonial period (J. Rowe, 1946; Gasparini and Margolies, 1980:189; Protzen, pers. comm., 1988-89) (again see Figure 5.1).

As stated earlier, Huaccoto is closer to Cuzco than Rumiqolqa being at a distance of 19 km as opposed to 35 km. Also higher in elevation at approximately just below 4100 m (13,500 ft), Huaccoto is on the plateau high above the Rio Huatanay valley. As such, a downhill gradient would help in transport of quarry material to
Cuzco, especially considering it is nearly half as far away as Rumiqolqa. At this point it is unknown why Rumiqolqa was abandoned, considering the high number of extant ashlars mostly dressed and ready for transport. Whether or not the death of Pachacuti coincides with Inca abandonment of Rumiqolqa or whether civil war and subsequent Spanish conquest halted Rumiqolqa quarrying as the major source of andesite is a question for the historians. Since Rumiqolqa was never worked to extinction (indeed it has been worked sporadically up to the present time), either hypothesis is possible. It is, however, equally possible in the colonial period that Huaccoto’s proximity to Cuzco and downhill gradient to Cuzco made it preferable to Rumiqolqa as a source of building stone. This could be due at least to that fact that considerably less manpower and time would be required for transport to Cuzco from Huaccoto as opposed to from Rumiqolqa. Furthermore, the loss of mita (the Inca corvee or forced labour) workforce might limit quarrying to exploitation of the nearer source. Likewise, the lower volume of immediate building in the early colonial period would mean lower stone consumption, thus obviating the need to use the more distant Rumiqolqa quarries. It is more problematic attempting to answer why Huaccoto quarries were not used by Pachacuti. The possible logical suggestions are that they were either unknown or their location forgotten or even perhaps deliberately ignored (for unknown reasons) if they were in fact known earlier.

Huaccoto stone quarries are still worked on a minor scale. The flow structure of Huaccoto stone "favors separation into slabs suitable for [road] paving, curbstones, and door facings" (Gregory, 1916:92). In most hand specimens, Huaccoto material
displays a thin flat cleavage and a lighter colour than Rumiqolqa stone. The Huaccoto material is ideal for cover as road surface and stone floors. Because of general lighter colour of the stone, its phenocrysts are more visible to the naked eye. Sampling from Huaccoto quarries took place between 1984-88 by J.P. Protzen, who accompanied this researcher in Peru at Rumiqolqa and at least two other Inca quarries. Huaccoto quarry samples numbered over 22, all of which were thin-sectioned for petrography or provided polished sections for SEM with EDS analysis.

5.3.2 Petrography of Huaccoto Material

The initial petrographic analysis of samples from the Huaccoto quarries, again by Gregory in 1916, resulted in the classification of the material as hypersthene andesite (Gregory, 1916:92). By present standards, however, it would be categorized as biotite andesite (see Table 5.3). The primary phenocrysts in Huaccoto quarry material in order of total volume are plagioclase feldspar and biotite. A small volume of resorbed hornblende and occasional xenoliths of apatite are found in Huaccoto material.

Gregory identified the feldspar in the Huaccoto material as ranging from andesine to labradorite (Gregory, 1916:92), which is accurate. The feldspars occur in greater quantity and with longer laths than in the Rumiqolqa lava. Additionally, as indicated by Gregory's use again of the term "hyalopilitic" (Gregory, 1916:92) the feldspars display a strong textural alignment, much more marked than in Rumiqolqa lava. The Huaccoto plagioclase feldspars make up approximately 39% of the total volume in laths from 0.4-0.6 mm in length and show both Carlsbad and albite twinning.

The characteristic Huaccoto phenocryst is biotite, which oc-
curs in long acicular laths up to 2mm in length, easily double the size of Rumiqolqa biotite. This acicularity can even be seen in hand specimens by the naked eye. The volume of the biotite with its green to brown birefringence is approximately 24% of the total. Occasional glomerocrysts or clusters of biotite are found in the Huaccoto lava as well (see Plate 5.4 for overall texture).

The hornblende in Huaccoto material is infrequent and is in a heavily-altered or resorbed state, making up less than 2% of the total volume. It is possible that Gregory, who doesn’t mention hornblende in his petrographic description for Huaccoto, considered the few characteristic resorbed amphibole traces as pseudomorphs of hornblende.

The typical Huaccoto groundmass appears to be made up of glass (also see Gregory, 1916:92) and the same constituents found as phenocrysts. Gregory described this Huaccoto groundmass as "cryptocrystalline" (ibid.) which fits Huaccoto material more than Rumiqolqa material. The total volume of the groundmass at 32% is less than that of Rumiqolqa material. Vesicularity at 3% is also lower than in Rumiqolqa lava.

Textural analysis of Huaccoto material is summarized in Table 5.1 with some discussion here. A distinct flow structure is seen in Huaccoto lava, justifying Gregory’s use again of the term "hyalopilitic" (1916:92), with definite phenocryst alignment when compared to Rumiqolqa lava. Another distinctive feature is the relative freshness and clarity of Huaccoto lava, although Gabelman maintains nearly simultaneous formation, probably in the Miocene period (Gabelman, 1964:31-33). For absolute dating of the Rumiqolqa and Huaccoto materials on a geologic basis, it would be
(Plate 5.3 [above]) RUMIQOLQA HORNBLENDE ANDESITE petrographic texture w/ typical hornblende, plagioclase feldspar and groundmass; 
(Plate 5.4 [below]) HUACCOTO BIOTITE ANDESITE petrographic texture w/ typical biotite, plagioclase feldspar and groundmass.
helpful to conduct laser-controlled K-Ar dating tests. Relative freshness of source material is an important consideration for weathering discussions in subsequent chapters (Chapters 8 to 10). Nevertheless, the hydrothermal alteration of some Rumiqolqa material could account for partial difference in that portions of the Rumiqolqa lava is of a reddish hue even when freshly fractured, indicating a subsurface volcanic vent, whereas the Huaccoto lava appears fresher at the time of fracture although its lighter grey colour after half a millenium is often weathered to a red-brown hue (Gregory, 1916:92-3). This will be discussed in Ch. 10.

5.4 Textural Characterisation of Stone Source Contexts

Important textural features are the mineral type, size and volume of phenocrysts in Huaccoto lava as compared to Rumiqolqa lava, as shown by Tables 5.1 & 5.2. For purposes of determination of provenance, discussion of textural feature differences as seen in petrographic analysis is a vital part of the distinguishing process between known sources relatively proximal to each other.

Table 5.1 RUMIQOLQA : HUACCOTO COMPARISONS

<table>
<thead>
<tr>
<th>(Petrographic: Textural)</th>
<th>Rumiqolqa</th>
<th>Huaccoto</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Groundmass volume</td>
<td>greater (42%)</td>
<td>lesser (32%)</td>
</tr>
<tr>
<td>2. Phenocryst volume</td>
<td>lesser (53%)</td>
<td>greater (65%)</td>
</tr>
<tr>
<td>3. Vesicularity</td>
<td>greater (6%)</td>
<td>lesser (3%)</td>
</tr>
<tr>
<td>4. Freshness</td>
<td>&lt;</td>
<td>&gt;</td>
</tr>
<tr>
<td>5. Alignment</td>
<td>&lt;</td>
<td>&gt;</td>
</tr>
<tr>
<td>6. Phenocryst size</td>
<td>(0.2-1.2 mm)</td>
<td>(0.5-2 mm)</td>
</tr>
<tr>
<td>7. Phenocryst shape</td>
<td>shorter</td>
<td>longer</td>
</tr>
<tr>
<td>8. Major Phenocryst (after feldspar)</td>
<td>hornblende</td>
<td>biotite</td>
</tr>
<tr>
<td>9. Glomerocrysts</td>
<td>none apparent</td>
<td>several apparent</td>
</tr>
</tbody>
</table>
Table 5.1 (cont., Rumiqolqa : Huaccoto Comparisons)

(in hand specimen)

<table>
<thead>
<tr>
<th></th>
<th>Rumiqolqa</th>
<th>generally</th>
<th>Huaccoto</th>
<th>generally</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Colour</td>
<td>darker grey</td>
<td>reddish grey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Alteration Colour (hydrothermal)</td>
<td>reddish *</td>
<td>reddish (weathered)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Vitrification</td>
<td>glassier</td>
<td>less glassy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Fracture Features</td>
<td>most often conchoidal</td>
<td>flat, tabular</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Hardness</td>
<td>harder</td>
<td>softer</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Weathering colour of Rumiqolqa material is qualified thusly:
Whereas Huaccoto material invariably weathers reddish-brown in most contexts, dark grey Rumiqolqa andesite stains with a reddish brown hue while the originally-red Rumiqolqa andesite stays red.

Key: > or < means in comparison to each other

The following table (Table 5.2) provides textural comparisons of the three known sources discussed in this chapter.

The archaeological material from Korikancha, Colonial Cuzco, Ollantaytambo, and Pisaq Initiwatana sites will be correlated to one of the three sources in the site discussions to follow.

<table>
<thead>
<tr>
<th></th>
<th>Rumiqolga</th>
<th>Huaccoto</th>
<th>Pisaq (both Intiwatana and Riachuelo Kitamayo Quarry)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Groundmass</td>
<td>42%</td>
<td>32%</td>
<td>27%</td>
</tr>
<tr>
<td>2. Vesicles</td>
<td>6%</td>
<td>3%</td>
<td>0-1%</td>
</tr>
<tr>
<td>3. Phenocrysts (53%)</td>
<td>a. plagioclase feldspar 31%</td>
<td>a. plagioclase feldspar 39%</td>
<td>a. plagioclase feldspar 54%</td>
</tr>
<tr>
<td></td>
<td>b. oxyhornblende 16%</td>
<td>b. biotite 24%</td>
<td>b. clinopyroxene</td>
</tr>
<tr>
<td></td>
<td>c. biotite 5%</td>
<td>c. oxyhornblende (resorbed) 2%</td>
<td>c. orthopyroxene 6%</td>
</tr>
</tbody>
</table>

The above textural data was obtained by repeated petrographic observations of estimated volumes. The range of variations occurring in each archaeological context could be summarized as being different from the above totals by less than 5%.

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5.5 Chemical Characterisation of Stone Source Contexts

Chemical composition was studied with a view to finding a parameter that would serve to distinguish Rumiqolqa and Huaccoto material. The following discussion is provided as an analysis of the chemical makeup of the stone from both the geological and archaeological contexts discussed in this chapter. Because plagioclase feldspar is the one common mineral in all the basalts and andesites of the present study, and those of Chapter 5 in particular, the focus of chemical analysis was the plagioclase phenocryst. The chemical analyses nearly always included portions of groundmass. Table 5.3 presents chemical analysis averages for all contexts discussed.

Table 5.3 CHEMICAL ANALYSES AVERAGES (in Wt %)

<table>
<thead>
<tr>
<th></th>
<th>Rumiqolqa</th>
<th>Huaccoto</th>
<th>Korikancha</th>
<th>Cuzco Colonial</th>
<th>Ollantaytambo</th>
<th>Pisaq ***</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>64.63</td>
<td>65.22</td>
<td>64.01</td>
<td>64.80</td>
<td>65.20</td>
<td>59.23</td>
</tr>
<tr>
<td>Na₂O</td>
<td>1.89</td>
<td>1.56</td>
<td>1.61</td>
<td>2.04</td>
<td>1.59</td>
<td>2.04</td>
</tr>
<tr>
<td>MgO</td>
<td>0.60</td>
<td>1.06</td>
<td>1.05</td>
<td>1.02</td>
<td>0.91</td>
<td>3.54</td>
</tr>
<tr>
<td>CaO</td>
<td>5.12</td>
<td>4.88</td>
<td>6.64</td>
<td>6.14</td>
<td>5.59</td>
<td>7.95</td>
</tr>
<tr>
<td>K₂O</td>
<td>5.38</td>
<td>4.85</td>
<td>5.34</td>
<td>4.20</td>
<td>4.61</td>
<td>4.02</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>5.54</td>
<td>6.06</td>
<td>4.90</td>
<td>5.09</td>
<td>5.39</td>
<td>7.23</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.05</td>
<td>0.99</td>
<td>0.91</td>
<td>0.97</td>
<td>1.02</td>
<td>1.18</td>
</tr>
<tr>
<td>SIO₂</td>
<td>0.22</td>
<td>0.17</td>
<td>0.35</td>
<td>0.92</td>
<td>0.44</td>
<td>0.06</td>
</tr>
<tr>
<td>Cl₂O₂</td>
<td>0.49</td>
<td>0.47</td>
<td>0.84</td>
<td>0.33</td>
<td>0.78</td>
<td>0.20</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.12</td>
<td>0.09</td>
<td>0.12</td>
<td>0.16</td>
<td>0.17</td>
<td>0.16</td>
</tr>
<tr>
<td>MnO₅</td>
<td>0.23</td>
<td>0.24</td>
<td>0.36</td>
<td>0.14</td>
<td>0.15</td>
<td>0.13</td>
</tr>
</tbody>
</table>

This stoichiometric normalised chemical analysis is by Link System 10-25 S EDS @ 20 kv on all material, with a cobalt standard as reference. Lifetime was 100 seconds, elevation was 31.46°, and the area of analysis was that within the field of vision of the SEM CRT @ 35 X.

* Rumiqolqa SiO wt % at 64.6 is high for andesite but falls within an andesite range, particularly as no quartz is found in Rumiqolqa material (which could suggest dacitic range). The number of samples analysed was over 51; 171 analyses. The SiO range was between wt % of 64.2 to 64.7; averaged at 64.6.
** Huaccoto SiO wt % at 65.2 is high for andesite but falls within an andesite range, particularly as no quartz is found in Huaccoto material (which could suggest dacitic range). Number of samples analysed was over 22; 69 analyses. The SiO range was between wt % of 64.9 to 65.8; averaged at 65.2.

*** Pisaq SiO wt % at 59.2 is normal within the andesite range. Number of samples analysed was over 27; 88 analyses. The SiO range was between wt % of 59.1 to 59.7; averaged at 59.2.

Korikancha samples numbered 8; 26 analyses of 6 samples; SiO range between 63.2 to 64.8; averaged to 64.0.
Colonial Cuzco samples numbered 10; 22 analyses of 7 samples; SiO range between 64.5 and 65.3; averaged to 64.8.
Ollantaytambo samples 9; 21 analyses of 7 samples; SiO range between 64.5 and 65.8; averaged to 65.2.

It should be noted that any of the above analyses with less than 0.3 wt % are most likely to be 2 sigma results and are not generally significant results as detected by the Link EDS. This also applies to subsequent analyses in following chapters. While the chemical analyses did not provide clear distinction for all of the material, the tendencies observed in elemental EDS data suggest some consistencies, as noted in the following individual and overall discussions.

Since all the Rumiqolqa and Huaccoto andesites have very similar chemical makeup, the volume percentages of SiO and the elemental ratios of CaO : K₂O : FeO were chosen to suggest any potential distinct "signature" in respect to each other in these calc-alkaline andesites. More quantitative analysis would be better undertaken in trace element comparisons which were not possible in the present study. These specific comparison ratios were chosen over others for several reasons: 1) Overall wt % of SiO is still an important general distinction between the intermediate and acid extrusives (Thorpe and Brown, 1985:31 & ff;
LeMaitre, 1989:23-28); 2) CaO % would be significant in contrasting anorthitic-albitic ranges of plagioclase feldspars (Read and Watson, 1973:101) and particularly for the acid andesites of the Central Andes—which these are (Gill, 1981:169); 3) Many Andean andesites are known to be high in K2O relative to other global andesites (Thorpe, 1982); and 4) FeO would be common to biotite, hornblende, or pyroxene andesites. Unfortunately, as can be seen from Table 5.3, the actual range of variation between CaO, K2O, and FeO in volume of total percentage is nominal, raising problems for any clear distinguishing chemical features by using the above chemical analyses. Based on petrographic texture as an initial distinguishing analysis, it might be possible to suggest that Rumiqolqa and Korikancha are to be correlated and that Huaccoto, Colonial Cuzco, and Ollantaytambo are to be correlated as source clusters. If this is true, although it becomes a circular argument, the range in variation between clusters could be more significant.

In particular, the most distinctive parameter for chemical characterisation of known and potential Rumiqolqa material could be its relatively higher K2O percentage than in the known and potential Huaccoto material. This K2O percentage averaged 5.36% in known and potential Rumiqolqa samples as opposed to 4.55% in known and potential Huaccoto samples. This variation in K2O percentage was also greater than the variations seen in comparing CaO and FeO percentages. This K2O variation, however, is nominal, and does not in itself reinforce the petrographic evidence of mineralogic and textural matches to Rumiqolqa source and Huaccoto sources. In tandem, however, with the higher K2O percentage of potential Rumiqolqa source material was the consistently lower
volume of SiO at 64.6% in the potential Rumiqolqa sources in contrast with the potential Huaccoto source material which had a higher volume of SiO at 65.2% as well as lower K₂O percentage.

As a cautionary note, however, the fact that all of these chemical analyses show the comparable chemical proximity of all the material (within a 1-2 % range including the low to high analyses which were averaged into the chemical averages shown here) suggests more detailed and more quantitative analyses ought to be performed, particularly for trace elements. Whether or not the K₂O and SiO wt percentages can be construed as evidencing a definite source cluster of any consistency based on chemical analysis remains to be seen. Furthermore, the low number of total elemental analyses (usually 3 per sample) recommends these findings as tentative until further sampling and analyses can be undertaken, especially for the archaeological material. Features of weathering which might have preferentially leached elements will also be discussed in Chapter 10 (see section 10.41).

In reality, the analytical potential for error in elemental detection, the low number of samples, and the human element in which arbitrary decisions are made in both the focus of analysis and the actual choices of specific areas to analyse for SEM with EDS, can render the chemical differences between analyses of different materials to be insignificant.

In summary, chemical characterization of Rumiqolqa and Huaccoto material cannot be ascertained by the present study other than in a possible tendency of SiO and K₂O percentages. If this tendency reflects a potential grouping, it correlates with petrographic analysis of minerals, textures, and other
5.6 **Stylistic Analysis of Site Contexts**

After petrographic and chemical analyses, a third basis for provenance characterization could be suggested in the shapes, sizes, and emplacement of Inca andesite ashlars. This overall category is suggested as stylistic conformity due to the general observations of this researcher along with others (Agurto Calvo, 1987; Protzen, 1988, pers. comm.) that, while greatly dependent on building to building, there are consistent grounds for distinguishing between Inca and later (Colonial) stoneworking in terms of stylistic features. These features include shape, size, degree of finishing, linearity or uniformity of stone courses as well as others.

While stylistic distinctions provide a weaker correlation than petrographic, they might be considered a stronger correlation than the chemical analyses. Four assumptions are held regarding any observable stylistic conformity: 1) that stone is most often dressed at a quarry source; 2) that shapes made at two different quarries were distinct; 3) that any distinctions were greater inter-quarry than intra-quarry); 4) and that the shape of the stone would determine its placement rather than vice versa.

In response to the first assumption, Protzen states "stones from Rumiqolqa were generally finished, or nearly finished, on five of their six surfaces while they were still in the quarry" (Protzen, 1986: 85). This may not always be the case, coming as it does from observations at the primary extant Rumiqolqa Inca (Llama Pit) quarry, but finished ashlars at Rumiqolqa which are
spread out over several kilometers on various ramps clearly bear out the correctness of Protzen's statement. Since Huaccoto quarries appear to have left no relict ashlars behind (Protzen, 1988, pers. comm.), it will be difficult to assess the relevance of this assumption other than to Rumiqolqa. However, Inca quarrying at Pisaq and Kachiqhata evidenced in relict ashlars observed by this researcher also bear out the general observation that dressed ashlars are primarily finished at the quarry sites (see Plate 5.2 again).

In response to the second assumption, it follows naturally in stone courses that uniformity of shape can be an asset. This is especially true for the many perfect stone courses in Cuzco from Pachacuti's building programs. If shape and dimensions were predetermined at the quarry as inferred from Protzen, then this indicator could be useful as a possible provenance evidence.

At least one other study has suggested some correspondences in the deliberate Inca stoneworking or dressing of the material along certain sought-for patterns. Agurto Calvo distinguishes about twenty-four different stone course patterns (Agurto Calvo, 1987:154-62; 170-75).

The period identified with Pachacuti rarely uses ashlars without rectangular or squarish shapes in medium to large sizes for most andesite contexts in Cuzco. On the other hand, the contrast in the colonial period is seen with much less rigorously-shaped andesite ashlars, and thus less perfect stone courses, and these are generally smaller in size than their predecessors, often approximately 25 by 25 by 30 cm or less (as opposed to Pachacuti's larger ashlars). For a Pachacuti period ashlar see Korikancha,
Thus a stylistic feature (e.g. linearity, size, and uniformity of ashlar) may also be used to render some evidence for the source of the material. This appears true since the Colonial contexts, which, if they do not reuse Inca ashlars, are the only contexts using smaller, shallower, and uneven ashlar courses, and are apparently often attributable to Huaccoto quarries (based mostly on the petrographic evidence). This stylistic argument may by ultimately circular, but is intended here only as a simple correlation of the petrographic and chemical characterizations.

Introduction to Other Contexts

Analysis of Rumiqolqa material in Cuzco will focus on the archaeological context of Korikancha, the Temple of the Sun, with some suggestions about other contexts. The discussion on Huaccoto material in colonial Cuzco will focus on a sector of streets near Koricancha, specifically the calle diagonal to Santo Domingo which is early Post Conquest. Several contexts outside Cuzco are also associated with Huaccoto material. Finally, an altogether different source and site context will follow in discussion, the Inca context of Pisaq and the determination of the provenance of the stone material used to build it.

As discussed, the three separate lines of evidence used here to suggest any determinations of provenance are petrographic, chemical, and stylistic conformity to the other contexts. No one line of evidence is strong enough on its own; it is the combined correlation that offers the strongest evidence of provenance.
5.7 Korikancha

The 16th c. chronicler Guaman Poma de Ayala describes the building of Korikancha by Inca Pachacuti (Guaman Poma, p. 189). This is during the period of imperial expansion in which Rumigolqa quarries are exploited (Protzen, 1986:80), and the Temple of the Sun is an important focus of imperial energy in rebuilding the Inca capital. Discussions of the fabulous and legendary elements of Korikancha such as Inca Garcilaso's 1616 account (e.g. sheets of solid gold over the interior stone walls, naturalistic representations of flora and fauna moulded in gold) are not in order here, whereas the Instituto Nacional de Cultura (Peru) survey in 1978 for restoration and conservation is succinctly summarized in an account with interest in scientific detail (Aguirto Calvo, 1987: 146-50).

It appears that the dark grey andesite extant in the Korikancha complex is from Rumigolqa, based on petrographic, chemical, and stylistic analysis. The following discussions provide details of this provenance determination (Plate 5.5). Korikancha material studied derives from over 8 samples collected by this researcher from ashlar fragments in 1988 or provided by the British Museum of Natural History from the Pentland Expedition of 1837 and its collection housed in the Mineralogy Dept, B.M.N.H. All samples were thin-sectioned or made into polished sections for SEM with EDS analysis.

Petrography of the Korikancha Material

Visual examination and petrographic analysis shows the
internal Korikancha complex (partially within the colonial Iglesia Santo Domingo) to be hornblende andesite. The texture, including percentages of volume, size and distribution of phenocrysts, flow structures, and groundmass features fall within the Rumiqolqa lava range as represented by the Llama Pit and adjacent Rumiqolqa quarries.

The plagioclase feldspars are in the andesine to oligoclase range, are twinned according to the Carlsbad law, and are approximately 0.2-0.5 mm in length of lath. The hornblende is of the oxyhornblende variety with typical amphibole 120° angle cleavage and minor alteration and inclusions of pyroxene can be found in some hornblende phenocrysts. The biotite quantity is minimal as in the Rumiqolqa source material. Accessory minerals include apatite and opaque ilmenite. The petrographic match is fairly conclusive and is confirmed by the chemical analysis for consistent characterization (see Plate 5.6).

Stylistic and Other Features of Korikancha Material

The andesite ashlars of Korikancha easily fit into the Rumiqolqa range, being highly-finished and regular and in nearly perfect linear courses. In Agurto Calvo’s terminology, they are all "mediano" to "grande" in size, "sedimentario" in type, "recto" or "rectangular" in shape, "lisa" in finished texture, "pulida" in joints, and "plana llana" in worked courses, showing uniform "labrado" dressing throughout (Agurto Calvo, 1987:147-50), most likely shaped at the Rumiqolqa quarry (see Plate 5.5 again).

Furthermore, the colour and weathering of the andesite in the Korikancha context is consistent with Rumiqolqa material, being normally of a dark grey hue and sometimes with traces of
Plates 5.5 & 5.6

(Plate 5.5 [above]) external wall of KORIKANCHA, Inca Temple of the Sun, w/moderate iron oxide stain (ashlar scale = 30 cm sq.); (Plate 5.6 [below]) internal wall of KORIKANCHA w/petrographic texture showing typical unaltered hornblende in groundmass.
reddish stain from weathering only in highly-exposed locations.

Other suggested archaeological contexts in Cuzco using Rumigolqa source material in Cuzco would be too numerous to discuss here, but a few are worthy of note. These include many of the buildings around what is left of the Inca Huacaypata and Cusipata squares (especially the Cassana, Pachacuti's palace on the former square), the Aguajpinta, the Calle Maruri, and the Acclahuasi, to name but a few. These are suggested on a visual basis only (colour, weathering, and stylistic features) and could be verified by petrographic and chemical analyses, which would entail the systematic collection of samples. Such petrological research could not be undertaken without official encouragement from the Peruvian Instituto Nacional de Cultura, but would yield much archaeological information and advance scientific understanding of Inca stoneworking.

5.8 Colonial Cuzco

In the warren of narrow Cuzco streets just northwest of Koricancha and southeast of the Huacaypata are several streets whose walls conform to the colonial style of "ashlar" construction with uneven stone courses of low height with small stones. One such facade is the southwest side of the Intikijllu or Calleon del Sol (not the northeast side, which is Inca). Another is the northeast corner of the plaza of the Iglesia Santo Domingo and its street bearing immediately north out of the plaza back toward the town square (Huacaypata). This narrow street facade is highly weathered reddish to brown and its rough andesite is flaking off the wall.

Gregory states "During the Spanish building epoch in particu-
lar the Huaccoto lava was extensively used" (1916:92). Elsewhere he states "the basalt [sic] from Huaccoto weathers rapidly in the Cuzco climate and where found in ancient buildings it is chipped, broken, and pitted, and fragments may be pried from columns and lintels with a penknife. Disfiguration from weathering is however partly compensated with increased attractiveness of color" (1916: 92-3). This facade section conforms to Gregory's description of Huaccoto material used in building. Note that Gregory has now referred to the "Huaccoto basalt" which in the preceding paragraph he identified as "hypersthene andesite" (1916: 92), showing early overlapping of geological terminology regarding basalt and andesite in which andesite was often considered a subcategory of basalt. The following discussions present petrographic and chemical analyses of over 10 samples collected by this researcher from ashlar fragments in Colonial Cuzco in 1988 or obtained in 1988 from the British Museum of Natural History from the Pentland Collection, circa 1837. All samples were thin-sectioned or made into polished sections for SEM with EDS analysis.

As would be expected from Gregory's suggestions and the stylistic and weathering match already mentioned, this colonial Cuzco material is from Huaccoto, based mostly on petrographic and some stylistic evidence which the following discussions provide.

Petrography of Cuzco Colonial Material

Petrographic examination shows the Cuzco colonial material to be biotite andesite. The textural match, including percentages of volume, size and distribution of phenocrysts, flow structures, and groundmass features fall within the Huaccoto range of biotite
The plagioclase feldspar laths show strong flow alignment and range in length from 0.4-0.8 mm. They are in the andesine to labradorite range and show both Carlsbad and albite twinning. The biotite phenocrysts are also in strong flow alignment and many are up to 2 mm in long acicular laths, with biotite altered from green - brown birefringence to yellow-brown. Very few if any resorbed hornblende phenocrysts are visible in thin section. While the altered biotite contrasts with Huaccoto's fresh biotite colour, the petrographic match is fairly conclusive in all other respects, and is reinforced by the chemical analyses for what may be chemical characterization (see Plate 5.7). Weathering and alteration will be discussed in more detail in Chapters 8 -10.

As mentioned, numerous other colonial Cuzco contexts could be considered as well, including the Callejon del Sol or Intikijllu, possibly the Calle San Agustin, and, according to Gregory but undetermined at present, the "facades of the churches at San Geronimo and San Sebastian and of the Jesuit monastery now used by the University of Cuzco were probably built of stone from this locality [Huaccoto]" (1916:92), and many others, to name a few. San Geronimo and San Sebastian are to the east along the approach from Huaccoto in the Cuzco environs. Any further petrographic and chemical analyses would entail official encouragement from the Peruvian Instituto Nacional de Cultura.

5.9 Ollantaytambo

Another context which, lacking other known quarry sources, is tentatively identified with Huaccoto in this analysis is a small collection of stones at Ollantaytambo. This is at best a
perplexing situation, and has been briefly discussed with J. Rowe, Protzen, Kendall, and Bray, among others (see Figure 5.1).

Ollantaytambo has been amply discussed in the available literature (Gasparini and Margolies, 1980; Agurto Calvo, 1987), especially by Protzen, whose architectural and quarrying studies are perhaps both definitive and most germane here (Protzen, 1985 and 1986). About 20 m north of the Inkamisana religious sector on the Ollantaytambo ridge, several andesite ashlars were brought to the attention of this researcher by Protzen, who described them as being in a "fountain" context (i.e. part of a stone unit with both aesthetic and practical uses for flowing water, ostensibly conveyed by aqueduct). Andesite is unusual here because the local geological material is mostly meta-arkosic and arkosic greywacke on the north side of the Urubamba valley, of which much of the Inca complex is constructed (Protzen, 1986: 81), and porphyritic granite on the south side of the valley, which the Kachiqhata quarries supplied for the megalithic monuments at Ollantaytambo (Protzen, 1986: 80). Both of these geological materials and some of the Kachiqhata quarries have been examined by this researcher. Additionally, the arkosic and granitoid materials have been examined in petrographic thin sections along with the andesite from the Ollantaytambo context. The following petrographic and chemical analyses provide details of the petrologic conclusions. Up to 10 samples were collected from the andesite ashlar fragments of the Ollantaytambo "fountain" by this researcher in 1988, all of which were thin-sectioned or made into polished sections for SEM with EDS analysis.
(Plate 5.7 [above]) COLONIAL CUZCO petrographic texture w/ altered biotite, plagioclase feldspar and groundmass; (Plate 5.8 [below]) shows similarity of above to OLLANTAYTAMBO petrographic texture w/ altered biotite, plagioclase feldspar and groundmass.

Scale (of both photographs): 0.4 mm = 154
Petrography of Ollantaytambo Material

Petrographic examination shows the Ollantaytambo context material to be biotite andesite. The textural match, including percentages of volume, size and distribution of phenocrysts, flow structures, and groundmass features fall within the Huaccoto range of biotite andesite.

The plagioclase feldspar laths range in length from 0.3-0.8 mm and show features of flow alignment. They are in the andesine to labradorite range and have both albite and Carlsbad twinning. Few biotite phenocrysts have green to brown birefringence whereas many have an altered yellow-brown colour. Like Huaccoto material, however, they are in acicular laths up to 1.8 mm in length with strong alignment like the other phenocrysts and the groundmass. The rare oxyhornblende phenocrysts are also heavily altered or partially resorbed. The petrographic match, while raising questions about biotite alteration, appears fairly conclusive in other respects (see Plate 5.8). Weathering will be discussed in Chs. 8 - 10 with alteration detail.

Ollantaytambo Provenance Caveats

One difficulty with a Huaccoto source is the chronology of the major Huaccoto stoneworking as known and the assumed date of this andesite context at Ollantaytambo. Since Huaccoto material is usually associated with colonial quarrying and building, Ollantaytambo use would predate such quarrying, particularly if the period in question of building Ollantaytambo is identified with Pachacuti, as most historians suggest. It is also possible that
this use of andesite belongs to the Colonial period, when Huaccoto material was apparently more commonly used, rather than to the Inca period. It is also possible that the andesite comes from an unknown source much closer to Ollantaytambo.

Another possible resolution is provided here, requiring that some Huaccoto andesite is used prior to the known quarrying exploitation of Rumigolqa but not in the Cuzco area. It appears that the Wari site of Pikillaqta (between Rumigolqa and Huaccoto but far closer to Rumigolqa) has also employed Huaccoto material, as determined in this researcher’s petrologic analyses. It is easily possible that Huaccoto moraine or talus could be deposited by the Rio Huatanay below Pikillaqta which the Wari culture used in their walls. One question raised concerning this is why the Wari might use Huaccoto andesite with the Rumigolqa material being so near at hand (less than 7 km distant). The logical suggestion is that the Rumigolqa quarries would not have yet been developed. It is possible that Huaccoto material was used first at late Wari or early Inca dates but abandoned due to undesirable oxidation staining easily noticed within a generation or two (see ample discussion on comparative weathering in Chs. 8 & 10). After this, Rumigolqa quarrying was developed during the Inca expansion of Pachacuti, and finally Huaccoto material was again used in the colonial period. It is well known that Pachacuti’s predecessors extensively used porphyritic augite diorite from the plateau on and above El Rodadero (Gregory, 1916: 91-2; J. Rowe, 1988 in pers. communication; and Santiago Agurto Calvo, pp. 120-21 & ff.), and Pachacuti appears to have been the first Inca to exploit the Rumigolqa andesite for quarrying. If much of the Ollantaytambo complex is conflated, accounting for the diversity
of building styles found there, and portions such as the Inka-
misana with Tiwanaku-style granitoid stoneworking far precede
Pachacuti's later arkosic phase at Ollantaytambo, then it could
be suggested that early Inca (or even late Wari) stonemasons knew
of the Huaccoto source of andesite and were responsible for its
emplacement there in a minor way. Alternatively, a predecessor of
Pachacuti who (the predecessor) came after an initial Tiwanaku-
Wari style building phase set a tradition of using andesite which
Pachacuti then continued by developing Rumigolqa quarries. This
appears far-fetched, requiring as it does a whole string of spec-
culative contingencies, but should be examined more closely.

Perhaps the primary difficulty with this provenance suggestion
is the question of transport over a distance of more than 55 km
between Huaccoto and Ollantaytambo, and the formidable wall of
mountains between them without any obvious transport route. The
problem of transport would in fact make Huaccoto a less likely
source than Rumigolqa, which, despite its even greater land
distance could suggest water transport down the Rio Vilcanota-
Urubamba with fordings over the considerable rapids.

This poses an huge hurdle to such a provenance suggestion. At
present no resolution to this problem can be offered except the
following conjectural idea: if the stone was transported down the
mountain to the Rio Huatanay in the wet season when the river was
at a higher level, the stone could then be rafted down the Huata-
nay and into the Vilcanota-Urubamba and downstream to Ollantay-
tambo. The actual transport barrier of mountains would thus be
circumvented (with higher water over some rapids and fording over
others) and the actual transport burden would be borne by the
swift river. In this scenario, actual human transport distance would constitute perhaps a total of only 25 km out of the total water-distance of approximately 90 km (since the Huatanay doglegs southeast and northeast before connecting with the Vilcanota). No great faith is attached to this possible transport route, although water transport of stone has been used worldwide for millennia (e.g. Egyptian, Greek, Roman, and Medieval in the Old World; Olmec in the New World). Certainly Inca engineering involved channeling, canalization, agricultural irrigation, aqueducts and other riverine modifications. Perhaps Inca engineers and mita workforce would find this no greater challenge than the others they mastered. For lack of evidence to support this idea, however, perhaps a source should be sought closer to Ollantaytambo, with the following qualifying factor to be considered.

One problem with this is the geological nature of this section of the Urubamba watershed as it is known to date which feeds through this last great arch of the Eastern Cordillera of the Andes. Most of the area is either intrusive (granitic and syenitic) or meta-arkosic (Gabelman, 1964:22-30), with no known extrusive formations. As already stated, it is conceivable that further geological survey will find additional volcanic sources.

Therefore caution is urged in a problem which could apply to all provenance questions: when only a few geological sources are mapped out in such arduous and often inaccessible terrain, with only a handful of Inca quarries established with certainty, it is unquestionably easier to say which known quarries are not the source for material than to make successful determinations of provenance. In this case, given the at least 75 sq. km. of possible sources in which the other quarries are found, it is reasona-
ble to assume other geological sources could be found within that area which are as yet unmapped, and which could approximate the Ollantaytambo context material more closely than Huaccoto.

In any case, the closeness of this Ollantaytambo context in terms of petrographic and chemical analyses to Huaccoto material cannot be overlooked. A better explanation is warranted than the suggestions tendered above for this archaeological and geological anomaly.

5.10 Pisaq

Another important Inca use of andesite for ashlars can be found at Pisaq, approximately 20 km overland from Cuzco on the Rio Vilcanota. Because it is downstream from Cuzco, Inca Pisaq is at an approximate elevation of 3310 m (10,920), with a major archaeological complex covering at least 4 sq. km (not counting andene terraces) spread over the north bank ridge above the Vilcanota (same as the Urubamba but here called Vilcanota) river.

Pisaq has been widely discussed in the literature, including archaeological, architectural, and other discussions (Cook, 1916; Gasparini and Margolies, 1980; Agurto Calvo, 1987) with perhaps the most definitive as yet being that of Victor Vargas in his P'isq: Metropoli Inka (Vargas, 1970) (again see Figure 5.1).

The primary andesite context at Pisaq is the main structure, the Intiwatana or sun temple, which is itself built around and incorporated with a dark natural volcanic breccia bedrock forming the base and gnomon of the sun temple. The andesite ashlars here are finely worked in extant courses up to 2.5 m and have mostly weathered to a light pinkish hue. A total of 8 samples were collected from ashlar fragments around the Intiwatana by this
One of the most important questions to be resolved by the expedition undertaken with J.P. Protzen and D.R. Griffiths at that time was the location of the andesite source. No mention in the available literature suggested a likely source, other than unfortunately vague information about a local andesite source (Vargas, 1970: 98 and ff.). The available geological literature suggests some thin volcanic flows in the Pisac [sic] Formation but these appear to be west rather than north of the colonial Pisaq town and away from the ridge (Gabelman, 1964:22).

One possible scree-filled canyon below the main ridge on which Intiwatana is built was suggested by Protzen as a possible Inca quarry. Northwest and approximately 0.3 km below Intiwatana on the west side of the stream Riachuelo Kitamayu and below Kalla Qasa was a widely-scattered scree area in which Griffiths found nearly-finished ashlars and in which Protzen found numerous hammerstones for working the material. Additionally, ramps and working platforms were identified. By all indications it was indeed an Inca quarry for some of the Pisaq complex, and both the size and weathering (pinkish hue) of the quarry ashlars approximated those features of the Pisaq Intiwatana above. The following discussion provides petrographic and chemical analyses of both the Pisaq complex material (i.e. Intiwatana) and the newly-identified (1988) quarry material. Over 20 samples were collected from this quarry by the present researcher in 1988.

Petrography of Pisaq Monument and Quarry Material

Petrographic analysis showed the material for both Intiwatana and quarry to be texturally and mineralogically identical with...
thin a 1-2% range of difference. Thin section examination showed
two pyroxenes in a fine-grained groundmass of mostly plagioclase
feldspar. The plagioclase was almost microcrystalline whereas the
pyroxene phenocrysts were phanerocrystalline. Any accessory min-
erals are probably too microlitic to identify.

The plagioclase in percentage of volume was roughly 54% of
the total, and the tiny laths ranged in size from 0.06-.09 mm in
length. At this size it was not possible to determine the type of
plagiclase but it is suggested that it falls within the
oligoclase to labradorite range. The plagioclase exhibits
Carlsbad twinning and some normal zoning and possibly oscillatory
zoning.

The pyroxenes in percentage of volume were approximately
19% of the total, with clinopyroxene and orthopyroxene present as
separate phenocrysts. The clinopyroxene at approximately 13% of
the volume is probably augite but there is some uncertainty about
the identity of the orthopyroxene, possibly hypersthene or ensta-
tite, approximately 6% of the total volume. In length the pyro-
xene phenocrysts range from 0.5-1.4 mm across, with the augite in
larger phenocrysts than the orthopyroxene.

The groundmass is too fine-grained to identify constituent
minerals, but it is likely that it is mostly made up of plagio-
clase and pyroxene. The volume of the groundmass is small, appro-
ximately only 27% of the total. Vesicularity was almost nonexis-
tent in this groundmass. (See Table 5.2 and Plates 5.9 & 5.10).

Some discussion is necessary regarding this Pisaq andesite in
its differences when compared to other known Cuzco province vol-
canics. In mineralogy this andesite would be common; pyroxene
andesite being perhaps the most common worldwide. However, in the Cuzco province this is the only pyroxene andesite known to this researcher, others being known near Huaraz far north in some of the Western and Central Andean Cordilleras in the Calipuy Volcanics (Cobbing et al., 1981). This singularity reinforces the match of Pisaq material and quarry. In texture this pyroxene andesite is distinctive: its tiny plagioclase laths in contrast to the phaneritic pyroxene phenocrysts aid in the determination of provenance which matches this quarry with the Intiwatana.

Stylistic, Weathering, and Chemical Features of Pisaq Material

Other features which correlate the Intiwatana and the quarry of the Riachuelo Kitamayu are the stylistic features with common size and shape, observable in the stone courses of the Intiwatana and the abandoned andesite ashlars in the newly-found quarry, as well as observable weathering hues. The ashlars in both contexts have a pinkish weathering hue, which is also comparable in hue to pyroxene andesites this researcher has examined in North American contexts (particularly orogenic pyroxene andesite from Burdell Mtn., at Olompali in Marin, California) and also island arc pyroxene andesite from an Aegean context (from Cape Mavrarakidi, Santorini, Greece). This weathering hue is discussed again in Chapter 10.

Finally, the chemical analyses undertaken as given in Table 5.3 show that the archaeological material from Pisaq Intiwatana and Riachuelo Kitamayu quarry andesite ashlars to be virtually identical. Of all chemical analyses presented in this chapter, it is the Pisaq provenance determination which is most secure. The
chemical analyses confirm that this quarry is indeed the source of material for the archaeological site of Intiwatana.

In summary, the material from both Intiwatana and the quarry can be seen as 2 pyroxene andesite, and based on the petrographic and other evidences it is strongly suggested that the determination of provenance is secure for this Riachuelo Kitamayu andesite quarry to be the Intiwatana source.

5.11 Potential Stone Selection Criteria for Inca Use of Volcanic Stone

While it is not assumed that Inca stoneworking technology had an articulated understanding of differences between rock types such as would suggest a geological appreciation or a systematic scientific appraisal of stone, they would possess an experiential working knowledge of certain stones which was sufficient for them to make the deliberate stone choices which can be seen in the Vilcanota-Urubamba watershed.

The relevant question which could be asked for any culture's stone choices is applicable here: "Why did they choose one stone over another? Naturally, it would depend greatly on the tasks to be accomplished, as well as on potential criteria offered here. It is probable that at least some of these natural criteria would be formulated even in the Inca culture: workability, aesthetics, availability and perhaps what could only be called metaphysical reasons (although tradition could also be included in this category). These discussions develop the basic ideas found in Chapter 2, but are limited here to only the Inca material.

Workability of volcanic material could be broadly extended to
such practical considerations as hardness (basalt and andesite could be suggested as having most minerals around 5-6 on the Mohs scale of hardness), cleavage and general fracture tendencies (usually with conchoidal fracture or flakes) or a grain-by-grain deterioration (as opposed to exfoliation and heterogeneity of material). Volcanic material, due to homogeneity of either fine-grained or coarse-grained texture, would allow stoneworking with a more-or-less controlled modification and would be easier to carve than granitic, doleritic or quartzitic material whose main minerals often exceed 7 on a relative Mohs scale of hardness.

Aesthetic appreciation of volcanic material could have been as simple as stone choice for the colour of the stone, in this case, the dramatic dark stone (basalt and often andesite) colour could be perceived as an asset for whatever reasons. Another feature of the material examined in the present chapter is the uniformity of design possible with a stone of the same colour (although long-term weathering could easily change the surface colour and appearance of stone).

Availability of basalt and andesite in this region of Peru (Cuzco Province) appears to be both limited and somewhat removed from Cuzco, the Inca capital city. While this material is not in abundance (compared to known limestone, sandstone, and granodiorite sources) known sources in Rumigolga, a 35 km distance from Cuzco, evidence that while the Inca could have much more easily worked the immediately local (within 0.5 km of Cuzco) and softer Yucay Formation limestone (which they did on occasion), or softer Huallyabamba sandstones (within 0.7 km of Cuzco) or the softer Qquilque Formation sandstones (also within 0.5 km of Cuzco), the Inca Pachacuti appears to have built many structures
from the harder, more distant Rumigolga andesite (Yucay, Qquilque and Huallyabamba formation discussions found in Gregory, 1916).

Selection of less available, less easily-worked (although perhaps with a more uniform aesthetic result) Rumigolga andesite would suggest factors other than the obvious workability and availability criteria at work.

In some sense, durability might also be involved. Since it would be likely that after a few generations the Yucay limestone material would be discoloured with an inconsistent, blotchy but dark weathering stain, it is possible Inca masons profited from observation by the time of Pachacuti that earlier stone discolouration such as at Tambo-Machay demanded more durable stone material.

Philosophical or metaphysical appreciation of one stone over others could also be the result of religious rationales, sources identified with myth or tradition, or some other reason which the Inca culture might have had. For example, the amphibole crystals seen with the unaided eye in Rumigolga material can easily, on close examination at 1 m or less, sparkle or scintillate out of the dark (fresh or weathered) stone like miniature myriad Inti (sun god) manifestations being reflected from the stone. Or, in their observations of volcanic eruption, it is possible that Inca rulers wished to appropriate the 'magic' properties of this stone from the heart of the mountain for personal power or prestige. Or it could have been possible that andesite was merely chosen as a continuation of a tradition for which experience offered familiar material. However, in the case of Pachacuti's sudden and dramatic quarrying of Rumigolga andesite without a known precedent (other
than possibly at Huaccoto), it appears tradition was not the most important potential criteria but that aesthetic and religious appreciation (e.g. Inti reflections out of the somber, dignified dark grey stone) were possible considerations.

These are only a few of the possibilities regarding Inca stone selection criteria. Other potential criteria not mentioned here could also have been involved with these potential criteria far less involved than has been hypothesized in this discussion.

It is also most likely that no one potential stone criteria would operate independently of the others; i.e. they probably would be weighed in combinations such as workability with aesthetic appreciation or availability with philosophical reasons or sometimes on one criteria such as aesthetics overruling the other criteria which oppose a particular stone selection, as may be the case mentioned above with Rumigolqa andesite appreciated aesthetically over practical criteria such as workability and availability. It is hoped that further research will provide more opportunities to refine this tentative approach to reconstructing potential Inca stone selection criteria, if and where possible.

5.12 Conclusions

Based on observable petrographic, chemical, and stylistic (including shape, size, and even weathering colours in certain cases) analyses which are available for the first time for this Inca stone material in correlations, certain Inca contexts at Korikancha-Cuzco are matched in determination of provenance to the Rumigolqa quarries; certain Inca and colonial contexts in Cuzco, and possibly Ollantaytambo and the Wari site of Pikillaqta (petrographic only) are matched in determination of provenance.
to the Huaccoto quarries; and the Inca context of Pisaq is match-
ed in determination of provenance to the Riachuelo Kitamayu-Pisaq
quarry newly identified in 1988. These determinations are expec-
ted to be refined with additional analyses as new and wider
ranges of Inca material become available for examination in the
Cuzco province and as better geological surveys and mapping add
to geological understanding of volcanic material in this region.

Potential stone selection criteria for Inca use of the
andesite materials includes workability, aesthetics, availability
and possibly metaphysical reasons, including what could be called
mythical identification or philosophical appreciation.

Further research should clarify the determination of
provenance and selection criteria of Inca andesites.
Chapter Six

PROVENANCE AND USE OF VOLCANIC STONES
IN OLMEC MONUMENTS AT TRES ZAPOTES

6.1 Introduction: Tres Zapotes and Review of the Literature

Tres Zapotes is an Olmec site located in the State of Veracruz, Mexico. The site is 15 km west of the Tuxtla Mountains on a plateau tilted down westward away from the hills at the margin of the volcanic Tuxtla province, in a zone transitional to the last ridges of the Tuxtlas and the lowlands further west. It is an area of broad canyons (arroyos in Spanish) which are often dry riverbeds, although permanent streams also flow through this tropical area which supported a dense low jungle only a century ago. Tres Zapotes is also approximately 150 km southeast of the city of Veracruz and is a few miles east of the Rio Papaloapan-San Juan watershed into which its streams flow to the west (Figure 6.1).

Prior provenance study of the sources of stone used in Tres Zapotes monuments has been limited, mostly subsumed to general studies of Olmec monument sources in which discussion of Tres Zapotes was primarily as one of the three major Olmec centres after San Lorenzo and La Venta (Stirling, 1943; Heizer and Williams, 1960; Williams and Heizer, 1976; Coe and Diehl, 1980). These prior provenance studies drew attention to the need for further petrologic analysis as necessary for definitive provenance. It seemed timely, therefore, to provide an appraisal of prior studies by new fieldwork and the use of new techniques mostly unavailable to early researchers. Some of the analytical
techniques used in the present study include scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDS) and electron probe microanalysis (EPMA) (as discussed in Chapter 3 on provenance study). This reappraisal of Tres Zapotes stone sources would also be an opportunity to further test the portable field laboratory for petrography (as discussed in Chapter 4 and in Hunt and Griffiths, 1989). Where possible, this study would be focused exclusively on Tres Zapotes material in situ.

Tres Zapotes has been amply discussed in the literature, beginning with general topographic and ethnographic accounts of the area (Melgar, 1869; Melgar, 1871; Seler-Sachs, 1922; Weyerstall, 1932) and proceeding to the specific archaeological analyses, some of which have been mentioned (Drucker, 1943, 1981; Stirling, 1943; Weiant, 1943 and 1952; Heizer and Williams, 1960; Kubler, 1962; Coe, 1965; Williams and Heizer, 1976; Wicke, 1971; Joralemon, 1971, 1973; Grove, 1973, 1981; Krotser, 1973; Coe and Diehl, 1980; Benson, 1981; de la Fuente, 1981; and Miller, 1986; and Porter, 1989).

Olmec chronology at Tres Zapotes may cover a long period from Early Preclassic Formative (approximately 10th c. B.C.) to Late Preclassic Formative (ending c. 1st c. B.C.). According to Wicke, occupation at Tres Zapotes appears to be mostly datable to the late period ending c. 1st century B.C. (Wicke, 1971:163). Such a late relative chronology for Tres Zapotes may also be derived from ceramic seriation studies (Drucker, 1943; Drucker, 1952), some radiocarbon dates (Coe and Diehl, 1980) and by the first known Mesoamerican calendric hieroglyph example, Stela C at Tres Zapotes, which appears to postdate the La Venta Olmec period (Coe, 1965). Roughly speaking, these calibrated evidences suggest...
major Olmec occupation from 4th c. to 1st c. B.C. at Tres Zapotes or Late Preclassic Formative (Miller, 1986).

However, these solely late dates for Tres Zapotes may be questioned for the following reasons. First, Stirling believed some of the monuments to represent early Tres Zapotes periods, especially all of the major monuments (Stirling, 1943:31). This is consonant with Drucker's later belief that the colossal heads are to be dated early (c. 10th c. B.C.) (Drucker, 1981: 29-47 & esp. 39-40). Second, petrographic analyses not connected with the present study suggest that some San Lorenzo monuments derived from the same geologic source as Tres Zapotes (Heizer and Williams, 1976:4), and since San Lorenzo is generally held as the earliest known Olmec site (Coe and Diehl, 1980; Sabloff, 1990 esp. pp. 32-42), it could easily be the c. 11th to 9th c. B.C. as the period in which most colossal heads appear (Sabloff, 1990:35, 41). Thus, while much of the Tres Zapotes material could belong to a later period, it is tenable that at least some of the monumental Olmec sculpture could belong to the early period at Tres Zapotes, as Stirling assumed.

While little of this Olmec occupation other than lithic and ceramic material remains, the scale and uniqueness of Olmec monumental sculptures suggest a flourishing culture in the area of Tres Zapotes. Although the other primary Olmec sites of San Lorenzo and La Venta are considerably to the east, with La Venta on the other side of the Tuxtla Mtns. and at distances of nearly 90 (San Lorenzo) to 160 km (La Venta) in the lowlands, in contrast to Tres Zapotes (see Figure 6.1 again), it is possible that the proximity of Tres Zapotes to the Tuxtla as potential
stone sources for Olmec monuments is the very crux of its importance as an Olmec centre. This is tenable as the same basalt found at Tres Zapotes has also been found at San Lorenzo, as has been already mentioned (Williams and Heizer, 1976:4).

Olmec sculpture and a culture shrouded in mystery has been a fascination of historians for decades. It is not surprising that the Olmec colossal heads in particular have commanded global interest since the late 19th c. by virtue of their size and mysterious physiognomy (Stirling, 1943:7) as well as the mostly little-understood method of production and their significance, whether as totemic ruler portraits (Sabloff, 1990:41), deity figures, or something. The present study has little to offer in illuminating such questions.

To date approximately twenty-eight monumental sculptures ranging in size from almost 1m in height to more than 4m in height have been found in contexts in or around Tres Zapotes. They appear as stelae (5); various zoomorphic figures (11); receptacles, vessels, slabs, columns or platforms (8); stone boxes (2); and colossal heads (2). Most of them are carved in what has been referred to as either basalt or sometimes olivine basalt (Stirling, 1943; Williams and Heizer, 1976) and many are mutilated to some degree or only extant in fragmented form, which has been observed by this researcher and others (Porter, pers. comm., 1989). Date of the mutilation has not been determined, but while arguably ancient, it is unlikely to be contemporary with the original carving. While evidence for such dating will be discussed on a scientific and cultural basis in Chs. 8 to 10 (and specifically Ch. 10), the weathering colour of the different areas (fresh rock, mutilated or secondary surface,
and original carved surface) is different for each area. The fresh surface of this rock (where recently marred or broken by modern emplacement) is dark greenish grey, the mutilated surface is a paler greenish grey, and the original carved surface is a very pale hue of grey with a green tinge. Thus it is unlikely that the mutilation is either contemporary with the original carving or immediately modern; it is more likely an intermediate stage with as-yet unidentifiable chronology. Based on research presented in more detail in the subsequent chapters already mentioned (Ch. 10 especially), it is the opinion of this researcher that the mutilation took place a little closer to the present than to the original time of carving. This will be discussed in greater detail in Ch.10 (see Plates 10.8 & 10.9).

6.2 Fieldwork and Sampling Considerations for Geological Material

Fieldwork was done in the Tuxtla Mountains of Veracruz, Mexico, in the late spring of 1989 with 24 sampling areas over a range of 100 km between Saltillo (southeast of Soteapan) in the east and quarries in the vicinity of Volcan San Martin (northwest of Santiago Tuxtla) in the west (see Figure 6.1). The Tuxtlas are a major volcanic mountain province on the Isthmus of Mexico, on the eastern or Gulf of Mexico side of the isthmus. Much of the volcanic activity is from the Cenozoic period, especially the eastern Tuxtlas, and some of the western Tuxtlas, including the area around Santiago Tuxtla and Tres Zapotes, is from the Plio-Pleistocene period (Coe and Diehl, 1980:16).

Samples were collected from volcanic flows dated to the Plio-Pleistocene period (Williams and Heizer, 1976:4) and thus most
likely available and accessible in the Olmec period. Samples were also taken from giant (often 2-3 m in diameter) boulders which were roughly spherical, also from the Plio-Pleistocene period (Williams and Heizer, 1976:4). It is most likely that such volcanic boulders provided the basic working material for the Olmec colossal heads, an observation shared by others (Drucker, 1981:39-40 esp.). Therefore, such boulders can be seen as potential reference material for the Olmec colossal heads at Tres Zapotes and other Olmec sites.

A surprising observation of this Olmec provenance survey was that an enormous quantity of these basalt boulders exist throughout the Tuxtla Mountains, naturally rounded by conchoidal fracture and subsequent weathering (Plates 6.1 & 6.2). This natural phenomenon no doubt provided Olmec sculptors with a readily-available and suitable source of raw material for their colossal heads, already "worked" to some extent by nature. Over 115 geological samples were collected from Soteapan to Tres Zapotes itself; over 36 samples collected in the base area around Cerro El Vigia, the peak overlooking the town of Santiago Tuxtla.

Archaeological samples were provided prior to fieldwork by, among others, Dr. James Porter, University of California, Berkeley, Anthropology Dept. Much of this material was from the archaeological context of the Great Mound at Tres Zapotes. These samples were first analysed at the Petrographic Laboratory, U.S. Geological Survey, Menlo Park, prior to the fieldwork.

The primary stone medium for Tres Zapotes sculpture is seen in many Olmec sculptures at the Santiago Tuxtla Museum, and is a distinctive pale gray with a greenish tinge with many huge dark
(Plate 6.1 [above]) TUXTLA MTNS. volcanic boulder from Cerro El Vigia, naturally rounded to a 1 m diameter; (Plate 6.2 [below]) also Tuxtla Mtns. near SOTEAPAN. Note volcanic boulders under trees, some are approximately 2–3 m in diameter.
crystals visible to the unaided eye (some up to 1 cm across), although most of the crystals (phenocrysts) are around 5 mm in diameter.

6.3 Cerro El Vigia

According to the earlier study (Williams and Heizer, 1976:4), the geological source of the distinctive volcanic stone used in Tres Zapotes sculpture was held to be the upper slopes of Cerro El Vigia, a peak on the most western flank of the Tuxtla Mtns. The peak is between the town of Santiago Tuxtla and Tres Zapotes, approximately 10-12 km east of the current Tres Zapotes village (Plate 6.3). The first to suggest Cerro El Vigia as the probable source for much Tres Zapotes sculpture was Stirling, although his vague identification seems not to have been based on petrographic analysis. Stirling states "The stone monuments of Tres Zapotes carved from basalt, a rock which is abundant in the region, especially around the base of the nearby Tuxtla Mountain" (Sterling, 1943:11). This possible description of source is only slightly different than the "upper slopes of Cerro Santiago," as referred to by Williams and Heizer (1976:4) for the same peak which can be seen above the town of Santiago Tuxtla on its east flank, therefore named accordingly. No discrepancy should be inferred with the slight differences between accounts: certainly some stone which may have originated on upper slopes would have found its way to the base by both erosional and gravitational processes; and differences in name could easily reflect local perspective, variation or flux in traditions. It may be of note that the idea of Cerro El Vigia as meaning "The Lookout Peak" or possibly even "The Vigilant One" could be of great antiquity,
perhaps even in the Olmec period (also see Figure 6.1 again).

In the fieldwork of 1989, sampling was first undertaken in an area east of Santiago Tuxtla, including some quarries of hexagonal columns of prismatic basalt approximately 15 km north-east of the town itself (Plate 6.4). This was suggested as one possible source of Olmec basaltic prisms by Dr. F. Bustamente (Director of Santiago Tuxtla Museum). This quarry was closer to the region of Volcan San Martin than to Cerro El Vigia, and while the columnar basalt from this quarry may be found at some point to have supplied Olmec prismatic or columnar basalt also found at Tres Zapotes and other Olmec sites (Stirling, 1943:3, 13, 28), basalt samples collected there and along the way were dissimilar in hand specimens to the distinctive Tres Zapotes material, as were all other samples collected at that time in the Tuxtlas from Soteapan in the eastern Tuxtlas to Santiago Tuxtla in the west.

Cerro El Vigia itself was the next sampling area, with stone samples collected around the circumference of the base of the peak for a distance of 8 km. Near the bottom of the mountain, mostly in arroyo streambeds on the southeastern and southern ridges of Cerro El Vigia, three sampling areas turned up stone which appeared visually identical to both the archaeological samples examined in prior analyses and the sculptures in the Santiago Tuxtla Museum. This sampled material had the same distinctive grey-green weathered hue and huge dark crystals, and was collected along streambeds approximately 9, 11, and 12 km (by dirt track) from the town of Santiago Tuxtla. These samples were visually examined with the unaided eye and these same arroyo (canyon) contexts also showed quantities of large boulders with comparable spherical shape (rounded by conchoidal fracture and
(Plate 6.3 [above]) CERRO EL VIGIA peak from Tres Zapotes, estimated at 15 km distance across plateau; (Plate 6.4 [below]) COLUMNAR HEXAGONAL BASALT QUARRY between Volcan San Martin and town of Santiago Tuxtla (scale: 1 basalt column = 30 cm diameter)
subsequent weathering) and size to the Tres Zapotes colossal head sculptures (Plate 6.5).

Water transport and gravity not only most likely deposited material from the upper slopes of Cerro El Vigia into the arroyos at its base, but water also probably naturally transported some of the stone material into streambeds very close to Tres Zapotes. Volcanic flows under current alluvium could also bring material much if not all the distance of 15 km from Cerro El Vigia to Tres Zapotes itself. Stirling reported a large platform of basalt at the bottom of Arroyo Huayapan adjacent to the site (Stirling, 1943:10).

The following discussions of this distinctive Tres Zapotes stone material for Olmec sculpture and the Cerro El Vigia source provide petrographic and chemical analyses of the archaeological and geological contexts.

6.4 Petrography of Archaeological and Geological Material

Prior petrological analyses at U. S. Geological Survey in Menlo Park, California, had already established the nature of the archaeological stone samples from Tres Zapotes as pyroxene-olivine basaltic andesite where the studies of Stirling and the team of Williams and Heizer identified this material as basalt (Stirling, 1943:11; Williams and Heizer, 1976:4, 15-16, 34).

The representative samples from and around Cerro El Vigia were thin-sectioned for petrographic examination and polished sections for SEM with EDS and EPMA analyses were also made. A total of 11 thin and polished sections of the 36 samples were analysed for the present study.
(Plate 6.5 [above]) CERRO EL VIGIA riverbed boulders on east lower flank of peak w/ unaided eye resemblance to Olmec sculpture material (Plate 6.9 [below] LAKE CATEMACO w/ cinder cones.
Petrographic analysis shows both materials from Tres Zapotes and Cerro El Vigia to be basaltic andesite. That has been defined earlier as rock with andesitic feldspar composition and basaltic ferromagnesian minerals such as olivine (Le Maitre, 1989:50).

Petrographic analysis shows a coarse-grained texture and has identified the large mafic pyroxene phenocrysts as clinopyroxene. Many phenocrysts are up to 5 mm in length, although an occasional giant pyroxene is 1 cm across, quite visible to the unaided eye. The estimated percentage of total volume of clinopyroxene is 28%. The clinopyroxenes are also distinctive for being finely zoned. Clinopyroxene is also present in smaller phenocrysts up to 1 mm. The other major phenocryst is anhedral olivine up to 0.9 mm in diameter, often with iddingsite Fe oxide rims, making up an estimated percentage of volume of 19%. The other major mineral is plagioclase feldspar which is the primary constituent of the groundmass. The plagioclase ranges between 0.3–0.6 mm in length of lath, with both albite and Carlsbad twins and oscillatory as well as normal zoning. The estimated percentage of volume of plagioclase is around 42%. Smaller clinopyroxenes make up an estimated volume of 9%; with the remaining 2% being iron oxides and opaques. Since both the Tres Zapotes site material and the Cerro El Vigia geological material are essentially identical, one petrographic analysis is provided for both (Plates 6.6 & 6.7).

6.5 Chemical Analyses of Archaeological and Geological Material

Field analyses and laboratory analyses conducted at the Institute of Archaeology, University College, University of London, and U.S. Geological Survey, Menlo Park, California, have
(Plate 6.6 [above] petrographic texture of TRES ZAPOTES archaeological material and (Plate 6.7 [below] of CERRO EL VIGIA source material w/large clinopyroxene, olivine and plagioclase feldspar phenocrysts in groundmass. Note iddingsitized olivines.)
confirmed tentative provenance identifications. SEM with EDS and EPMA analyses show the mineralogies of both archaeological and geological materials to be essentially identical. The chemical analyses using SEM with EDS and EPMA provide data not offered in prior studies.

Chemical Analyses Using SEM with EDS

The following elemental analyses show both the archaeological material from Tres Zapotes and the geological material from Cerro El Vigia as seen below in Table 6.1 to be very similar. The analyses adds credibility to earlier studies suggesting Cerro El Vigia as the proposed source for many Tres Zapotes monumental sculptures. It is important to note that the SEM with EDS analyses of the material discussed in the present chapter were conducted solely on plagioclase feldspars. It has already been noted earlier in this study (Chapter 1) that the basaltic andesites "have feldspars usually expected in the andesite range" (Le Maitre, 1989:50). Since these feldspars represent the most common component between all the basalts and andesites of the present study, it can be reasoned that analysis of feldspars might be a logical focus of interest.

Table 6.1 PYROXENE-OLIVINE BASALTIC ANDESITE AVERAGES:
CHEMICAL ANALYSES USING SEM WITH EDS
(In Wt %)

<table>
<thead>
<tr>
<th>Tres Zapotes *</th>
<th>Cerro El Vigia **</th>
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</thead>
<tbody>
<tr>
<td>SiO2</td>
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</tr>
<tr>
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</tr>
<tr>
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<tr>
<td>K 2O</td>
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<tr>
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<td>CaO</td>
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<tr>
<td>FeO</td>
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</tr>
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<td>TiO2</td>
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<tr>
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<td></td>
<td>11.654</td>
</tr>
<tr>
<td></td>
<td>1.102</td>
</tr>
<tr>
<td></td>
<td>***</td>
</tr>
</tbody>
</table>

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Notes to Table 6.1:

Analyses were conducted on a Hitachi S-570 SEM with Link Systems 10/25 S EDS @ 20 kV, livetime 100 seconds, elevation of 31.46 using a cobalt standard as reference. Area of analysis was that within SEM CRT field of vision at 35 X.

*TZ averages represent a total of 9 analyses of 3 polished sections. Wt % of SiO variation ranges were between 49.3 and 52.2; averaged to 51.4.

**CEV averages represent a total of 26 analyses of 8 polished sections. Wt % of SiO variation ranges were between 49.2 and 51.8; averaged to 49.5.

*** denotes 0.00 % (some 2 sigma results are provided here; see note in Chapter 5 on Table 5.3 and notes below).

Note: While the low SiO wt % (around 51% SiO) is indicative of a high basalt range, it is on the basaltic andesite margin (Le Maitre, 1989:28).

The overall ratios of oxides given above actually show greater similarity, particularly in the range of variations, than might be inferred from the data averages. It can be seen that the range of variations in, for example wt % of SiO, for both materials is very close: within 0.1% at the low end (49.2 : 49.3) and within 0.4% at the high end (51.8 : 52.2). Semiquantitative difference of less than 2 sigma (approx. 0.3%) result in this EDS detection count rate should be insignificant (D. Griffiths, pers. comm., 1990). At the same time, given the margin for error in a semiquantitative analysis, the low sampling volume, and the arbitrary elements in choosing mineral areas for analysis on both the overall level (plagioclase and groundmass) and the specific level (which plagioclase and where in the groundmass), the results of these analyses should be considered tentative.

For the purpose of providing a specific focus, SiO was chosen as the optimum "signature" due to the following reasons: 1) SiO is the dominant oxide in all the minerals present in phenocrysts;
2) the mafic range of oxides in the pyroxenes and olivines does not suggest a uniform mineralogy for a "signature."

Furthermore, the nominal differences between the oxides given in the above analyses should also reflect the factor of the large phenocrysts in both materials. Given the analytical "window" for detection was only that obtainable @ 35 X and given the fact that some clinopyroxene phenocrysts had diameters of 5 mm, detection windows were chosen in both materials which usually presented plagioclase feldspar laths wherever they could be found between the other larger phenocrysts. Thus, chemical variability might be exaggerated by the overall large size of mineral grains in both materials. Elsewhere in the above analyses, the elemental ratios between the oxides appear to be consistent as well.

In summary, the SEM with EDS analyses suggest the likelihood of a common source for the archaeological and geological material due to chemical similarity.

It was also important in the present study to use additional chemical analyses where possible to provide a reference for comparison as a means to calibrate the different analyses to each other. EPMA was used for this purpose, partly because it offered some optical capabilities (see Chapter 3), and partly because it was available at a given period in the research.

Chemical Analyses Using EPMA

Chemical analyses were also undertaken at U.S. Geological Survey in Menlo Park, California, in 1990 in the Microprobe Laboratory. Both archaeological and geological samples were analysed from polished sections by Dr. M. Clynne, Branch of
Igneous and Geothermal Processes. The microprobe used was a Cambridge Instruments 9 Detector Microbobe. Not all the analytical parameters (livetime, kV, beam width, detection area or sample preparation) are known to this researcher. Samples believed to be representative were provided by this researcher. Table 6.2 below presents the EPMA results obtained.

Table 6.2 PYROXENE-OLIVINE BASALTIC ANDESITE: CHEMICAL AVERAGES USING EPMA
(In wt % of Oxides)

<table>
<thead>
<tr>
<th>Tres Zapotes</th>
<th>Cerro El Vigia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clino-</td>
<td>Clino-</td>
</tr>
<tr>
<td>pyroxene</td>
<td>pyroxene</td>
</tr>
<tr>
<td>Ground-</td>
<td>Ground-</td>
</tr>
<tr>
<td>mass</td>
<td>mass</td>
</tr>
<tr>
<td>Sector 1</td>
<td>Sector 1</td>
</tr>
<tr>
<td>---------------</td>
<td>---------------</td>
</tr>
<tr>
<td>SiO2</td>
<td>51.07</td>
</tr>
<tr>
<td></td>
<td>52.81</td>
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<tr>
<td></td>
<td>38.03</td>
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<tr>
<td></td>
<td>50.73</td>
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<tr>
<td></td>
<td>51.45</td>
</tr>
<tr>
<td></td>
<td>38.39</td>
</tr>
<tr>
<td>Al2O3</td>
<td>4.23</td>
</tr>
<tr>
<td></td>
<td>2.34</td>
</tr>
<tr>
<td></td>
<td>***</td>
</tr>
<tr>
<td></td>
<td>4.48</td>
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<tr>
<td></td>
<td>3.80</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
</tr>
<tr>
<td>FeO</td>
<td>5.92</td>
</tr>
<tr>
<td></td>
<td>8.83</td>
</tr>
<tr>
<td></td>
<td>22.33</td>
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<tr>
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<td>4.69</td>
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<td></td>
<td>8.86</td>
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<td>22.73</td>
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<tr>
<td>Fe2O3</td>
<td>2.02</td>
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<tr>
<td></td>
<td>0.71</td>
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<tr>
<td></td>
<td>***</td>
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<tr>
<td></td>
<td>1.77</td>
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<td>***</td>
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<tr>
<td></td>
<td>***</td>
</tr>
<tr>
<td>MgO</td>
<td>15.15</td>
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<tr>
<td></td>
<td>15.46</td>
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<td></td>
<td>39.17</td>
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<td>0.34</td>
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<td></td>
<td>0.44</td>
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<td>0.13</td>
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<tr>
<td>TiO2</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>0.77</td>
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<td></td>
<td>***</td>
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<tr>
<td></td>
<td>0.68</td>
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<td>1.18</td>
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<tr>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>Cr2O3</td>
<td>0.03</td>
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<tr>
<td></td>
<td>0.01</td>
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<td></td>
<td>***</td>
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<tr>
<td></td>
<td>0.14</td>
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<td></td>
<td>***</td>
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<tr>
<td></td>
<td>***</td>
</tr>
<tr>
<td>CaO</td>
<td>20.94</td>
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<td>19.46</td>
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<tr>
<td></td>
<td>0.20</td>
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<tr>
<td></td>
<td>22.08</td>
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<tr>
<td></td>
<td>21.47</td>
</tr>
<tr>
<td></td>
<td>0.32</td>
</tr>
<tr>
<td>Na2O</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>0.47</td>
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<tr>
<td></td>
<td>***</td>
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<td></td>
<td>0.32</td>
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<tr>
<td></td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>***</td>
</tr>
</tbody>
</table>

4 polished sections were made (2 sections for each material); a total of 32 probe analyses are represented in the above EPMA averages. Range of chemical variations found not available, however, in clinopyroxene core of TZ material wt % of SiO was 54.09; wt % of MgO was 17.40; and wt % of CaO 23.69. Also, in clinopyroxene core of CEV material wt % of SiO was 53.57; wt % of MgO was 16.44; and wt % of CaO was 23.38.

Again, note as in Table 6.1, wt % of SiO around 51% is at the high end of the basalt range but also on the basaltic andesite margin (Le Maitre, 1989:28).

It is immediately obvious that while the focus of the SEM with EDS chemical analyses was solely on feldspars within the groundmass of both materials, the EPMA analysis was focussed on groundmass as well as the other phenocrysts in both materials. This will provide different data for the EPMA analysis which will
be discussed in the following subsection.

The close approximations seen in many of the above comparisons emphasize the chemical similarity of the materials. For example, in 17 out of 30 oxides reported (not counting 0.00 results posted as ***) detected difference between TZ and CEV was less than 0.5%; furthermore, detected difference in the FeO between the two groundmasses was 0.03% and several of the detected differences between the two olivines were only 0.01%, strongly underscoring the chemical match between archaeological and geological materials. Of course, as already mentioned, due to the semiquantitative nature of the analyses and the potential margin of error as well as the low volume of samples analysed, these strongly-correlated results are best presented as tentative data.

Some comments of M. Clynne are especially appropriate here. "The pyroxenes and olivines in these...samples are very similar and support your petrographic match of the two rock types... There are some subtle...differences. The only clear difference between the two rocks...is that CEV pyroxenes are more calcic (when both have the same MgO range)..." One possible reason which Clynne posits for the calcic difference is "that the phenocrysts of CEV grew at higher temperatures than TZ." Clynne continues by saying "...the many similarities between the samples suggest that they could be the same rock. They probably are at least related by being different flows of the same magma batch" (Clynne, 1990, pers. comm.).
Comparisons Between SEM with EDS Analyses and EPMA Analyses

Several important differences are noted in comparing the two sets of analytical data where they shared a common focus. First, as could be expected, there is a major difference in the MgO wt % in the groundmass (around 2.5% in the SEM with EDS analyses and around 14-15% in the EPMA analyses). The logical explanation for this is that the former excluded the small phenocrysts and microcrysts of clinopyroxene and olivine wherever possible and the latter included them. This would account for the apparent discrepancy. The second area of discrepancy is in the detection of Al2O3 where SEM with EDS consistently show 18-19 wt % of Al2O3 while EPMA consistently shows 2-7 wt % of Al2O3. Since both analyses were set up to detect the same AlO oxide, and since the AlO of the feldspar should be more detected in the EPMA analyses, this is a perplexing problem. The only possible explanation posited here is that the EPMA analyses of the groundmass was more directly focussed on small phenocrysts and microcrysts of the mafic minerals than on the feldspars. This could also be an explanation for the other major discrepancy of comparing the differences in CaO wt % in the SEM with EDS and EPMA analyses. Finally, where SEM with EDS analyses show Fe2O3 wt % in both materials at between 9-11%, EPMA shows a wt % near 9% in the two groundmasses (or on mafic phenocryst rims of TZ material) but of FeO only, rather than Fe2O3. Again, this could be an analytical result for which the same explanation as above has been offered: the SEM with EDS analyses are focussed solely on plagioclase feldspars whereas the EPMA focus also encompasses the small mafic phenocrysts within the groundmass.
On the other hand, the analytical consistency within both SEM with EDS analyses and EPMA analyses are supportive of their overall reliability, i.e. they are mostly consistent in their portrayal of the chemical similarity between the archaeological and geological materials. Furthermore, in the oxide with the highest wt % (SiO), the EPMA chemical analyses corroborate the SEM with EDS analyses in that the chemical ratio is consistent overall between both analyses with a wt % of SiO most often showing a ratio of 1:1 between TZ and CEV and each other.

Summary of Chemical Analyses

In summary, all analyses to date in the study of Olmec stone material source determinations for Tres Zapotes material confirm each other: the petrographic, based on common mineralogy as determined by optical textural analysis; the SEM with EDS, based on semiquantitative elemental analyses for plagioclase feldspars in the groundmass; and the EPMA, also based on semiquantitative elemental analyses for all phenocrysts and the groundmass. Thus, it is strongly suggested that Cerro El Vigia is the geological source for Tres Zapotes monuments sculpted from the distinctive basaltic andesite based on the analyses provided.

Probable Tres Zapotes Monuments
Sculpted from Cerro El Vigia Material

Although this provenance analysis does not cover all the stone monuments from Tres Zapotes, the following major monuments appear to derive from sources on Cerro El Vigia: Monument A (the colossal head at Tres Zapotes Museum); Monument Q (the colossal head at Santiago Tuxtla Museum); Monument C (now at the

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National Museum in Mexico City); and Monuments F and G (2 tenon altars at Santiago Tuxtla Museum). Monuments A, Q, F & G are suggested in this study as a result of visual identification of the monuments as being the distinctive basaltic andesite with the large clinopyroxene phenocrysts and virtually the same weathering hue of pale greenish grey. These attributions are also partially confirmed by in situ microscopic examination with the field microscope (Swift FM-31) of the portable field laboratory. Other monuments not seen by this researcher which were suggested by Williams and Heizer as being from the same material include Monument C (now in Mexico City), and Monument 9 at San Lorenzo (see Figure 6.1), as well as two other pieces, the "Frog Altar" and the "Jaguar Throne" (now both in the Jalapa Museum, Veracruz) (Williams and Heizer, 1976:4).

It is possible that other Tres Zapotes sculptures as well as additional sculptures from other Olmec sites, including pieces now in the National Museum of Anthropology in Mexico City, will also be determined to trace their geological provenanced to Cerro El Vigia in the near future. This will entail wider sampling of archaeological material, requiring official permission from the appropriate Mexican archaeological authority, necessarily broadening the limited scope of the present study.

Specific quarries on Cerro El Vigia may be impossible to locate given the fact that accessible boulders are made spherical by rounded conchoidal fracturing and weathering processes and are scattered abundantly around the base of Cerro El Vigia in arroyo streambeds, as previously mentioned (also mentioned by Drucker, 1981:39-40; and Coe and Diehl, 1980:16, for all Olmec use of such
volcanic boulders). Thus, they are naturally prepared for being worked. This might suggest that few, if any, quarries may be found on Cerro El Vigia since the availability of stone boulders could have made them unnecessary.

The question of where the stones were worked, either at the source or at the site, cannot be satisfactorily answered at this time, although fragments of material such as found in the Great Mound at Tres Zapotes (which supplied research material for the present study) suggest some stoneworking and dressing at the site itself. Unfortunately, the earlier excavations of Stirling and Drucker in the late 1930's and early 1940's have removed most of the potential evidence for reconstructing a stoneworking locus if any major dressing of the stone was done at the site, since the stratigraphy has been for the most part removed.

6.6 Potential Stone Selection Criteria for Olmec Use of Volcanic Material

Questions of potential Olmec stone selection criteria as well as stone technology and stoneworking methods are also raised by provenance. Much of this is beyond the scope of this research. However, several fundamental ideas can be suggested which, while preliminary, could be pursued in subsequent research.

Following the discussions in Chapter 2 on potential selection criteria for stone in general, Olmec selection of volcanic stone will be discussed in regard to potential criteria of workability, aesthetics, and availability, as well as other choices possibly dictated by philosophic (metaphysical) ideas or tradition. While a perceived technology for stoneworking is neither likely to have been developed or articulated by the Olmec, nonetheless certain
deliberate stone choices were made which appear consistent.

One such deliberate choice could be found in the use of volcanic stone throughout all three major Olmec centres and many minor sites as well. Indeed it could be called the primary surviving Olmec medium. However, archaeological constraints show that artefact survival must not be assumed to have necessarily preserved what would have been considered important to the any culture or even the most prolific element of their productivity. This is particularly true for many North American Native Indian populations whose primary working materials were often organic. It would also be true for the Olmec, dwelling in what has been deduced from palynological and other paleoenvironmental research as a long-term tropical environment (Coe and Diehl, 1980:22). No prioritizing of potential stone selection criteria is intended in the following paragraphs. The primary question to ask in attempts to understand potential Olmec stone selection criteria is raised perhaps by Tuxtla basalt from Cerro Cintepec being found almost 100 km away at La Venta (Coe and Diehl, 1980:399): not so much how did it get there by why?

Workability of the volcanic boulders has already been mentioned several times in this chapter, particularly mentioning the spherical conchoidally-fractured and weathered boulders of comparable size to Olmec sculptures, notably colossal heads. All the masons would have to do in many cases would be to follow the natural curves of the boulders. The economy of carving and proportions seen in Olmec monumental sculpture has been discussed by others (de la Fuente, 1981), and in some way can evidence the fact that nature had already done much of the work.

Aesthetics could also have had a part in the deliberate
choice of this particular distinctive Cerro El Vigia material. It is the opinion of this researcher that this basaltic andesite, with its unusually-large phenocrysts visible to the unaided eye even in the samples of fresh (unweathered) dark grey rock with a green tinge, is rare among the other Tuxtla volcanic materials. This belief is based on fieldwork and the available literature. The fact that the volcanic boulders were in some sense already preshaped by nature to resemble human heads may have caught the aesthetic (and perhaps even religious) imagination of the Olmec. As aesthetically-minded as their naturalistic sculptures show the Olmec to be, it is plausible that the atypical stone colour and its phenocrysts could represent at least a partial criterion for stone selection. That the Olmec appreciated the stone is obvious, especially as their actual occupation centres are found usually at some distance from the volcanic region, and the local geological environment of all the major centres is either on limestone or sandstone formations (even the immediately-local environment of Tres Zapotes is sandstone).

Certainly related to workability, the availability of the volcanic boulders in such abundance in the Tuxtlas also suggests this as a possible criterion. What cannot be ascertained is, of particular importance to the site of Tres Zapotes - so close to a volcanic source - as opposed to the other Olmec centres in the lowlands, whether or not Tres Zapotes existed as a site before the nearby mountain source of unique stone was appreciated or was selected as a site because of proximity to Cerro El Vigia, for these reasons of available and unique stone or some other reason (some discussed in the following paragraphs). In any case,
the availability of volcanic boulders throughout the Tuxtla was
known to Olmec sculptors who indeed brought them to their other
centres at San Lorenzo and La Venta, among others.

Metaphysical reasons may have also been important for the
selection of volcanic stone. The material for Tres Zapotes may
have been important coming from the flank or even the heart of a
local prominent peak. Furthermore, other important questions can
be raised about metaphysical reasons for choosing volcanic stone
for sculpture and monuments. According to the stratigraphic
evidence (Stirling, 1943:22), the Olmec must have observed actual
volcanic eruption, deposition, and solidifying of lava, which
would be both terrifying and ostensibly religiously interpreted.
A scenario such as the following could appear in many cultures.
For example, the heart of a mountain pours out its fiery blood
which then miraculously and quickly cools from its red-hot,
almost translucent viscous but "living" and moving state to a
dark, hard and immobile rock. Is it possible that some Olmec
appreciation of volcanic origins of such rock extended to a
religious appropriation of its underworld sources of 'power' and
'magic' for their mound (mountainous and volcano-like) complexes,
distributed for the most part considerably distant from but still
located where they had visibility of the volcanic Tuxtla Mtns.? Underworld power and connotations are a recurring feature of
Olmec religion as understood from their mounds and artefacts
(Reilly, 1989). Others have also maintained the correlation
between Olmec conical mounds and the volcanoes of the Tuxtla
which provided stone for Olmec monuments (Bernal-Garcia, 1989)
(Plate 6.8 & Figure 6.2).

Another criterion to be discussed in more detail in Ch.7 is
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Plate 6.8 & Figure 6.2

(Plate 6.8 [above]) OLMEC MOUND AT LA VENTA of main complex; Figure 6.2 [below] OLMEC MAIN MOUND COMPLEX at LA VENTA (after Sabloff/Coe). Also note resemblance to typical cinder cones at Lake Catemaco in Plate 6.9 (adjacent to Plate 6.5).
the possible resistance of basalt and andesite (in this case basaltic andesite) to burning. It is known that relative to other stone material, basalt does not discolour easily or fracture to the same degree that limestone, for example, is prone. Winkler discusses the coefficient of thermal expansion of many stones, with quartz (very rare in basalt) expanding roughly four times more than feldspars (normal in basalt), and also states that the carbonates (limestone and marble) are also susceptible as marbles may be highly stressed. Intense heating of limestones "may cause superficial burning which is soon followed by slaking, leaving ugly shallow scars" (Winkler, 1975:175) where calcination occurs. Winkler also states "basic igneous rocks [having no quartz] should be preferred where exposure to high temperature is expected" (Winkler, 1975:175).

Pugh also discusses Olmec traditions of sacrifice and even child sacrifice by burning among Olmec or Olmecoid peoples (Pugh, 1981:7). This practice may not be widespread, but it is possible that in whatever fire-related context Olmecs may have employed basalt (including as well as in addition to sculpture), their observations and experience showed them this advantage of using basalt over other stones.

Finally, tradition itself may be considered important as a criterion (although this is not necessarily only a metaphysical criterion). Both in terms of understanding a stone material by a stoneworking tradition whose origins may not be fathomed by distant generations and in terms of a known source as a tradition to be continued, there is some cultural security in continuing and finding one's place in tradition. Such may also have shaped
the Olmec stone selection criteria not initially but as the Olmec
developed. As to other potential reasons for working volcanic
stone, the giant and beautiful caldera, Lake Catemaco, may hold
hints. Lake Catemaco lies in the centre of the Olmec heartland in
the Tuxtlas, and itself deserves further consideration for Olmec
origins as possibly being from the volcanic Tuxtlas region.
Could this lake be a sacred lake to the Olmecs or even an ancient
home from which they migrated in order to flee volcanic havoc?
(Plate 6.9 [adjacent to Plate 6.5]). These hypotheses will need
testing as further understanding of Olmec preference for volcanic
stone is acquired.

6.7 Conclusions

Provenance research undertaken in the Tuxtla Mtns. of
Veracruz, Mexico to reappraise or identify the Olmec source for
much of the monumental sculpture at Tres Zapotes has determined,
along with prior studies and in analyses not used by prior
studies, that Cerro El Vigia should be considered the geologic
source for a distinctive Tres Zapotes archaeological material. In
some ways the present study has redefined the material itself as
a basaltic andesite according to the most recent indices (Le
Maitre, 1989). Petrographic, SEM with EDS, and EPMA analyses all
shed much light on the mineralogical and textural questions and
were the analyses used for determination of provenance. Potential
stone criteria for Olmec selection of volcanic stone were also
addressed, further developing the criteria which were introduced
in Chapter 2. Hypotheses relating to Olmec use and even their
understanding of volcanic stone were suggested as means by which
the Olmec people and their origins may be better understood.
7.1 Introduction

Cenozoic vulcanism in the Great Rift Zone between Asia and Europe has occurred along the several plate margins which bisect Israel, and has been a major factor in creating the geomorphology of the Golan Heights, the Galilee plateau, and the Huleh Sill as major basalt regions which have been produced in the rift zones delineated by the Golan and Jordan - Esdraelon valleys. This is an area greater than 500 sq km covered with olivine basalt lava flows intermixed with limestone and alluvia (Figure 7.1) (Freund et al., 1965; Glikson, 1966; Schulman, 1967).

Many cultures have appropriated this basalt for various uses over a long time span. In the Golan during the Lower Paleolithic (c. 500,000 B.P.), the Benot Ya'aqov Bridge site attests to a local basalt tool industry (Nemlich, 1987) and the 'Ubeidiya site evidences Lower Pleistocene use of basalt in the Central Jordan (Great Rift) valley which is roughly contemporary with Olduwan II in Olduvai Gorge, Africa (Stekelis, 1966). In the Golan during the Neolithic period, basalt tools were also produced from local flows (Nemlich, 1987) and basalt was widely used in the Neolithic and later at Jericho for grinding tools (Dorrell, 1983). Again, in the Golan Ghassoulian Chalcolithic period (c. mid-4th millenium B.C.) basalt was used for pillarform figures, dolmens, altars, grinding tools and other artefacts (Epstein, 1978, 1985).

In the Middle and Late Bronze Ages, Hazor, a major Canaanite city 25.5 km north of the Sea of Galilee-Kinneret, was located along a vital north-south trade route between the Levant and Mesopotamia. At Hazor, the Canaanites (or Amorites) used basalt for religious
Figure 7.1 MAP OF LEVANT

JORDAN RIVER VALLEY HAS FOLLOW THE GREAT RIIF ZONE (EXTENDING NORTH AND SOUTH OF THE AREA COVERED BY FIGURE 7.1)

VOLCANIC FLAMES

A-D-A-Y = ALMA, DALAB, AL-WAD, YARON (HULA)
K = KORATIM
TP = TIBERIUS-POIYVA
QH = GAHRH HITIM
WR = WADI RAML
sculpture and as a temple *temenos* or "sacred precinct-marker" in the Holy of Holies (Yadin et al., 1958). Beth Shan is another locus of Canaanite temples in the Late Bronze Age where a strong religious context is noted for basalt (A. Rowe, 1940). Also an important Middle to Late Bronze site (as well as earlier and later), Megiddo in the Esdraelon valley evidences cultic use of basalt (Loud, 1948) in addition to the usual grinding and weight uses of basalt universal throughout the Levant in any period. In the Byzantine era (6th c. A.D.) the synagogue of Khirbet Korazim (among others) was made of local Galilean basalt (Yeivin, 1987).

While not the subject of this discussion, cultures outside this part of the Levant were also noted for their use of basalt. In what would today be northern Syria and southern Turkey, the Late Bronze Age Hittite Empire used basalt extensively for many uses, notably religious sculpture (Garstang, 1929). As much of the Taurus mountain range in the Euphrates watershed has basaltic character and as the Hittite homeland in central Anatolia to the north (Hattush or Boghaz Khoy) in the Halys watershed is also plentiful in basalt, it is possible that Hittite masons passing on stoneworking traditions would recognize the usefulness and/or propriety of basalt in the Northern Levant. In fact, one Hittite text refers to millstones made from *kunkunuzzi* stone, which has been identified as basalt (Hoffner, 1974). Further to the east (although also in the same western area) in the later Iron I through III periods, the Assyrians used basalt extensively for religious sculpture as well. Indeed, Assyrian words for basalt probably include *adbaru*, *salamtu*, and *kasurru* for various forms or textures of basalt lava (Campbell Thompson, 1936; Stol, 1979).
In the Homs valley between the Lebanon and Antilebanon ranges north of Damascus, local basalt deposits were used at the vital nexus Kadesh (Tell Nebi Mend) in the Middle and Late Bronze Ages as a medium for grinding tools (Parr, personal comments, 1990; and unpublished documents, Williams-Thorpe, 1990a). Trade in such basalt material for tools and other uses is an issue which could be discussed but is not a focus of this chapter. Transport of Levant basalt to Cyprus (which already had its own sources of basalt in the copper-rich Troodos Mtns.) has been convincingly demonstrated (Elliott et al., 1986; Xenophontos et al., 1988).

Aside from desirability for grinding tools, based on durability and hardness, some other feature such as colour for example, might explain a Chalcolithic female deity basalt head so distant from basalt sources at Shiqmim near Beersheba, Israel (Levy and Alon, 1985; see Table 7.1 below).

These few representative examples cited attest to a broad stone technology and a long succession of sculptural traditions in which basalt was used as a major stone source for architecture and other uses. While this is by no means a comprehensive list, availability and workability of these basalts would in themselves suggest that basalt use ought to be ubiquitous except for the fact that in some of these areas any source of basalt is roughly equal in distance and accessibility to limestone, particularly at Hazor where basalt artefacts to date seem overwhelmingly tied to religious contexts. Naturally, nearly every site in northern and central Israel on a continuum through antiquity can evidence basalt as a primary grinding tool material for querns, mortars, pestles, and related tools where a rough but durable stone was required. It is not this obvious ideal use which is a main
concern of this chapter but rather the intriguing use of basalt in primarily Late Bronze Age religious or cultic contexts. This will be elaborated in discussions to follow on Hazor, Beth Shan, Megiddo and Jericho after Table 7.1, a summary of basalt use.

Table 7.1 SUMMARY OF ARCHAEOLOGICAL BASALT USE IN LEVANT

<table>
<thead>
<tr>
<th>Period</th>
<th>Site</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Paleolithic (500,000 B.P.)</td>
<td>Benot Ya'aqov Bridge Golan</td>
<td>Flake Tool</td>
</tr>
<tr>
<td>2. Paleolithic (233,000 B.P.)</td>
<td>Birket Ram Golan</td>
<td>Flake Tool</td>
</tr>
<tr>
<td>3. Neolithic (8,000-4000 B.C.)</td>
<td>various sites Golan &amp; Jericho</td>
<td>Grinding Tools</td>
</tr>
<tr>
<td>4. Chalcolithic (c. 3500 B.C.)</td>
<td>Rasm Harbush &amp; el-Majami' Golan</td>
<td>Architectural Elements</td>
</tr>
<tr>
<td>5. Chalcolithic (c. 4th mill. B.C.)</td>
<td>Shiqqim, nr. Beersheba Negev</td>
<td>Sculpture (Statue head)</td>
</tr>
<tr>
<td>6. Chalcolithic (c. 3500 B.C)</td>
<td>el-Majami' &amp; Tell Turmus Golan</td>
<td>Pillarform Figures</td>
</tr>
<tr>
<td>7. EB IV - MB I (c. 2250 B.C.)</td>
<td>Qatsrin, Abu Fila, etc. Golan</td>
<td>Dolmens</td>
</tr>
<tr>
<td>8. EB IV - MB I</td>
<td>Jericho, Jordan Valley</td>
<td>Grinding Tools</td>
</tr>
<tr>
<td>10. MB III - LB III Canaanite (17th-12th c. B.C.)</td>
<td>Megiddo Va,VII, XV Esdraelon Valley</td>
<td>Cult Objects &amp; Sculpture</td>
</tr>
<tr>
<td>11. Late Bronze (14th c. B.C.)</td>
<td>Beth Shan Central Israel</td>
<td>Cult Objects &amp; Sculpture</td>
</tr>
<tr>
<td>13. Hellenistic (4th-1st c. B.C.)</td>
<td>Tell Dor, Central Coast</td>
<td>Grinding Tools</td>
</tr>
<tr>
<td>14. Roman (1st c A.D.) Gamla, Golan</td>
<td>Sculpture</td>
<td></td>
</tr>
<tr>
<td>15. Byzantine (c. 6th c. A.D.)</td>
<td>Korazim, Galilee</td>
<td>Architecture</td>
</tr>
</tbody>
</table>
Table 7.1 (also see Plates 7.1 & 7.2) is compiled from the literature, and while it is representative, it is not exhaustive for all the uses of basalt in the geographic area or time period.

Proximity to northern (i.e. mostly Galilean or Golan) basalt sources is noted for most of the above examples. Where proximity is not found, it is likely that determination of provenance may be very tenuous until extensive further research and sampling has been conducted. This is due to the abundance of chemically-similar basalt flows over the wide geographical area of over 500 sq. mi. (Williams-Thorpe et al, 1990b). The exceptions to a northern location include: Jericho in the lower Jordan valley to which basalt cobbles were probably transported naturally by river, around 70 km from the nearest geological basalts (Dorrell, 1983: 491); Tell Dor on the central coast, also about 50 km from the nearest geological basalt and requiring overland and/or marine transport; Ashkelon on the southern central coast, about 100 km from the nearest geological source and requiring overland and/or marine transport; and Shiqmim-Beersheba in the northern Negev (or the extreme southern Judean watershed), far removed from any natural means of transporting basalt about 100 km from the nearest geological source. Naturally, the use of basalt in these last three loci would be more likely to demonstrate deliberate choice where the availability and accessibility of basalt is quite low compared to the sites in and around the Golan and Galilee. However, even with the proximity of basalt at Hazor, for example, the choice of basalt in some contexts can only be deliberate in the opinion of this researcher, as will be discussed in the following section.

Aside from the obvious use of basalt for tools (e.g. mortars,
(Plate 7.1 [above]) CHALCOLITHIC PILLARFORM FIGURES/ALTARS from
the Golan basalt area, Qatsrin Museum, Golan; (Plate 7.2 [below])
BYZANTINE SYNAGOGUE SCULPTURE, lintel from the Golan basalt area,
Qatsrin Museum, Golan. Scale on both: 1 inch = roughly 30 cm.
pestles, querns, and related grinding tools), it is the cultic or shrine use of basalt at Bronze Age Hazor, Beth Shan and Megiddo (and possibly others like Tell es-Sa’idiyeh in Jordan) which is under discussion in this chapter on basalt use and provenance. Some possible reasons for this deliberate use will be suggested in the conclusions of this chapter.

7.2 Basalt at Hazor

As mentioned, Hazor (Tell el Qedah) is equidistant from both basalt and limestone deposits (Figure 7.1), allowing for choice between stone sources. There is Korazim (Rosh Pinna Sill) basalt to the immediate south and Alma-Dalton-Aswad and Yarda (Hula) basalts to the immediate north as well as Tiberias-Poriyya, Qarne Hittim, and Wadi Raml basalts further south, and Golan (Hauran) basalt to the east. There are also many limestone formations (Bina, Timrat, Biria, Bar Kokhba) on which this research will not focus (Eliezri, 1965; Freund et al., 1965:37-44; Schulman, 1966a; Schulman, 1966b; and Schulman, 1967:104-6).

As noted, the major archaeological use of basalt at Hazor appears to have strong religious or ritual associations. These include cultic shrine, temple precincts and the Canaanite Holy of Holies, deity sculptures, and sacrificial apparatus. Furthermore, distinct phases of different cultural influence operate at Hazor over a time span of almost half a millennium, although the cultural aegis is assumed by Yadin and others to be primarily Canaanite (Garstang, 1928; Yadin, 1972; Shanks and Ben-Tor, 1990).

Concentrating on Hazor, preliminary provenance fieldwork in 1984 turned up some basalt artefacts used as floor pavingstones
in the Holy of Holies, Sector H. According to Yadin, the bulk of
the religious uses of basalt in Area C (including sculptures and
mazzeboth [menhirs] associated with the Canaanite-Hittite cults
of the Hittite moon god Sin of Harran) seem to date from the Late
Bronze II period, circa 14th to 13th c. B.C. (Yadin et al., 1958:
87-89, 92). In contrast, the Area H Canaanite Holy of Holies and
its Canaanite-Hittite basalt sculptures and offering table are
linked with the Hittite storm god Hadad (sometimes identified as
Baal-Hammon) and date roughly from the Late Bronze III period,
circa 14th c. B.C. (Yadin et al., 1961: Pl. CXVII-CXXIX, CCCXXIV-
XXXIV; Yadin, 1972). Area A also turned up basalt cultic objects
in the Long Temple during the last season Yadin worked at Hazor
(1968), also in Late Bronze III contexts (Yadin, 1972:101). Area
F also contained cultic installations with basalt objects (Yadin,
1975). Table 7.2 below lists known Hazor basalt cult objects.

Table 7.2 HAZOR CULTIC OBJECTS OF BASALT

<table>
<thead>
<tr>
<th>Excavation Reference</th>
<th>Context No.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Area C</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. 10 stelae</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(stelae also referred to as mazzeboth herein)</td>
</tr>
</tbody>
</table>
|                      |             | (see Yadin et al., 1958, Pl. XXVIII-XXXI and pp.
|                      |             | 83-90, esp. 87)                                 |
|                      |             | (Yadin et al., 1960, C 6178 Pl. XXXVII)          |
|                      | H 2190      | b. 10+ orthostats or "temenos" wall & steps      |

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Table 7.2, cont. Hazor Cultic Objects of Basalt

<table>
<thead>
<tr>
<th>Excavation Reference</th>
<th>Context No.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area H, cont.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(see Yadin et al.</td>
<td>H 127</td>
<td>c. deity stone</td>
</tr>
<tr>
<td>1961, Pl.</td>
<td>H 134</td>
<td>d. altar</td>
</tr>
<tr>
<td>CXVII—CXXIX;</td>
<td>H 135</td>
<td>e. cultic basin</td>
</tr>
<tr>
<td>&amp; CCCXXIV—XXXIV;</td>
<td>H 136</td>
<td>f. ritual krater</td>
</tr>
<tr>
<td>Yadin, 1972, ch. 7)</td>
<td>H 137</td>
<td>g. libation table</td>
</tr>
<tr>
<td>H 138</td>
<td></td>
<td>h. libation table</td>
</tr>
<tr>
<td>H 143</td>
<td></td>
<td>i. offertory table</td>
</tr>
</tbody>
</table>

3. Contexts Related to 2.

| H 760                | a. deity statue |
| H 526                | b. bull for a. |
| H 666                | c. Lion orthostat 2 |
| H 1027               | d. (deity?) statue |
| H 2118               | e. libation table |
| H 2119               | f. cultic stele with e. |
| H 2126               | g. libation altar |

Area A

4. Long Temple (LB III)
   (Yadin, 1972, Ch. 7)
   a. temple threshold

5. Temple (MB II, Stratum 3)
   (Yadin, 1972, pp. 75-77)
   a. 2 "capitals"
   b. ashlar temple steps

Area F

6. Courtyard 8067
   F 8067
   a. orthostat
   (Yadin, 1961, Pl. CXXVII) F 8545
   b. threshold slab

Table 7.1 is an original table compiled for this chapter from the literature on Hazor, like all tables in the present study which are original to this researcher except where noted.

Not counting individual finely-sculpted ashlar thresholds or various temple steps or capitals, a minimum total of 53 basalt units directly found in or associated with presumed cultic use can be identified at Hazor to date. While an expected quantity of grinding tools, door sockets, etc., were also found of basalt material at Hazor, it is suggested here that a deliberate choice of basalt was made for Late Bronze Age cultic contexts at Hazor,
although no direct criteria will be offered at this point but will be suggested near the conclusion of this chapter. This suggestion of deliberate choice of basalt is raised as a correlation with Beth Shan and also with Megiddo, which are other contemporary city states and transport route control centers already connected in the literature with Hazor (Yadin, 1975).

7.3 Basalt at Beth Shan

Bronze Age Hazor is not the only MB-LB site where basalt is the material used to make what appear to be cultic objects. Beth Shan also has a significant number of basalt cultic objects from excavations in the first half of this century (A. Rowe, 1930 and 1940). While it cannot be suggested where the precedent was set for basalt as a medium for Canaanite religious use, Beth Shan marks another locus to demonstrate more than an isolated use of basalt at Hazor. However, known sites synchronous with both Hazor and Megiddo as well as Beth Shan, e.g. Shechem, are not as close to basalt sources as Hazor, Beth Shan, and Megiddo (although Megiddo is less proximal than Beth Shan and Beth Shan is less proximal than Hazor; see Figure 7.1) and have less basalt use except as thresholds, grinding tools, door pivots and utilitarian contexts where basalt wear resistance recommends it in contrast to the Levant limestones.

Nonetheless, confirmed contact between Hazor and Beth Shan could strongly argue for likely cultural similarities in basalt use such as in religious contexts. Between the 1920's and 1940, A. Rowe had excavated four major temples at Beth Shan with strong Egyptian elements in the Canaanite city, ranging from the Late Bronze or Egyptian New Kingdom (15th c. B.C.) to the Early
Iron or Ramesside dynasts (12th c. B.C.), these temples and their stratigraphies have had their chronologies modified by Albright and Wright (Thompson, 1970:12).

The Bronze Age tell of Beth Shan (Tell el-Hosn), near modern Beisan, is at the juncture of the Jordan (Great Rift) Valley and Esdraelon-Jezreel Valley faults, making it both historically and geographically important as an ideal transport route nexus between the Mediterranean and distant Mesopotamian trade interests, doubtless well understood by Egyptian mercantile regimes to whom Beth Shan seemed in vassalage as a Canaanite city state. The local deity as described by Rowe was identified as "Mekal, lord of Beth Shan" from a stele found depicting an Egyptianized Ba'āl (A. Rowe, 1930:15; Thompson, 1970). Among other cultural influences noted at Beth Shan are North Syrian (Albright, 1929; Glueck, 1946), Cretan (Thompson, 1970:101, 114), and Hittite and Syro-Hittite (Garstang, 1929; Watzinger, 1933; Thompson, 1970:114). Evidences for Hittite influence are quite compelling in the opinion of this researcher and will be noted in detail near the conclusions of this chapter. There will also be discussions on potential criteria for basalt selection at the other primary sites mentioned in this chapter, and discussion on Levant basalt use in general.

Of the basalt geological sources closest to Beth Shan, the Neogene basalt of the Cover Basalt Formation, some 3-5 km north of Beisan (modern counterpart of Beth Shan) can be found around the Jabul-Nahal Yissakhar area. This Neogene basalt has been suggested as Upper Pliocene in age (Freund et al., 1965:38). This particular lava region near Beth Shan is also quite close
geographically to the Wadi Raml basalt. Without artefactual material to analyse, the provenance of basalt artefacts at Beth Shan can only be suggested by the closest possible geological source.

Table 7.3 below, compiled from Rowe (1940, pp. X, 12, 20, 34) and Thompson (1970, pp. 15, 22, 36, 42 and all of Chapter Four) shows the major cultic use of basalt at Beth Shan.

Table 7.3 BETH SHAN CULTIC OBJECTS OF BASALT

<table>
<thead>
<tr>
<th>Date</th>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Thutmose III level</td>
<td>(Rowe, 1930, p. 11)</td>
<td>a. mazzebah (stele)</td>
</tr>
<tr>
<td>Canaanite Temple</td>
<td>&quot; LXIX A, 4 **</td>
<td>b. figurine head *</td>
</tr>
<tr>
<td>(14th c. B.C.)</td>
<td>&quot; LXIX A, 11, 2</td>
<td>c. portable altar</td>
</tr>
<tr>
<td></td>
<td>&quot; LXIX A, 3</td>
<td>d. &quot;baetyl&quot; or cone</td>
</tr>
<tr>
<td>(Level IX)</td>
<td>(Thompson, 1970:22)</td>
<td>e. libation bowl</td>
</tr>
<tr>
<td>Mekal Temple</td>
<td>(Thompson, 1970:15 &amp; Ch. 4)</td>
<td>f. Lion-Dog Panel</td>
</tr>
<tr>
<td>2. Pre-Amenophis III</td>
<td>(Thompson, 1970:35)</td>
<td>a. altar</td>
</tr>
<tr>
<td>Canaanite Temple</td>
<td>(Thompson, 1970:36)</td>
<td>b. column base (4?)</td>
</tr>
<tr>
<td>(Early 13th c. B.C.)</td>
<td>(Rowe, 1930)</td>
<td></td>
</tr>
<tr>
<td>3. Amenophis III level</td>
<td>&quot; XIX 13, XLVIII A, 1-4</td>
<td>a. sacred chair or throne</td>
</tr>
<tr>
<td>Canaanite Temple</td>
<td>&quot; XXII, 6</td>
<td>b. incense stand</td>
</tr>
<tr>
<td>(14th c. B.C.)</td>
<td>&quot; XXII, 20</td>
<td>c. libation tank</td>
</tr>
<tr>
<td>4. Early Seti I level</td>
<td>&quot; XXVIII, 17</td>
<td>a. defaced stele *</td>
</tr>
<tr>
<td>Canaanite Temple</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(late 13th c. B.C.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Ramesses III level</td>
<td>&quot; XXVIII, 18</td>
<td>a. statue of king or prince *</td>
</tr>
<tr>
<td>Canaanite Temple</td>
<td>&quot; XXXV, 3 LXV A 1</td>
<td>b. stele fragment *</td>
</tr>
<tr>
<td>(Northern)</td>
<td></td>
<td>c. Antit sculpture</td>
</tr>
<tr>
<td>(12th c. B.C.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canaanite Temple</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Southern)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(11th c. B.C.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Level V)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* listed by Rowe as object found in temple, not necessarily cultic; all others listed as cultic objects by Rowe

** all Pl. in Roman Numerals, e.g. XXII are (Rowe, 1930)
While all of the above 16 basalt objects were found in temple contexts in Rowe's excavations, most of the cultic objects found were of ceramic material. However, where stone was used all cult objects were of basalt; the only exceptions being an alabaster figurine of the goddess Ashtoreth and a limestone sacred table (Rowe, 1940:12). Many articles for which basalt would be the most logical medium, including milling querns, weights, or doorsockets are also given by Rowe as basalt in various stone object lists.

Thompson, however, (1970:22) clarifies one purpose of an important basalt object (baetyl) which could have ramifications for many sites where "baetys" or small portable conical stones are found. "Baetyl" is given in quotes because it is so-called by Rowe and Thompson but not a universal name for the objects:

"The most significant item in No. 8, was a "baetyl" or small portable conical basalt stone about 10 inches high...It is, of course, emblematic of a Canaanite god, like the mazzabah."

Thompson provides a substantial documentation for this identity of "baetyl" cones as cultic deity emblems (Thompson, 1970:22, note 78). However, nearly all his sources are from Rowe's work at Beth Shan which may dilute the authority attached to this identity only because Thompson quotes from but one source (Rowe). For examples of what may be identified by some as "baetyl", see Plate 7.3. On the lower portion of this plate, two of these objects are from the Pre-Pottery Neolithic A (PPNA) at Jericho (the truncated cone on the left, JpD 405.7 3784 and the central cone JPE 503.21 2708 Type P), while the right-hand cone is from the Early Bronze period at Jericho (Plate 7.3).

In personal comments made to this researcher, P. Dorrell and D.R. Griffiths, Institute of Archaeology, London, suggest with due caution that some dual function may operate for these and
(Plate 7.3 [above]) "BAETYLS" or cones from Jericho, 4 out of 5 cones are Pre-Pottery Neolithic (PPN); especially the top 2 and bottom left and center. Only the bottom right cone is later, from the Early Bronze Age. All cones or "baetyls" (see Thompson, 1970: 22, note 78) are from the Kenyon Jericho Collection, Institute of Archaeology, London.
other such artefacts coming from sacral contexts.

Without establishing which uses are primary and which secondary, Dorrell and Griffiths note clear tool use but unknown ritual use possibilities for objects like "baetyl." In addition, both of the above identify clear tool use wear on some "baetyl"; with Dorrell adding that precedent for dual function can be found in Hazor's Shrine Stelae, serving dually as both mazzeboth and as saddle querns (Dorrell and Griffiths, personal comments, 1990). The PPNA objects are probably outside the focussed chronology of this query-discussion of basalt as a possible religious medium.

The options, then, for the significance of these objects are that a) grinding tools, especially what are called "baetyl", are merely grinding tools and no more, regardless of excavation context; b) grinding tools found in temples and cultic contexts could be interpreted as property of a deity and therefore qdsh i.e. set apart as "holy" utensils (numerous chronologically-comparable biblical texts give literary support of such practice: Exodus 28:36; 30:29; 39:30; Leviticus 27:28; and 1 Samuel 21:4-6; see also Ezra 8:28) c) such objects are primarily ritual or deity emblemata but were sometimes used as tools (perhaps in food preparation for deity or even temple personnel); and d) that such "baetyl" were strictly cultic objects and not tools at all. The first and last possibilities appear weakest: a) ignores the excavation context and the identification of Rowe and Thompson; d) ignores the clear tool use wear found on some objects such as Dorrell and Griffiths identified. Whatever the case, options b) and c) are fraught with ambiguity and vagueness which will be unlikely to be clarified any further.
This researcher has seen scores of small conical "baetys" in Levant archaeological collections and site report photographs, primarily from excavations in the first half of the 20th c. Most often they are subsumed under assumed grinding uses with mortars, pestles, querns and other basalt tools, but the question raised here is immediately apparent: how many "baetys" could be brought into consideration here as basalt cult objects, thus reinforcing a deliberate choice of basalt for a religious use? Discussion here must of necessity be limited to the overall pattern, but such a question has a bearing on the ultimate conclusions in this chapter if even half of the "baetyl" cones thus mentioned are in fact cult objects. This controversy will be taken up again in a later section of this chapter discussing overall basalt use.

Another suggestion of Rowe's is also noted as germane to this discussion. In an inner temple sanctuary were found small basalt weights for which Rowe raised the explanation of Exodus 30:13, 24 (and texts in Leviticus) as "sacred weights" or shekelim. These texts do support a "shekel of the sanctuary" (Rowe, 1930:14). Basalt would be especially important here if it is highly prized as a sacred medium. Novel as such ideas appear, there is no doubt that these Beth Shan objects were found in a sanctuary context, which correlates with basalt use in Hazor sacred contexts. This idea will also be continued in later discussions of this chapter.

7.4 Basalt at Megiddo

Megiddo controlled one of the most strategic passes in the Mt. Carmel area through which travellers, merchants and invaders must have journeyed from Egypt and Mesopotamia in antiquity. At the western end of the Esdraelon valley, control of the Megiddo
site is as vital to any imperial interest in the Levant as is control of the Hazor site in the north (controlling the Jordan-Great Rift valley) and Beth Shan at the east end of the Esdraelon-Jezreel valley (with Jordan Valley access) (see Figure 7.1).

Levels XV through Va of Bronze Age Megiddo (circa 16th-12th c. B.C.) in particular as excavated by Loud and the Oriental Institute of the University of Chicago between 1935-39 have yielded a significant number of basalt artefacts (Loud, 1948).

Parallel with Hazor and Beth Shan in evidences of basalt cult object use, Megiddo also shows a significant quantity of basalt objects in sacral contexts, as seen below in Table 7.4 compiled by this researcher from Megiddo I & II site reports (Loud, 1948).

Table 7.4 MEGIDDO CULTIC OBJECTS OF BASALT

<table>
<thead>
<tr>
<th>Stratigraphy and Date</th>
<th>Context</th>
<th>Loud's Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Level XV</td>
<td>Temple 4040 (MB II- LB I ?) (nr Altar 4017)</td>
<td>Pl. 290, £2 d 772</td>
<td>a. phallus *</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Level VII</td>
<td>Temple 2048 (LB II ?)</td>
<td>Page 105 (cf. Fig. 254)</td>
<td>a. 6 squared blocks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pl. 267, £5 a 132</td>
<td>b. 1 circular (within temple)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>c. statuette</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pl. 267, £7 a 543</td>
<td>d. statuette 2085 **</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pl. 262, £15 a 1170</td>
<td>e. mortar? [on stand]</td>
</tr>
<tr>
<td>3. Level Va</td>
<td>Cultic Room 2081 (LB III - Early Iron I)</td>
<td>Page 44, Fig. 101-2 *** Page 161</td>
<td>a. 4 legged</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pl. 263, £22 a 732</td>
<td>b. vessel ornamental vessel</td>
</tr>
<tr>
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</tr>
<tr>
<td></td>
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<td>Pl. 263, £23 a763</td>
<td></td>
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</tbody>
</table>

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Notes to Table 7.4:

* Loud's description tentative; ** Context 2085 = favissa or he marked these with (?) well associated w/Temple 2048

*** All items in Context 2081 appear cultic according to Loud, 1948:44 (with Fig. 101-2) and footnote, p. 161 of Megiddo II Text

These 8 basalt items from Megiddo are all clearly associated with sacral contexts, either being found directly within temple precincts or cultic storage loci. As such, the lower quantity of basalt artefacts at Megiddo when compared to Hazor and Beth Shan, must be noted (not counting "baetyl" with their ambiguous cultic identity and potential problems in being able to authenticate any such small cone as a "baetyl"; note numerous small ceramic cone "baetyle" at Megiddo; Pl. 288 of Loud, 1948, found among cult objects from context 2081, cf. Fig. 101). Again this small number of basalt objects does not include the usual mortars, querns, and grinding tools. It is also notable, however, that the limestone which is a plentiful source material all around Megiddo is poorly represented in cult objects. Ceramic artefacts were far more plentiful than limestone artefacts in association with sacral centres at Megiddo.

The geological basalt source closest to Megiddo would be found at the foot of Mount Tabor, approximately 23-26 km eastward (often visible from Megiddo on a clear day). Some debate exists as to whether this flow, overlain by Neogene sediments, is from a Pre-Cover Basalt (Freund et al.,1965:42), or from Intermediate volcanics as suggested by Freund individually (ibid.), or from the Lower Basalt Formation as suggested by Shulman (ibid.). Again without artefactual material to analyse, any suggestion of the provenance of Megiddo basalt objects can only be a guess,
with a bias towards the closest geological source.

It is worthy of note that if Mount Tabor were indeed a source for Megiddo basalt cult objects, the suggestion of the concept of a "sacred mountain = sacred stone = sacred use" context might be raised (i.e. cult object in a temple, etc.). This possibility formed part of an address by this researcher on potential stone selection criteria of the Canaanites for whom Ba'ālism was their primary religion, particularly as sacred mounts are part of this religion (Hunt, 1990b; also see Oldenburg, 1969, Kapelrud, 1952).

Also worthy of note is the fact that most of the basalt cult objects at Megiddo seem to have Late Bronze contexts, paralleling the same phenomena at Hazor and Beth Shan. This offers some evidence of a possible common regard for basalt among Canaanite city-states who are contemporaries of each other. This will be elaborated in a section near the end of this chapter.

7.5 Petrological Analyses

Petrological analyses of basalts in this chapter include petrographic, the optical examination of minerals and their textures by polarized transmitted light microscopy, and chemical analyses using scanning electron microscope (SEM) with energy-dispersive X-ray spectroscopy (EDS), SEM with EDS especially for semiquantitative elemental analyses. These analyses were conducted between 1987 to 1990 at the Institute of Archaeology, London, and the Petrography Laboratory, Igneous and Geothermal Processes, U.S. Geological Survey, Menlo Park, California, and the Mineralogy Dept., British Museum of Natural History, London.

Having lived in Israel in the winter of 1984-85, this researcher conducted field survey of the geology of Israel,
Galilee and Golan regions in particular. Also, site surveys of Hazor, Beth Shan, Megiddo, Jericho and many other sites were done for analysis of basalt objects in situ wherever possible. Additional analyses of the geology collection of the Mineralogy Dept., British Museum of Natural were conducted in 1988, 1989, and again in 1990. Nonetheless, it remains to be seen what specific determinations of provenance can be made for Hazor, Beth Shan, Megiddo, and Jericho archaeological basalts. No determination of provenance can be attempted for material from Beth Shan and Megiddo in particular because no archaeological materials could be obtained from these sites, although as already mentioned, a local South Galilee source in nearby Cover Basalt Formation flows around Qarne Hittim/Wadi Raml areas would be most likely for Beth Shan, and Pre-Cover or Lower Basalt Formation flows from around Mt. Tabor in eastern Galilee would be most likely for Megiddo. Provenance of Jericho archaeological material is difficult to assess not because of insufficient archaeological material but because natural transport by river could bring river cobbles downstream to Jericho from many possible basalt sources including the two just mentioned for Beth Shan and Megiddo as well as perhaps at least 35 other sources within the Jericho River watershed a minimum of 70 km to the north. Some provenance suggestions for Hazor will follow the petrographic and chemical analyses of archaeological and geological material.

7.5.1 Petrography

a) Hazor Archaeological Basalt

The archaeological material from Hazor analysed to date is
a fine-grained olivine basalt. Analysis of constituent minerals and their textures by transmitted polarized light shows olivine as the sole phenocryst in a microcrystalline groundmass. The anhedral and subhedral olivine phenocrysts make up approximately 19% of the total volume, averaging 1 mm in diameter for the former and 2 mm in length for the latter. The outer (0.1-0.3 mm) rims of each olivine phenocryst is altered to iddingsite. Microcrysts of olivine, which comprise 9% of the total volume, and are 0.2-0.4 mm across have completely altered to iddingsite. Plagioclase feldspar is the only other mineral and is present as microcrysts with lath length of around 0.2 mm with a 40% total volume. The cryptocrystalline groundmass appears to consist of wholly iddingsitized olivine, with possible feldspar, and opaque minerals which cannot be identified. The total groundmass volume is estimated at 79%. Vesicles make up approximately 2% of the remaining total volume. The low volume of plagioclase feldspar as a phenocryst is distinctive in contrast to all the other regional Levant basalts analysed. No flow textures are visible in the petrographic thin sections (Plate 7.4).

Although Hazor archaeological basalt material exists in great quantity, it is very limited in the samples available for analysis, thus the 6 samples thin-sectioned which are essentially from the same source as determined by petrographic analysis, may not be representative of all the archaeological basalt at Hazor. No geological source has yet been identified for the archaeological material analysed, which is dissimilar to local geological basalts identified near Hazor, Aswad, Alma, Dalton, and Chorazim (Figure 7.1) These other local basalts are "petrographically similar [to the] Qarne Hittim basalts" (Freund 220
et al., 1965: 38,40, and especially 42), whose petrographic analysis will follow. Hazor, Aswad, Alma, and Dalton basalts are designated as being either of the Cover Basalt formation or of the Qarne Hittim Complex basalt formation, dating respectively to the Upper Pliocene-Lower Pleistocene and to post Middle Eocene to Pre-Miocene periods (Freund et al., 1965:41). Not as local as the above flows, i.e. at a distance of approximately 40-50 km, Golan (Hauran) basalts assigned to the Meso-Pleistocene Cover Basalt Formation (Schulman, 1967:104) have also been examined and so far found to be petrographically and chemically dissimilar to the Hazor archaeological basalt analysed in this research.

b) Jericho Archaeological Basalts

Samples of Jericho archaeological basalts derive from the collection of the Institute of Archaeology, London. In particular the 1952-58 excavations and reports of Kathleen Kenyon and Peter Dorrell (and the collection under his care) are sources for this material (Kenyon, 1960, 1965, 1981, 1983; Dorrell, 1983).

Most of the Jericho artefact material examined and analysed is from the Pre-Pottery Neolithic (PPN) period. Its relevance to the discussions regarding Bronze Age cultic use of basalt is not to be assumed as primary. Rather, Jericho is included here for the following reasons: a) as indicative of distribution of basalt for tool use in a naturally-derived (riverine cobbles in the Jordan valley) locus; b) use of basalt at Jericho is early in the time continuum (Pre-Pottery Neolithic or assumed circa 8th millennium B.C.); c) weathering profiles at Jericho may be useful in establishing relative basalt weathering dating (tied to the preceding point and elaborated in Ch. 8); and d) it has been
(Plate 7.4 [above]) HAZOR ARCHAEOLOGICAL MATERIAL petrographic texture w/ iddingsitized olivine and pyroxene, microcrystalline feldspar and groundmass; (Plate 7.5 [below]) JERICHO 2025 olivine phenocrysts with massively ingrown plagioclase feldspars.

Scale (of both photographs): 0.4 mm = 222
Jericho archaeological basalts (presumably of many different formations and lava flow deposits washed down as river cobbles or wadi pebbles) do not appear to originate from one homogenous geological unit. However, all material (archaeological and geological) analysed by this researcher is olivine basalt, some porphyritic and highly vesicular and some extremely fine-grained. Two samples at either end of this spectrum are seen in Jericho 2025 and Jericho 2509. The artefact numbers are from Kenyon’s Jericho excavations (see Dorrell, 1983) from the Pre-Pottery Neolithic period (PPNA). Jericho 2025 is a PPNA grooved stone and Jericho 2509 is a PPNA cone-shaped ("baetyl?") long pestle. The archaeological sample material itself consists of only two samples of the many Jericho basalt objects. This low number of samples thin-sectioned, however, is to be expected due to wide range of potential Jericho material from a potentially high number of sources. Furthermore, considering the reduction of the Jericho archaeological collection, particularly the PPN material, to be non-constructive for future research, thin sections were kept to a minimum. Therefore, as basalt objects from this collection were examined, these two seemed most representative of the range of basalts used at Jericho. 2 Thin sections were made from each basalt or basaltic andesite object.

Jericho 2025

Jericho 2025 could be considered porphyritic olivine basalt but is more likely to be basaltic andesite. Petrographic analysis
shows the primary phenocryst to be euhedral olivine with minor alteration to iddingsite along the olivine fractures. These phenocrysts are estimated to constitute approximately 10% of the total volume, ranging from 0.8-1.5 mm in length. There is also a tendency for some olivines to be in glomerocryst form with iddingsite along the fractures of the olivine. The secondary phenocrysts are of olivine but massively intergrown with the groundmass plagioclase feldspar. This olivine shows no iddingsite alteration, makes up approximately 10% also of the total volume, and ranges in size from an anhedral 1.0-1.7 mm in diameter. Pyroxene makes up the third type of phenocryst, also massively intergrown with plagioclase and even some iddingsitized olivine microcryst inclusions. The mostly anhedral pyroxene comprises about 5% of the total volume and ranges from 0.7-1.8 mm in diameter. Microcrysts of iddingsitized olivine and some pyroxene, also comprise roughly 3.5% and 1.5% respectively of total volume. The groundmass is comprised of acicular plagioclase feldspar phenocrysts with normal twinning, making up about 60% of the total volume and ranging in size from 0.4-1.1 mm in length. A distinctive feature of this material is a high volume of vesicles at 10% of the total volume (high in comparison with other Levant olivine basalts studied, usually below 3%). No apparent flow structure is apparent in this material. This material appears basaltic andesite in range (Le Maitre, 1989:28,50), as could also be deduced from its chemical analysis which follows the petrographic discussions (Plate 7.5).

Jericho 2509

Jericho 2509 is a fine-grained olivine-pyroxene basalt.
Petrographic analysis shows the two types of primary phenocrysts to be clinopyroxene and olivine. The pyroxene is euhedral, often zoned, ranging in size from 0.2 - 1.4 mm and making up 11% of the total volume, with some clinopyroxene occurring in glomerocrystic masses. The olivine phenocrysts are mostly euhedral with no iddingsite alteration, ranging from 0.3 - 0.4 mm in length and making up 9% of the total volume. The secondary (or tertiary) phenocryst is also pyroxene, probably orthopyroxene and ranging in size from 0.2 - 1.2 mm and making up 8% of the total volume. The groundmass is dark, probably glassy, with many tiny extremely acicular (needle-like) plagioclase feldspars ranging in size from an almost microcrystalline 0.1-0.2 mm (although very few may extend up to 0.4 mm in acicular length). The cryptocrystalline or glassy phase makes up about 10% of the groundmass volume. Many small microcrysts, anhedral olivine and pyroxene, are seen throughout the groundmass, in size usually less than 0.1 mm and comprise about 4% and 3% of the total volume respectively. Vesicles are almost wholly absent in this material and constitute less than 1% of the total volume. No flow structure is present in this material (Plate 7.6).

c) Qarne Hittim Basalt

The Qarne Hittim volcanic area is approximately 15 km southwest of the Sea of Galilee, one third the distance between the Sea of Galilee and Beth Shan. Its flow covers an area roughly 10 sq. km across in eastern Galilee (Figure 7.1).

The Qarne Hittim material is either a porphyritic olivine basalt or marginally considered as a basaltic andesite.
Textural analysis shows the primary phenocryst to be olivine, partly altered to iddingsite (especially along the cracks), and the secondary phenocryst is glomeroporphyritic augite. The large subhedral phenocrysts of olivine occur from 0.8 - 2 mm in size at approximately 12% of total volume. The euhedral phenocrysts of augite occur from 0.7 - 0.9 mm in size at approximately 5% of the total volume. The groundmass is mostly filled with plagioclase feldspar of an acicular texture, the needles being approximately 0.7-1.0 mm in length and constituting approximately 80% of total volume. Vesicles make up approximately 3% of the total volume. Microcrysts of pyroxene appear in idiomorphic (euhedral) prisms. The alignment of plagioclase acicles (or acicular laths) shows flow texture. Qarne Hittim basalt/basaltic andesite is attributed to Cover Basalt Formation, dating to the Upper Pliocene to Lower Pleistocene; or to the Qarne Hittim Complex, dating to post Middle Eocene to Pre-Miocene (Freund et al., 1965:41). 6 samples of Qarne Hittim material were examined; 2 thin sections were prepared from each sample for petrographic analysis (Plate 7.7).

d) The Wadi Raml Basalt

The Wadi Raml Basalt area is approximately 25 km south-west of the Sea of Galilee, midway between the southern end of the Sea of Galilee and Beth Shan. It also borders on the Qarne Hittim complex which is just to the north of it. Some of the watershed of Mt. Tabor drains into the Wadi Raml itself. Its flows cover less than half the area of the Qarne Hittim Basalt Complex on its northern edge (Figure 7.1).

The Wadi Raml basalt is a fine-grained olivine basalt. Textural analysis shows the primary phenocryst to be olivine,
(Plate 7.6 [above] JERICHO 2509 archaeological material petrographic texture w/ sector-zoned clinopyroxene and olivine phenocrysts in groundmass; (Plate 7.7 [below] QARNE HITTIM geological material petrographic texture w/ iddingsitized olivine, acicular plagioclase feldspar phenocrysts.

Scale (of both photographs): 0.4 mm = 227
partly altered to iddingsite and partly serpentinised, and the secondary phenocryst is titanomagnetite. The subhedral olivine phenocrysts range in length from 0.3–0.8 mm and constitute approximately 18% of the total volume and the augite phenocrysts occur from 0.2 – 0.5 mm in diameter at 4% of the volume. The groundmass, like Qarne Hittim’s, is filled with long laths of plagioclase feldspar (but not as acicular as Qarne Hittim) with a range from 0.2–0.4 mm in length and constituting approximately 77% of the total volume. Vesicles make up less 1% or less of the total volume. Microcrysts of augite and possibly iron oxides also occur as accessories between the feldspars along with some devitrified glass. The plagioclase laths show strong flow texture (Plate 7.8).

Wadi Rami basalt is attributed (Freund et al., 1965:41) to the Lower Basalt Formation with a Miocene date or to the Qarne Hittim Complex Formation with a post Middle Eocene to Pre-Miocene date. 8 samples were examined, with a total of 3 representative thin section preparations analysed.

e) Tiberias-Poriyya Basalt

The Tiberias-Poriyya basalt area is just west and along the plateau above the southern edge of the city of Tiberias, which is adjacent to the Sea of Galilee. Its thin flows cover an area of 3–4 sq. km marked by the Tiberias-Poriyya cliffs (Figure 7.1).

The Tiberias basalt is a heavily iddingsitized olivine basalt, with nearly all olivine altered to iddingsite. Textural analysis shows the iddingsitized (with primary and secondary rims) olivine to occur in euhedral grains of 0.15–1.5 mm in diameter which constitute approximately 10% of the total volume. Secondary
phenocrysts of augite range from 0.12-0.4 mm in diameter which constitute approximately 3% of the total volume. Many augite phenocrysts are arranged in glomerocrysts (phenocryst clusters). The groundmass is primarily filled with plagioclase laths, mostly around 0.4 mm in length at around 67% of the total volume. Olivine microcrystals and some opaque grains, most likely iron oxide or titanomagnetite, are also found in the groundmass. Vesicles make up approximately 2% of the total volume and there is some well-developed flow texture in the plagioclase alignment.

The relative geological age of this material is most likely to be Lower Miocene from the Lower Basalt Formation (Freund et al. 1965:41,43) associated with the Tiberias-Poriyya cliffs. Four samples were examined and determined to be representative; 3 thin sections preparations examined for petrographic analysis (Plate 7.9).

In summary, distinctive petrographic textures can be observed which are capable of distinguishing between all the materials analysed so far. Due to the preliminary nature of the sampling as being only partially representative because of a low number of samples for such a large volcanic region, the findings are to be seen as tentative and limited only to the materials discussed here.

7.5.2 Comparison of Petrographic Textures

For purposes of textural and mineral comparison of these basalts (and basaltic andesites), mineral components and volumes are discussed below in Table 7.5. The three archaeological materials (from Hazor, Jericho 2025, Jericho 2509) were compared
(Plate 7.8 [above]) WADI RAML geological material petrographic texture w/euhedral-subhedral iddingsitized olivine and zoned pyroxene and feldspar in groundmass; (Plate 7.9 [below]) TIBERIAS PORIYYA geological material petrographic texture w/pyroxene and completely-iddingsitized olivines, plagioclase, and groundmass.

Scale (of both photographs): 0.4 mm = 230
to each other and to the geological materials (from Qarne Hittim, Wadi Raml and Tiberias-Poriyya). No petrographic matches were found between any of the materials to recommend determination of provenance. While these materials exhibit similar mineral grouping (olivine, plagioclase, pyroxene), they also exhibit an overall heterogeneity of texture, which, while discouraging any immediate determination of provenance, encourages textural analysis for discrimination of different geological sources.

Table 7.5 MINERAL AND TEXTURAL COMPARISONS OF LEVANT MATERIAL

|        | A    | B    | C    | D    | E    | F    |
|--------|--|--|--|--|--|--|--|
|        | Hazor | Jericho | Qarne Hittim | Wadi Raml | Tiberias |
| Archaeological Basalt (HA) | Basalts (JA) | Basalts (QH) | Basalts (WR) | Basalts (T) |
| Ground-mass | (79%) | (65%) | (72%) | (80%) | (77%) | (85%) |
| a. plagioclase | 40% | 60% | 55% | 58% | 55% | 67% |
| feldspar | (crypto) | (phenocryst) | (crypto) | (phenocryst) | (phenocryst) | (phenocryst) |
| b. olivine | 9% | 2.5% | 4% | 22% | 18% | 10% |
| c. pyroxene | -- | 2.5% | 3% | -- | 2% * | 6% |
| microcryst | -- | -- | -- | -- | -- | -- |
| d. opaques | -- | -- | -- | -- | 2% ** | 2% |
| e. other | 30% @ | -- | 10% £ | -- | -- | -- |
| (crypto) | | | | | | |
| Vesicles | 2% | 10% | < 1% | 3% | 1% | 2% |
| Phenocrysts | (19%) | (25%) | (24%) | (17%) | (22%) | (13%) |
| a. olivine | 19% | 10% | 9% | 12% | 18% | 10% |
| b. augite | -- | 5% | 11% | 5% | 4% * | 3% |
| c. other | -- | -- | 8% | -- | -- | -- |
| pyroxene | 10% (olivine intergrowths) | -- | -- | | | |

As already stated, the primary petrographic contrast between the HA material and the QH & WR material is the lower volume of

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plagioclase and absence of phenocrysts in HA other than olivine. Additionally, WR & HA materials are much finer-grained than QH material but WR material is essentially the same as QH material in other visible respects, i.e. major phenocrysts and groundmass (although both JA 2025 especially and QH possibly could be called basaltic andesite based on other parameters (Le Maitre, 1989:50). As such, QH and WR basalts are representative of the "Korazim-Golan Cover Basalt - a formation uninterruptedly exposed from Beth Shan [south] to the Hermon [north], of uniform character and similar structural history" (Schulman, 1967:104). JA 2025 appears to be olivine basaltic andesite and also appears to be young material (based on its low level of alteration of olivine to iddingsite. Its distance (minimum of 70 km) from any volcanic deposit, the nearest logical riverine source being just north of Beth Shan in the Jordan River valley watershed, makes it difficult to attempt determination of provenance. The distinctive characterisics of JA 2025 lie in high vesiculatry, intergrowths of plagioclase in both olivine and clinopyroxene phenocrysts, and low level of iddinsitized olivine compared to the other materials. Based on visual (textural) appearances, some similarity exists between QH-WR basalts and JA 2025. On this tenuous link it might be suggested that JA 2025 could derive from a yet-unsampled flow in this general area to the southwest of Lake Tiberias (Fig. 7.1), although any such link requires confirmation by future research. JA 2509 distinctions are found in the 2 pyroxene phenocrysts with clinopyroxene in a slightly higher abundance than olivine, larger clinopyroxene phenocrysts than olivine phenocrysts, and with an absence of iddinsite alteration in the olivine (suggesting fresh or young basalt).
It is natural to expect that archaeological basalts found at Jericho should reflect a wide range of geological deposits washed down the Jordan valley (except in the cases of saddle querns which due to size required human transport).

It is possible that many petrographic distinctions exist for each separate source with little variation in the chemical data as determined by EDS microprobe analysis (without trace element data). Nonetheless, given other research wherein minimal variation in major element composition was seen even with WDXRF (wavelength dispersive X-Ray Fluorescence) in discriminant analyses of many Levant olivine basalts (Elliott et al., 1986; Xenophontos et al., 1988; Williams-Thorpe et al., unpublished Open University paper, 1990b, and Williams-Thorpe, pers. comm., 1990), it seems wise to make the most of the petrographic data. In this case with extensive lava flows of a uniform chemistry, petrography may ultimately be a more thorough provenance method than microprobe or XRF analysis because it possesses capability for textural discrimination and interpretation.

7.5.3 Chemical Analysis

Chemical analyses were carried out by scanning electron microscope (SEM) with energy-dispersive X-ray spectroscopy (EDS) spectroscopy on a Hitachi S-570 microscope with Link System 10-25 S X-Ray analyser. Analyses were conducted solely on the plagioclase feldspars in the groundmass, although mafic minerals in microcrysts and between feldspars would also be included in chemical analyses. Because plagioclase feldspar is the one common mineral in all the basalts and andesites of the present study,
including this chapter, it was deemed most important for the
analysis to focus on the plagioclase feldspars in phenocryst or
microcryst textures of the various groundmasses of the Levant
basalt and andesite materials, also consistent with the other
chemical analyses conducted and presented in the previous chapter
discussions (Chapters 5 and 6) using SEM with EDS analysis. The
previous discussions in these chapters present the parameters of
analysis in more detail. Table 7.6 below presents results of
these analyses in averages.

Table 7.6 CHEMICAL AVERAGES OF LEVANT (JORDAN-RIFT VALLEY)
BASALTS AND ANDESITES

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<td>11.54</td>
<td>10.25</td>
<td>12.67</td>
<td>11.28</td>
<td>11.59</td>
<td></td>
</tr>
<tr>
<td>Fe2O3</td>
<td>15.60</td>
<td>12.99</td>
<td>8.74</td>
<td>14.65</td>
<td>14.30</td>
<td></td>
</tr>
<tr>
<td>MnO</td>
<td>0.41</td>
<td>0.41</td>
<td>0.28</td>
<td>0.30</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>TiO2</td>
<td>3.08</td>
<td>2.49</td>
<td>1.18</td>
<td>2.62</td>
<td>2.56</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>0.95</td>
<td>0.00</td>
<td>1.12</td>
<td>0.10</td>
<td>0.02</td>
<td></td>
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<tr>
<td>Cl</td>
<td>0.16</td>
<td>0.38</td>
<td>0.47</td>
<td>0.14</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

This stoichometric normalised chemical analysis is by SEM with a
Link System 10-25 S EDS @ 20 kV, with a cobalt standard as
reference. Livetime was 100 seconds, elevation 31.46 , and the
area of analysis was that within the field of vision of the SEM
CRT @ 35 X.
1) Hazor Archaeological Material (HA): 6 samples, 15 analyses; SiO wt % range between 44.4 to 45.3; averaged at 44.8.
2) Jericho 2025 Archaeol. Material (JA): 2 samples; 12 analyses; SiO wt % range between 53.2 to 54.8; averaged at 53.7.
3) Jericho 2509 Archaeol. Material (JA): 2 samples; 10 analyses; SiO wt % range between 48.7 to 49.9; averaged at 49.5.
4) Qarne Hittim Geological Material (QH): 6 samples; 18 analyses; SiO wt % range between 50.1 to 51.3; averaged at 50.4.
5) Wadi Rami Geological Material (WR): 8 samples; 15 analyses; SiO wt % range between 46.2 to 47.3; averaged at 46.9.
6) Tiberias-Poriyya Geol. Material (T-P): 4 samples; 14 analyses; SiO wt % range between 48.1 to 48.7; averaged at 48.3.

+ Jericho 2025 is in the basaltic andesite range (Le Maitre, 1989:28); Qarne Hitttim is marginal for basaltic andesite.

As can be seen, chemical analysis corroborates the distinct nature of the Hazor archaeological material (HA) in having a low SiO content. As could be expected, the low feldspar content as observed petrographically matches the 44.8% SiO chemical average (compared to the other 5 materials with abundant feldspar and higher SiO averages). However, this difference is contrasted by similarity between HA/WR/T-P analyses for Ca:Fe ratios. Here HA/WR/T-P have similar ratios of roughly 1:1.5 where QH material shows the opposite 1.5:1 for Ca:Fe. Also, the overall chemical similarity between HA and WR/T-P might suggest a common general source except for the striking petrographic contrasts. Otherwise all these basalts fall well within the alkali olivine basalt range (Mackenzie et al., 1982:87) with relative SiO content between 44-50% (except for JA 2025 and possibly QH which should be basaltic andesite with 53.5 wt % SiO content and 50.4 wt % SiO respectively) (Le Maitre, 1989:28, 50). With these distinctions noted, the materials analysed are quite similar in most respects, which suggests that the chemical analyses as
conducted here without trace element data will probably be insufficient for accurate determination of provenance, although even with trace element data the problem will remain due to, among other factors, both the high volume of lava flows along Great Rift plate boundaries between Europe, Asia, and Africa, and in this area, the chemical similarity between flows.

This view of the limited value of analyses between major and minor elements in provenance studies of this region is reinforced by other researchers as well. As already mentioned in this chapter, Shulman (1967:104) and Thorpe and Williams-Thorpe suggest a uniformity of material in terms of chemical composition over a wide geological region which could take in the whole Cover Basalt Formation from the Golan-Hauran area in the north to the central Jordan valley in the south (Williams-Thorpe et al., 1990b; and Williams-Thorpe, pers. comm., 1990). This is to be expected for such a broad volcanic area covering over 500 sq. km in Israel, Jordan, and Syria where either the flows are related as both being from the same magma chamber and time of eruption or even if from the same magma chamber in related times if not too much magma mixing has occurred (Clynne, 1990, pers. comm.).

Discriminant analyses as plotted by Williams-Thorpe et al., using TiO, FeO, KO, AlO, and Zr:Nb ratios, provide evidence that determination of provenance in the Levant "remains extremely difficult because of the factors of extent and complexity...it covers a very large geographical area and includes flows of similar chemical type" (Williams-Thorpe et al., 1990b:11). The research conducted towards this thesis is in full agreement with William-Thorpe's finding. Provenance analyses in the Levant are
complex problems even with instrumental methods proven successful in other contexts.

7.6 Possible Criteria of Basalt Use in Neolithic and Canaanite Cultures in the Levant

This research on Jordan-Rift Valley basalts found no match of any of the many petrographic textures examined, and a general uniformity of chemical composition throughout. Only two limited avenues of future provenance enquiry are briefly suggested in the chapter conclusions, specifically a possible relationship between Mt. Tabor and Megiddo and a possible relationship between Mt. Hermon and Hazor. As will be seen in the following sections these are based more on theoretical cultural grounds than any firm analytical evidence. Should these prove to be convincing, it might be suggested that future studies of provenance should be familiar with the cultural side of the issue as well as with the necessary scientific approaches in determination of provenance.

On the other hand, in terms of correlations between stone technology of the Late Bronze Age sites discussed here, are there potential criteria of stone selection (as also discussed in Inca and Olmec contexts in Chapters 5 and 6)? Do observable factors of availability, workability, aesthetics, durability, and possible metaphysical perceptions influence stone selection in whatever necessary combinations?

Several questions must be asked, and answered where possible, before any suggested conclusions can be reached regarding the use of basalt in these selected Levant contexts. Furthermore, it must be acknowledged that any such suggestions are limited to the sites chosen. If these suggestions are applicable to other sites,
then the hypotheses must be evidenced there as well.

The first question to be asked is how representative of the total picture in the Middle to Late Bronze Age Levant are the sites and contexts discussed here? Have enough sites been examined chronologically and geographically for any such general suggestions to be useful? One immediate response to this is that these selected sites (which were mostly-continuous demographic units in excess of 300 dunams or houses) existed as important nexus points along the major trade routes throughout the Early to Late Bronze Ages (unlike the majority of Levant sites). This fact of continuity should then reflect patterns general to all Bronze Age sites in the Levant. Furthermore, contacts between these sites can be suggested both by external epigraphic evidence and obvious transport patterns between Egypt and Mesopotamia (Thompson, 1970:8-9).

A second question to be asked in correlating basalt material from Late Bronze periods and including sanctuary contexts at Hazor, Beth Shan and Megiddo is whether such basalt use is merely a matter of convenience and availability at these (and other) sites or something more. Availability at all three sites can be seen as practical, convenient, or even somewhat necessary considering the proximity of basalt sources as within 3-5 km at Hazor and Beth Shan and 25 km at Megiddo. This could also be extended to Jericho, which is noted already as being close to riverine basalt cobbles in the Jordan watershed if not close to basalt sources (70 km distant).

A third question to be asked is how closely is the distribution of basalt objects related to geological sources? If
ceramic or limestone objects dominate the further removed a site is from available basalt sources, or conversely if the number of basalt cult objects diminishes the more distant a site is from any basalt sources known in antiquity (assuming early awareness of even some stone identities), then limitations must be placed on any conclusions about sacral basalt choice exercised by these Canaanite city-state cultures. This question is suggested by the second question, with partial answers already provided above. This factor of diminishing basalt use with increased distance is true as it regards other known cultic loci of a comparable Middle to Late Bronze chronology and size: mazzeboth at Gezer and Shechem are of limestone; the other types of rock used to make other cult objects including altars, sculpture, incense stands, etc., are not recorded (MacAlister, 1912; and Wright, 1965, respectively). However, for grinding tools at these two Bronze Age sites (Gezer and Shechem, also see Figure 7.1) basalt is used extensively, suggesting that distance from the closest basalt sources at Gezer (approx. 70 km) and Shechem (approx. 55 km) does not greatly affect stone choice here. Where basalt is regarded at Hazor, Beth Shan, and Megiddo as appropriate for cultic purposes as well as grinding purposes, the data from Gezer and Shechem and other known sites to date supports the observation that basalt appears ideal mostly for grinding purposes.

A fourth fundamental question to be asked is statistical in nature: of all the known basalt artefacts in the Levant, what percentage in a) the three sites mentioned and b) in other sites can be evidenced as other than sacral, i.e., grinding or other use? This is very difficult to answer because any archaeological record is always fragmentary for all known sites and cannot be
considered complete until all possible sites have been discovered and subsequently excavated, inventoried, published, etc.

Based on inventories at the three above sites and including MB-LB Jericho, basalt makes up approximately 18% at the low end (Jericho) and 77% at the high end (Beth Shan) of the stone "tool" category where stone type is named (usually greater than 70% of the time). This contrasts with cultic objects (where a great majority at Beth Shan and Megiddo are ceramic, not stone) where basalt makes up approximately 44% at the low end (Megiddo) and 81% at the high end (Hazor). Other sites outside these four have not been examined in detail except as noted. Table 7.7 below presents basalt use in these categories as single ratios.

Table 7.7  PERCENTAGES OF BRONZE AGE BASALT CULT OBJECT USE TO OTHER * BRONZE AGE BASALT USE

<table>
<thead>
<tr>
<th>Site</th>
<th>Cultic</th>
<th>:</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Hazor **</td>
<td>81% (54 of 67) : 73% (252 of 347)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Beth Shan</td>
<td>59% (16 of 27) : 77% (40 of 52)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Megiddo</td>
<td>44% (8 of 18) : 32% (45 of 140)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Jericho</td>
<td>N.A. : 18% (38 of 169)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. All other sites</td>
<td>N.A. : 15-25% ***</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* mostly grinding tool, architectural use not included;
** Hazor, Beth Shan, Megiddo, and Jericho counts based on excavation reports already cited in this chapter; approximate because based on overlapping site reports.
*** based on observed estimates rather than actual counts at Gezer, Shechem, Gibeon, Tell Dor, Beersheba, and other sites. Sources include these sites'excavation reports and related volumes.

This table is compiled from excavation reports as well as observation from the fieldwork of this researcher. It is to be noted that other materials in the cultic category should include
cultural, limestone, bronze, etc., (and likely in that order: a low percentage of cultic objects appear to be made from bronze or metal, estimated at never greater than 5% based on sites examined or researched for inclusion in the present study).

At Beth Shan, for example, the actual volume of basalt cult objects is compared to other stone (limestone, alabaster, etc.) rather than ceramic cult objects (a total volume of 155). One observation or interpretation suggests that the more northern the context, the higher the basalt use, roughly corresponding to the proximity to more northern basalt sources. While potential sources of basalt are equally proximal to both Hazor and Beth Shan, potential limestone sources are plentiful south, east, and west of Beth Shan whereas both limestone and basalt can be found in all directions at Hazor (and Megiddo’s sources of basalt are to be found mostly east). Nonetheless, the overwhelming use of basalt in cultic contexts at Hazor is still difficult to interpret solely in terms of availability of basalt.

Also, for Beth Shan and Megiddo, it is again emphasized that for cultic objects made from stone (not counting ceramic objects) including basalt, limestone, sandstone, quartzite, alabaster, and others, the percentage of basalt cultic objects is 20-25% higher than the combined percentage of all other stone types. It is not known if this same percentage compares to non-cultic objects. If the same basic percentage difference could be observed in non-cultic objects, it would be more likely to suggest primarily availability and convenience rather than workability, aesthetic appreciation, philosophical preferences, or some other criterion of stone selection.
It must be noted that any percentage totals of basalt use are fraught with qualifications, not the least of which should be a sacral context for even obvious grinding tools. Would this make it qdš or "holy" and therefore sacral? Furthermore what is to be done with all the cone "baetyls" which, as mentioned earlier, Thompson considered to be deity emblems but are identified in most site reports (no doubt rightly in many cases) as merely grinding tools?

There is some additional evidence of interpreting "baetyls" as symbolic objects when no grinding "wear" appears on any of the stone surfaces of these basalt cones. Although many might be too large for such significance, "baetyl" cones at Pre-Pottery Neolithic (PPN) Jericho could function as pre-writing tokens, judging by Syrian and Mesopotamian parallels from 8000 B.C. as precise measures of grain (Schmandt-Besserat, 1986), which may be related to Rowe's much later "sacred shekelim" at Beth Shan.

The following suggestions are offered as tentative use criteria in this chapter. The preliminary nature of these ideas requires considerable additional confirmation (or negative evidence to eliminate them) in other Bronze Age sites comparable to the Canaanite culture and chronology discussed.

First, a discussion of the cultic use of basalt and its possible origins is appropriate. These possible origins are posed as questions. Could Hittite use of basalt for cultic objects be seminal in influencing some northern Canaanite traditions? It has already been established by Garstang, Yadin, and Thompson that clear Hittite iconography and precedents can be seen at Hazor, Beth Shan, and Megiddo, particularly in the same Late Bronze contexts discussed in this chapter.
For example, evidences of Hittite influence are often cited at Hazor (Yadin, 1956; Yadin, 1970:90 & ff.; Yadin, 1975: 79-80, 85) in some temple orientations but more clearly in the lion- sculpted and ashlar basalt orthostats (stone blocks usually very finely dressed on at least four sides for public view) and the basalt sculpture of Hadad as storm god (like the Hittite Teshub) riding the bull; at Beth Shan (Thompson, 1970:67, 114-15 [esp. footnotes 192-93], 153, and 158) with Mekal’s conical helm, general Hittite influence, e.g. Teshub deity figurine, seals, and weapons in temple contexts, and Hadad-Resheph deity connections; and at Megiddo (Garstang, 1929: 5; Thompson, 1970: 158-9) with Hadad-Rimmon deity worship and cultic associations.

Furthermore, beyond the content and motif of the sculptural and cultural Hittite connections, the fact that the Hittites so often used basalt itself as a medium for stone sculpture may be a further corollary of Hittite influence in Canaan. This tradition can be traced from the early Hittite capital Hattush in Anatolia in the 16th -14th c. B.C. and later in the southern empire which extended to the 12th c. B.C., as Hittite use of basalt for cult objects, primarily religious sculptural friezes, is well-attested (e.g. Garstang, 1929: 115, 153, 155, 159, 209, 211, 217-19, 221-223, 225, & 230) at Boghaz Khoy (Hattush), the Hittite capital and other Central Anatolian sites like Alacha Huyuk (Yadin, 1975: 85) and at or near the southern Taurus mountain range at such loci as Kara Dagh, Kizil Dagh, Emir-Ghazi, Isbekjir, Derendeh, Asarjik, Kuru-Bel, Marash, Egri Khoy, Arslan Tepe (Hittite), Carchemish, Alalakh (Yadin, 1975:80) and many more. As stated at the outset of this chapter, Hittite masons may have transferred
stone preference (for reasons ranging from familiarity because of basalt availability, religious perception, or tradition) as well as technical skill in basalt treatment from experience with it in their northern centres. Thus, Hittite masons could have trained Canaanite masons in basalt stoneworking techniques. The distinctive black or dark rough character of basalt would be easy to recognize without much "scientific" observation (and in some cases volcanic eruption or fresh lava flows would aid in its identification). That the Hittite masons were familiar with basalt stoneworking technology needs no further elaboration judging by their extensive basalt sculptures. It has been noted already at the outset of this chapter that one Hittite word for millstone is *kunkunuzzi* stone, which has been identified as basalt (Hoffner, 1974).

Other Hittite associations may be possible as well. While this may be nearly a universal phenomenon in the Ancient Near East, Hittite shrines and peak sanctuaries on volcanic cone peaks (e.g. Garstang, 1929: 154, 157, 218) were most often sacred to Teshub the Hittite storm god, as noted, who Garstang says was the chief or national Hittite god (1929: 113). Oldenburg and others have evidenced Teshub connections to Canaanite high places and sacred mountain contexts such as Mt. Saphon (near Ugarit) and Mt. Hermon (near Hazor) among other peaks (Oldenburg, 1969; Hunt, 1990c). Mt. Saphon was also known as Mt. Hazzi [Casius] to the Hittites (Kapelrud, 1952; Lipinski, 1990, pers. comm.)

Furthermore, Mt. Hermon itself (2814 m and approximately 45 km from Hazor) was a sacred Ba‘al-Hadad peak and could have been important to the Ba‘al-Hadad cult at Hazor since it is both near and often visible from the tell of Hazor. The biblical texts
Judges 3:3 and I Chronicles 5:23 also refer to Ba’al Hermon. As "the Hittite storm-god [Teshub] resembles Hadad [Ba’al] trait for trait," (Oldenburg, 1969:64) the probability of Hittite, Syro-Hittite, and Canaanite peak sanctuaries at the foot of or on Mt. Hermon as well as the Ba’al-Hermon cultic centre implied from the texts of I Chronicles and Judges become more significant in terms of basalt associations with the fact that the lower slopes of Mt. Hermon are basaltic (Figure 7.1). This in itself raises a provenance possibility for the Hazor archaeological material which has as yet been undetermined as to geological source, being petrographically dissimilar to the immediately outlying basalts near Hazor. If found to be closely matched, it would further strengthen the "sacred mountain, sacred stone, sacred context" (i.e., as temple or cult object) motif hypothesized earlier in this chapter (Mt. Tabor and Megiddo), an idea discussed with and supported by Dr. E.A. Knauf of Heidelberg University (pers. comm. at Xth International Phoenicia Colloquium, Leuven: Hunt, 1990b).

Much more detailed analysis, including petrologic, is needed to support this last hypothesis, but the Hittite associations at the primary sites discussed in this chapter offer at least one possible explanation (beyond availability) for some basaltic cult object use in certain northern Canaanite contexts.

A second major possibility for origins of basalt use in many cult objects is also posed as a question. Aside from colour and appearance which have been briefly discussed in the preceding paragraphs as possible metaphysical selection criteria from Hittite to Canaanite cultures, how might the physical nature and properties of basalt affect its selection in the Levant?
The most obvious answer to this is found in the usefulness of the hardness and durability of basalt for the many objects found in nearly every Levant location and time period in which tool requirements for grinding and striking recommend basalt as ideal for hammers, querns, mortars, pestles, etc. In many ways the fact of utility alone in comparing basalt (usually estimated around 6 on a relative Mohs hardness scale) to limestone (with calcite usually around 3-4, although the Cenomanian, Eocene, and Turonian limestones in the Levant are varied with some up to 4.5 hardness, suggesting that some of these limestones may be silicified) should suffice as a primary explanation for the use of basalt in the Levant, particularly in conjunction with relative geologic abundance and accessibility. This is offered here as the simplest answer to the question, 'Why was basalt used so extensively in the Levant?' This is suggested as primary with the secondary answer being its high availability in the region.

However, another property consistently appearing in these and other cultural contexts is found in a probable use of basalt due to its resistance to burning. To the knowledge of this researcher, this has not been discussed before. A significant number of cult (i.e. temple) objects made of basalt include altar or incense stand burner uses, and also some sculptures with laps recessed as offering basins (Plate 7.10).

While the known practices of Canaanite live sacrifice offering by burning will not be discussed here, burnt offerings are well known to be widespread in Canaanite-Ugaritic contexts throughout the Bronze Age (Pfeiffer, 1973:98). It may also be important to note the resistance of basalt to staining (where burning deposits dark carbon on light stones such as limestone) as well as other
HAZOR BAAL-HADAD SCULPTURE (H 6136) from a Baal Shrine, accompanied by MAAZEBOTH (sacred stelae). Note the recessed lap for burnt offering and related sacrifices. Scale of sculpture and stelae: taller stelae = approx. 1.5 m in height. The inverted crescent on the statue's chest may be a Hadad-Rimmon sign and the upraised hands with crescent on Stele 5 may also have the same significance.
basalt properties which suggest a high durability compared to limestone, for example, the most abundant Levant stone. Basalt also has a high resistance to corrosion, i.e. not as soluble as limestone (or worse, gypsum) in aqueous environments. Naturally, it is implied that Levant cultures in the Bronze Age (and before) would have been able to observe and deduce such basalt qualities. Experience in these cultures with limestone objects in the same contexts would demonstrate that the calcium carbonate is itself burned or calcined (or certainly discoloured with carbon, which would not happen with the already dark basalt). Therefore, the geographically plentiful limestone would be perceived as not durable for use with repeated (daily) offerings or burnings as would be expected for temple or related use.

Other Canaanite sites providing support for this hypothesis are 1) a Late Bronze Age Temple at Amman, Jordan (Hankey, 1974) and 2) Strata XI A and XII (both also Late Bronze or very Early Iron I Age) areas at Tell es-Sa‘idiyeh, Jordan (Tubb, 1988). The latter contexts are from Areas AA and EE of the British Museum expeditions of 1986 onwards, from a Late Bronze temple and a probably-related favissa. Table 6.8 below compiles some known "fire-related" or other contexts requiring heat-resistant stone which have been filled by basalt objects.

The list of Levant "fire-related use" basalt objects so far includes 5 altars, 4 incense stands/burners, 2 offering tables, 3 ornamental-decorated multi-legged vessels, 5 dishes (without ampler description), and 2 deity statues with offering basins in their laps. Each of the sites represented, including Tell es-Sa‘idiyeh, does have proximity to basalt sources either
overland or in secondary deposits like riverine cobbles as at Jericho, although this does not imply that the basalt was chosen specifically only for its fire-resistant properties in such use.

Table 7.8 BRONZE AGE "FIRE-RELATED USE" BASALT CULTIC OBJECTS

<table>
<thead>
<tr>
<th>Site and Culture</th>
<th>Context</th>
<th>Object</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Altars</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Hazor H 134 2 altars</td>
<td>Canaanite H 2126</td>
<td>(Yadin, 1972 Ch. 7)</td>
<td></td>
</tr>
<tr>
<td>3. Beth Shan Thutmose III-style 2 altars</td>
<td>Canaanite Temple &amp; Room 1104</td>
<td>(Rowe, 1940:X) (Thompson, 1970:35)</td>
<td></td>
</tr>
<tr>
<td><strong>B. Incense Stand/Burners &amp; Offering Tables</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Hazor H 143 2 offering tables</td>
<td>Canaanite &amp; Shrine 6136</td>
<td>(Yadin, 1958 &amp; 1972)</td>
<td></td>
</tr>
<tr>
<td>6. Beth Shan Amenophis III-style 1 incense stand</td>
<td>Canaanite Temple XXII, 11,6</td>
<td>(Rowe, 1930:11,6)</td>
<td></td>
</tr>
<tr>
<td>7. Megiddo Temple 2048 3 &quot;legged&quot; vessels</td>
<td>&amp; Cult Room 2081</td>
<td>(Loud, 1948 Pl. 262-63)</td>
<td></td>
</tr>
<tr>
<td><strong>C. Deity Statues (with Recessed Basin Lap)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Hazor Shrine 6136 1 Hadad Sculpture</td>
<td>Canaanite</td>
<td>(Yadin, 1958)</td>
<td></td>
</tr>
<tr>
<td>10. Hazor H 127 1 deity sculpture</td>
<td>Canaanite</td>
<td>(Yadin, 1972)</td>
<td></td>
</tr>
</tbody>
</table>

* Vessels at Megiddo and Amman temples are only suggested as incense or fire-related; the legs on the Megiddo dishes are highly-decorated and as such are unlikely to be merely uti-
litarian, also they could allow fire below (and above).

Furthermore, as discussed in the previous chapter from Olmec contexts, calcination of limestone and stressing of marble as well as destructive thermal expansion of quartz as opposed to feldspars (Winkler, 1975:175) suggest "basic igneous rocks [having no quartz] should be preferred where exposure to high temperature is expected" (Winkler, 1975:175).

Relating to a question raised in the previous chapter (Ch.6), a possibility exists that "fire-related use" for basalt contexts in the cultures represented here may be a logical extension of a volcanic or observable fire-related origin. There is, however, no known recorded historical basis for volcanic activity in the last seven to nine millennia in this region of the Levant.

The only other known common variables are that these objects (excluding Jericho PPNA - EB material not being discussed here) are mostly Late Bronze Age (a few perhaps slightly earlier or later), were all recovered from temple or related contexts, and are basaltic. One other possibility to explain high proportions of basalt objects in "fire-related uses" is that limestone may have also been used but did not as often survive the calcining and therefore would not appear in excavations. This may be unlikely, however, as it would be expected that more calcined fragments of limestone would appear in site excavation reports.

Other possible support for this may come from outside the Levant region in cultures unrelated to the ones being discussed. Historical mention or archaeological evidence shows that basalt was used for altars (and possibly even infant sacrifice by burning) among Olmec and Olmecoid peoples (Pugh, 1981:7) and even Pliny in Historia Naturalis 36, 30 refers to certain
millstones as **pyrites** ("firestones"), which may be related to Strabo's observation that Mt. Aetna lava hardens on cooling into **lithos mulias** ("mill stone") (Moore, 1834:128-29). Another Greek term regarding millstone, very often basalt or andesite (Runnels, 1981) is **pyrimachos** or "fire-proof" as stone which "withstood fire in a remarkable degree" (Moore, 1834:128-29).

These three ideas relating to basalt use and its possible criteria of selection are offered here with the knowledge that other as yet unspecified criteria may also have operated. Again, it must not be overlooked that all such basalt use may have been fundamentally governed by the simpler geologic presence of abundant and accessible basalt. Further research will be helpful in better resolving these questions and the complex questions of provenance determination for the basalts of Bronze Age Hazor, Beth Shan, Megiddo and Jericho.

7.7 **Conclusions**

While basalt has been amply used in Canaanite contexts at Hazor, Beth Shan, Megiddo, Jericho and elsewhere, it is difficult to show conclusive evidence that volcanic material had any special significance beyond its availability. This has been shown by a higher volume of use in the Bronze Age sites closest to lava flows in the northern Jordan-Great Rift Valley. On the other hand it is nonetheless remarkable that Hazor (as close as Beth Shan to basalt deposits) had so many cult objects made of basalt, as if some uniformity were being sought in stone choice for aesthetic or religious reasons.

The other possible suggestions for some sacral basalt use as
discussed include strong Hittite influence and high resistance of basalt to burning (in altar, incense, and related contexts). However, in light of overall basalt use since the Paleolithic in obvious grinding tool uses, it is reiterated that the simplest answer to questions of selection criteria for basalt will remain to be availability (and durable practicality) unless shown to be otherwise in future research.

Determination of provenance for any of these basalt contexts must also be left to future research due to the large volume of area covered by volcanic material and overall chemical similarity as determined by semiquantitative EDS probe analysis and trace element XRF analysis. Perhaps distinctive petrographic textures unique to archaeological and geological material may be better used as "signatures" for identifying stone sources in light of the chemical similarities between the basalts of the Jordan-Great Rift valleys.
Chapter Eight

REVIEW OF BASALT AND ANDESITE WEATHERING RESEARCH

8.1 Review of Geological Weathering of Basalt and Andesite

Introduction

The primary type of weathering applicable to this research is chemical weathering rather than physical weathering. Chemical weathering produces visible physical changes and may accompany physical or mechanical weathering, but it is primarily defined in this research as involving dissolution and hydrolysis of the component minerals in the rock (Winkler, 1975:137) and involving the role of water and aqueous molecules more than any other agent (Ollier, 1984). The focus of this chapter is on chemical weathering as it applies to basalt and andesite.

8.1.1 Research of Colman et al.

The examination of basalt and andesite weathering under the same programme follows precedents established by prior research (Crandell, 1972; Crandell and Miller, 1974; Carrara and Andrews, 1975; Porter, 1975; Scott, 1977; Colman, 1977; Colman and Pierce, 1981; and Colman, 1982). Weathering can be evidenced both by the large-scale weathering rind development (Colman and Pierce, 1981; Colman, 1982) on individual rocks and by the small-scale leaching and alteration of individual grains such as biotite mica within one rock (Eggleton and Banfield, 1985), or comprehensively for a range of minerals in one rock or in related rocks (Colman and Dethier, 1986).

Naturally, the overall weathering of one rock is a cumulative process reflecting the small scale weathering changes. As such, it could be expected that weathering rind development (although
it is not applicable to all rocks) might often be measurable on a visible level while the individual grain weathering requires microscopic and quantitative assessments. Any review on basalt and andesite weathering from the geological perspective will be dependent on the work of Colman et al. (1977, 1981, 1982, 1986), research which will be widely referenced in the present study.

8.1.2 Weathering Rinds

A basalt or andesite weathering rind is defined as a "zone of oxidation colours whose inner boundary approximately parallels the outer surface of a stone" (Colman and Pierce, 1981:3). Assuming visible thickness, this definition suggests contrast of colour between weathered and unweathered areas (Plate 8.1).

An important premise regarding weathering rind development is that such weathering rinds are formed by a combination of oxidation, hydrolysis, and solution processes (Colman, 1977) and are to be distinguished from other stone weathering features such as obsidian hydration (Friedman and Smith, 1960; Stevenson et al. 1987) or desert varnish (Dorn and Oberlander, 1982). Oxidation-hydrolysis is defined as chemical weathering caused by ionised oxides such as CO in solution with rainwater or ground water (Read and Watson, 1973: 129-31; Winkler, 1975:146-52; Ollier, 1984:34-36).

An important consideration in the work of Colman et al. is the variety of andesite and basalt contexts they sampled, with three self-imposed sampling limitations (or parameters), i.e. constitution, situation, and climate. Their overall sampling area was regionally limited to the Western U.S.,
(Plate 8.1 [above]) OLompali AnDESite WEATHERING RIND of Burdell Mtn., Marin County, California. Normal (as per Colman et al.) weathering rind colour of light rind over darker fresh rock. Note rind thickness of nearly 1 cm. Also see Plate 1.2 for petrographic texture.
area of somewhat similar montane or intermontane climate, and to basalt and andesite rocks of a similar lithology (or mineralogy), and to sampling depths of 30 cm or less below the ground surface. Limitations were held to be necessary for eliminating undue influences of weathering variables (e.g. a wide range of climatic environments). The geology of the area was also well-known to Colman et al. and prolifically documented in the literature.

Much of the prior literature evaluated in this chapter is cited from Colman et al. as their studies are the most applicable to the present study. Nonetheless, important differences between the present work and the work of Colman et al. must be clearly stated here and again in Chapters 9 & 10. Perhaps a fundamental distinguishing passage is the following:

"Differences in thickness between rinds on surface stones and those on shallow subsurface stones may be related to differences in duration of exposure to weathering. A surface stone begins to weather as soon as it is exposed, but weathering of a subsurface stone is probably minor until the oxidation front migrates downward past the stone. Stones in unoxidized parent material have virtually no rinds...An interval of at least several thousand years seems to be required before the oxidation zone extends to the typical 30-cm sampling depth used in this study.

The formation of rinds on basaltic stones at the surface also may be controlled by different processes than those that control the formation of rinds on stones within the soil. Rinds on subsurface basaltic stones near Wallowa Lake, Ore[gon]...appeared considerably different than rinds on surface basaltic stones... The surface rinds were thicker on the average, but much more variable; many stones have no rinds. The surface rinds were also harder and redder than the subsurface ones." (Colman and Pierce, 1981:7)

While on the one hand, many basalt and andesite contexts of the present study are from comparable subsurface contexts as might be expected of excavated archaeological artefacts with original or possibly disturbed stratigraphy, other contexts of the present study are from very exposed surface contexts where the suggestions of Colman et al. are not as well-researched
(as their studies concentrated on subsurface contexts). This may result in some problems in the applicability of their research. The detailed evaluations of this and other potential problems are found in section 8.54 of this chapter and in Chs 9 & 10. However, with this proviso is the fact that the work of Colman et al. is the most comprehensive and comparable in the literature. The sections to follow discuss weathering rind characterizations as discussed by Colman et al. and others.

8.1.3 Weathering Rind Colour

The "oxidation colours" depend primarily on the individual mineralogies and textures of the parent rock and secondarily on the other weathering factors (presented in subsequent sections). Weathering rinds on basalt and andesite are generally in contrast to the dark (grey through black) colours of a fresh rock interior by being usually lighter in colour (white or grey to ochrous red colours) although the reverse has also been evidenced. A sample range of weathering rind colours seen by this researcher on a few basalts and andesites is included in Table 8.1.

Table 8.1 below shows that the range of weathering rind colours precludes at this point generalizations for a complete characterization of rinds for several reasons: a) it is too small a sampling (only 15 examples) to be representative; b) insufficient data is recorded for common variables like deposition age, weathering environment, etc.; c) it shows a wide variation range even for material likely to be of the same deposition (e.g. Miocene pyroxene andesite from Burdell Mtn. in Marin, California); and d) on the other hand it can be shown to
### Table 8.1 WEATHERING RIND COLOURS ON BASALTS AND ANDESITES

<table>
<thead>
<tr>
<th>Colours</th>
<th>Stone</th>
<th>Context</th>
</tr>
</thead>
<tbody>
<tr>
<td>A) white rind</td>
<td>1. pyroxene andesite</td>
<td>Burdell Mtn., Marin California</td>
</tr>
<tr>
<td>grey interior</td>
<td>2. pyroxene andesite</td>
<td>Yunguyu, nr. Puno, Peru</td>
</tr>
<tr>
<td></td>
<td>3. biotite andesite</td>
<td>Ollantaytambo, Urubamba, Peru</td>
</tr>
<tr>
<td>B) lt. grey rind dp. grey interior</td>
<td>4. pyroxene andesite</td>
<td>Burdell Mtn., Marin California</td>
</tr>
<tr>
<td></td>
<td>5. pyroxene andesite</td>
<td>Cape Mavrorachidi Santorini</td>
</tr>
<tr>
<td></td>
<td>6. hornblende andesite</td>
<td>Rumigolqa, Huatanay, Peru</td>
</tr>
<tr>
<td></td>
<td>7. biotite andesite</td>
<td>Ollantaytambo, Urubamba, Peru</td>
</tr>
<tr>
<td></td>
<td>8. olivine basalt</td>
<td>Jordan Valley (south), Israel</td>
</tr>
<tr>
<td>C) dk. grey rind blk. interior</td>
<td>10. leucitic basalt</td>
<td>Monte Porzio-Catone, Lazio, Italy</td>
</tr>
<tr>
<td></td>
<td>11. pyroxene andesite (glassy)</td>
<td>Cape Mavrorachidi Santorini</td>
</tr>
<tr>
<td>D) blk. rind *</td>
<td>12. hornblende andesite</td>
<td>Rumigolqa, Huatanay, Peru</td>
</tr>
<tr>
<td>grey interior</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E) rust-ochre rind lt. grey interior</td>
<td>13. pyroxene-hornblende andesite</td>
<td>Zepita-Yunguyu nr. Puno, Peru</td>
</tr>
<tr>
<td>F) dk. pink rind *</td>
<td>14. hornblende andesite</td>
<td>Rumigolqa, Huatanay, Peru</td>
</tr>
<tr>
<td>lt. pink interior</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G) pale green rind</td>
<td>15. pyroxene-olivine basalt</td>
<td>Santiago Tuxtla</td>
</tr>
<tr>
<td>dark grey interior</td>
<td></td>
<td>Veracruz, Mexico</td>
</tr>
</tbody>
</table>

* = contrary to expected lighter rind colour (Colman & Pierce, 1981:3) (Age of deposition and potential hydrothermal alteration are not taken into account in this brief sampling of rinds.)
exhibit a comparable rind colour for different mineralogies, as B) with a light grey rind colour on a dark grey interior for six varied lithologies including pyroxene, hornblende, and biotite andesites, pyroxene-olivine basaltic andesite and olivine basalt.

In A-C, E, and G a common feature of basalt and andesite weathering rinds is suggested by a predominant lighter "leached" (Colman and Pierce, 1981:3; Colman, 1982:3) appearance found on 13 out of the 15 weathering rind samples. It is also important to note that a distinction should be made between geological and archaeological material since most of the above are geological samples and the two exceptions already made (D, F) are found on archaeological material, a point to be developed in a chapter section on new finds in archaeological weathering (Chapter 10).

Thus, weathering rind colour is in contrast to fresh interior colour by "visible discolouration" (Colman and Pierce, 1981:3) and is usually lighter in appearance than fresh interior (ibid.) as exhibited on all geological material seen by this researcher. It can be an aim of future research to attempt further colour characterization of weathering rinds for specific variables of lithology, deposition age, situation, and climate. Some of these above variables in b) will be defined in chapter section 8.4.

8.1.4 Weathering Rind Thickness

In consideration of what has already been said by Colman and Pierce concerning subsurface and surface weathering contrasts, the first premise regarding weathering rind thickness is that it is recognizable in contrast but is not just a surficial contrast; it must have "visible" depth. Range of depth as defined
by Colman and Pierce begins at 0.0-0.1 mm (just visible at 5 x) "at the limit of measurement" (Colman and Pierce, 1981:9) and extends to beyond 3.5 mm (Colman and Pierce, 1981:19), especially as this researcher has found a 4.9 mm weathering rind at Jericho (J 2025, see Plate 10.4) and a 1 cm weathering rind (0.92 cm) at Olompali, Burdell Mtn. (see Plate 8.1).

The second premise regarding weathering rind thickness is that its contrast with fresh rock interior is not always dramatic but may only be a matter of slight contrast. In particular it may not be apparent even in a fresh rock section but may require polished sections for enhanced visibility. This research has used standard petrographic treatment for some polished sections with carborundum powders up to 5 micron polish (F 1000) and even up to 0.25 micron polish with diamond lapping compound (Buehler or Metadi) for otherwise faint weathering rinds.

In such situations where rind visibility is difficult to establish, high polish (e.g. 0.25 micron) may actually not show any visible contrast other than that the weathering rind will not take as much polishing. This may suggest alteration products like allophanes or deterioration to fine clay grains such as are found in pedogenesis (Colman, 1982:4-10).

The third premise regarding weathering rind thickness is that several factors are responsible for basalt and andesite rind development. While these are treated individually in the main chapter section 8.4, they are assumed to be primarily time and parent material (mineral lithology) and secondarily environmental factors such as climate, topography, and vegetative organisms (e.g. lichens) (Colman and Pierce, 1981:7-9 & ff.). Prior studies
agree in the assessment that basalt and andesite weathering rinds arise from a set of complex interrelationships between these factors, and that any one factor may have greater or lesser influence from geologic context to context (Colman and Pierce, 1981; Colman and Dethier, 1986).

A fourth premise regarding weathering rind thickness is that it is not expected that a weathering rind be of exactly the same thickness on every surface of the same stone (or even present at all). Naturally, this complicates any recording of measurements. As such the measurements might be made either by means of averaging, taking only extremes (greatest or least thick rind), and/or establishing as Colman and others have that some loss of advanced weathering rind surfaces is expected with erosional forces. Therefore measurements must be taken consistently from a common locus (such as within the first 30 cm under the ground as a consistent sampling depth and, where possible within the same topographical and climatic conditions) in order to rule out microenvironment variables both inside and outside the same multiple sampling area as much as possible in order not to introduce sampling as an additional factor to those listed above (Colman and Pierce, 1981:8-9).

In summary, weathering rinds on basalts and andesites are visible contrasting outer surface zones with a wide range of colours normally lighter than on fresh interior. Exposure to weathering factors is greater on the outside surface of basalts and andesites than on the inner margin of a weathering rind. Furthermore, the processes of oxidation-hydrolysis influenced by multiple factors such as time, parent material, and environment cause distinct changes in the surface rock which should be
capable of being measured with consistency.

Weathering rinds on stone in general includes discussion by Ollier of iron oxide protective rinds on rock surfaces with a range from a few millimetres to nearly 10 cm. He proposes models with either external hydration (possibly humid climates) or with internal capillary rise (possibly arid climates), suggesting that most weathering rinds are produced within a rock rather than upon a rock (although both silica and managanese oxides may also accumulate upon a rock surface from the outside, e.g. MnO in desert varnish or that silica may accumulate on a rock surface from within the rock). Ollier suggests patina thickness may be of use in archaeological dating, corroborating the research of Cernhouz and Solc (1966) in principle but not necessarily in method or material (Ollier, 1984:239 & ff.).

8.1.5 Research of Winkler

Winkler summarizes decades of silicate weathering research in stating "rates of silicate weathering are extremely difficult to evaluate because too many factors are involved which influence the process." (Winkler, 1975:147), which is the consensus of most geologists (Ollier, 1984:209-10, 212). Nonetheless, synthesizing observations of others, Winkler suggests that weathering by the activity of solubilization via hydrolysis or leaching (which Colman et al. also observed) shows a weathering whose rate is anomalously fast on some basalts compared to others where such weathering progresses normally slow (i.e. noticeable only after thousands of years). Basalts which weather "anomalously fast" are "developing grey spots on the black basalt surface, the first
sign of rapid deterioration. Crumbling may follow after about 5 years of exposure" and Winkler believed this could be the result of microcracks (Winkler, 1975:150). This idea will be developed in Chs. 9-10 on new findings in the weathering of archaeological material. Winkler also holds silicate weathering to be exponential: a) slow at the very beginning, b) then progressing to rapid deterioration once a crystal lattice has been exposed to sufficient oxidation and hydrolysis c) and eventually slowing down again once a weathered layer offers protection to unweathered surfaces underneath it (Winkler, 1975:150-51). Although Winkler does not elaborate on the variable rates at different times within the same material, it is likely that mineral alteration and replacement are involved. Exponential rates are also confirmed by the observations of Colman et al. (Colman and Pierce, 1982:24 & f.) and others (Cernohouz and Solc, 1966:806-7; Ollier, 1984:212; Ruxton, 1988:387, 393).

8.2 Individual Mineral Grain Weathering

As stated at the outset, weathering rinds are comprised of individual grain-by-grain changes at a level best measured by microscopic or quantitative chemical analysis. Petrographic and other petrologic assessments including SEM with EDS, EPMA, XRF, and XRD are some of the methods used for this purpose in prior research (Colman, 1982:2).

Ollier and Winkler list several main mineral weathering rate factors which for purposes of reference have been synthesized in an original compilation as Table 8.2 below (Ollier, 1984:60-61; Winkler, 1975: Chs. 5 & 7). Any oversimplification of these factors is not intended.
Table 8.2 MINERAL WEATHERING RATE FACTORS

<table>
<thead>
<tr>
<th>Factor</th>
<th>Low Rate</th>
<th>High Rate</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Crystal size</td>
<td>large</td>
<td>small</td>
<td>greater surface area per unit volume in more smaller crystals than fewer larger</td>
</tr>
<tr>
<td>2. Crystal shape</td>
<td>chunky</td>
<td>platy</td>
<td>greater surface area per unit volume in platy crystals than chunky</td>
</tr>
<tr>
<td>3. Crystal perfection</td>
<td>(perfect geometric lattice)</td>
<td>(imperfect geometric lattice)</td>
<td>greater number of loose bonds in lattice = less resistance</td>
</tr>
<tr>
<td>4. Crystal cleavage</td>
<td>poor (low cleavage)</td>
<td>good (high cleavage)</td>
<td>more cleavage planes = more surface area = more access to weathering</td>
</tr>
<tr>
<td>5. Mineral environment</td>
<td>(e.g. temperate)</td>
<td>(e.g. tropical)</td>
<td>more humidity &amp; higher temp. = higher solubility rate of dissolution</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B. more polluted = more acidic aerosols (SO₂, CO₂, etc.) which may accelerate weathering</td>
</tr>
<tr>
<td></td>
<td>(e.g. rural)</td>
<td>(urban)</td>
<td>more product removal</td>
</tr>
<tr>
<td>7. Solvent mobility</td>
<td>(stagnant water)</td>
<td>(running water)</td>
<td>low mobility = solution in equilibrium; high mobility = undersaturated = more product removal</td>
</tr>
</tbody>
</table>

Factor 4 (crystal cleavage) does not contradict Factor 3 (crystal perfection); presumably a low temperature-low humidity environment will be the most stable, yet deserts are low humidity.
high temperature and are very stable, so humidity may be more a factor than temperature alone as "water is the mobile phase that permits relatively rapid movement of the constituents transported in the weathering process" (Griffiths, 1990, pers. comm.)

Mineral alteration on a grain-by-grain basis and measurable relative elemental mobilities within the phenocrysts and groundmass of basalts and andesites are seen as the optimum gauges of such microscopic weathering. Weathering of glass is perhaps a main feature of groundmasses and weathering rinds in general (Colman, 1982:10). Mineral weathering products are more likely to result from degradational rather than formative processes (Colman, 1982:3) although as matter is conserved, the degradation of one mineral results in the formation of another. Alteration also occurs faster within a groundmass matrix (fine grains) than in individual phenocrysts (large grains) "presumably because of larger surface area of the [groundmass] matrix constituents" (Colman, 1982:3) as well as the fact that glass itself is less stable than the other constituents in the groundmass (Colman, 1982:10). However, large phenocrysts with multiple fractures may evidence rapid local alteration along the fractures Colman, 1982:3) due to a high crystal surface area ratio compared to volume of the attacking solution (Griffiths, 1990, pers. comm.).

Not all minerals are equally altered: both the mineral and elemental stability studies show unstable, metastable, and very stable trends. "Early stages of rind development are largely defined by oxidation colours produced by the alteration of [volcanic glass and olivine]" according to Colman (1982:1),

265
who offers the following estimate for selected minerals common to basalts and andesites with weathering rinds in Table 8.3 below. This table reflects chemical and physical properties of the selected minerals and is in general agreement with other studies which are also discussed in some detail (e.g., Ollier, 1984; Winkler, 1975) in the present chapter.

Table 8.3 RELATIVE STABILITY OF SELECTED MINERALS

<table>
<thead>
<tr>
<th>Least stable</th>
<th>Most Stable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass--</td>
<td>----</td>
</tr>
<tr>
<td>Olivine-----</td>
<td>Clinopyroxene-----</td>
</tr>
<tr>
<td></td>
<td>(Pyroxene)</td>
</tr>
<tr>
<td></td>
<td>Orthopyroxene---</td>
</tr>
<tr>
<td></td>
<td>Amphibole---</td>
</tr>
<tr>
<td></td>
<td>K Feldspar---</td>
</tr>
<tr>
<td></td>
<td>Opaques----</td>
</tr>
<tr>
<td></td>
<td>(e.g. Titanomagnetite)</td>
</tr>
<tr>
<td></td>
<td>Ca,Na--------</td>
</tr>
<tr>
<td></td>
<td>(Plagioclase Feldspars)</td>
</tr>
<tr>
<td></td>
<td>Na,Ca--------</td>
</tr>
</tbody>
</table>

(from Colman, 1982:22 & 14-16)

Colman notes some differences with other mineral stability studies which show the metastable minerals, pyroxenes and plagioclases, in reverse order, attributing this to compositional complexity of pyroxenes and isomorphous substitution within the plagioclase series (albite-anorthite) (Colman, 1982:15-17). This may also be due to complex zoning features in this researcher's opinion as plagioclases can show normal, reverse, or oscillatory zoning with varying Na:Ca concentrations in their magmatic crystallization (Gill, 1981:170 & ff).

Ollier also summarizes several mineral weathering studies in 266
listing relative mineral stabilities. For common minerals (found in basalt and andesite but not necessarily following this weathering series) the order of descending stability is:

\[ \text{biotite} > \text{hornblende} > \text{augite} > \text{olivine} \]

For fine-grained minerals (likewise found in basalt and andesite) Ollier also offers a relative stability series including feldspar

\[ \text{quartz} > \text{albite} > \text{biotite} > \text{olivine} \]

(albite being the sodic feldspar, anorthite being the calcic feldspar) (both from Ollier, 1984:69), although a comparable weathering series arranges these and other minerals in "a rough order of increasing resistance to chemical weathering" with the same general results:

\[ \text{olivine} > \text{calcic feldspar} > \text{pyroxene and amphibole} > \text{sodic feldspar} > \text{biotite} > \text{potassic feldspar} > \text{muscovite} > \text{quartz} \]

as presented by Read and Watson (1973:131) on mineral stability.

Specific mineral weathering is dealt with in the following paragraphs for minerals common to basalts and andesites examined by Colman et al. or in the present study. These include feldspar (specifically plagioclase), biotite, pyroxene, olivine and amphibole (specifically hornblende) as well as glass.

One of the most applicable elements of Colman's mineral weathering studies is the compilation of mineral and weathering product stages (Colman, 1982:5, 19,[Tables 2,3, & 6]) which is also included here as Figure 8.1 (from Colman) below. Its use in petrographic analysis of the present study will be seen in Chapter 10.
Table 8.1a COLMAN’S MINERAL WEATHERING STAGES

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Plane Light</th>
<th>Cross-Polarized Light</th>
<th>Principle Elements (XES)</th>
<th>Tentative Identity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>--</td>
<td>--</td>
<td>-- unaltered</td>
<td>fresh mineral</td>
</tr>
<tr>
<td>2a</td>
<td>-- clear, brn</td>
<td>-- optically</td>
<td>-- variable</td>
<td>stained glass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>to yellow-orange</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2b *</td>
<td>translucent</td>
<td>Si,Mg,Fe</td>
<td>iddingsite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>yell to red-brn</td>
<td>microcrystalline</td>
<td>at olivine fractures</td>
<td></td>
</tr>
<tr>
<td>2c *</td>
<td>opaque</td>
<td>Si,Mg,Fe</td>
<td>iddingsite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>yell to yellow-orange</td>
<td>isotropic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2d</td>
<td>clear, yell-grn</td>
<td>fine-grained</td>
<td>Si,Al,Fe</td>
<td>chlorophaeite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Ca,Mg,Na,K)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2e *</td>
<td>speckly yell</td>
<td>Si,Al,Ca</td>
<td>unknown</td>
<td></td>
</tr>
<tr>
<td></td>
<td>at plagiocl. border</td>
<td>speckled</td>
<td>Na,Mg,Fe</td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>clear, yell</td>
<td>microcrystalline</td>
<td>-- altered</td>
<td></td>
</tr>
<tr>
<td></td>
<td>yellow</td>
<td>Si,Al,Fe</td>
<td>chlorophaeite</td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td>clear to</td>
<td>Si,Al,Fe</td>
<td>-- palagonite?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>yellow</td>
<td>Si,Al,Fe</td>
<td>-- palagonite?</td>
<td></td>
</tr>
<tr>
<td>3c</td>
<td>massive</td>
<td>Si,Al,Ca</td>
<td>unknown</td>
<td></td>
</tr>
<tr>
<td></td>
<td>yellow to grey</td>
<td>low birefringence</td>
<td>K,Mg,Fe,Na</td>
<td></td>
</tr>
<tr>
<td>4a</td>
<td>clear to</td>
<td>massive, vague</td>
<td>Fe,Al,Si</td>
<td>unknown</td>
</tr>
<tr>
<td></td>
<td>orange</td>
<td>Si,Al,Ca</td>
<td>chlorophaeite</td>
<td></td>
</tr>
<tr>
<td>4b</td>
<td>massive</td>
<td>Si,Al,Ca</td>
<td>unknown</td>
<td></td>
</tr>
<tr>
<td></td>
<td>orange to red</td>
<td>-- massive,</td>
<td>Si,Al,Ca</td>
<td>unknown</td>
</tr>
<tr>
<td>4c</td>
<td>opaque, white</td>
<td>Fe</td>
<td>-- hematite</td>
<td>maghemite</td>
</tr>
<tr>
<td></td>
<td>ref. light</td>
<td>(Ca,Mg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-- grey to red-brn</td>
<td>indist. masses,</td>
<td>Si,Al,Fe</td>
<td>alfomphane hydroxide</td>
</tr>
<tr>
<td></td>
<td></td>
<td>does not go to (Ti)</td>
<td>iron oxide</td>
<td>extinction</td>
</tr>
</tbody>
</table>

(modified from Colman, 1982:5, Table 2)

Figure 8.1b COLMAN’S MINERAL WEATHERING STAGES

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Fresh Rock</th>
<th>Slightly Weathered</th>
<th>Moderately Weathered</th>
<th>Extensively Weathered</th>
<th>Completely Weathered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>1,(2a)</td>
<td>(2a,2d),3a</td>
<td>3b,4a</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Olivine</td>
<td>1,2b</td>
<td>2b</td>
<td>4a</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Pyroxene</td>
<td>1</td>
<td>(2d)</td>
<td>3a,3b</td>
<td>(4a)</td>
<td>5</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>1</td>
<td>2e</td>
<td>3c</td>
<td>4b</td>
<td>5</td>
</tr>
<tr>
<td>Amphibole</td>
<td>1,2c</td>
<td>1,2c</td>
<td>2c,3b</td>
<td>3b</td>
<td>3b,5</td>
</tr>
<tr>
<td>K-feldspar</td>
<td>1</td>
<td>1</td>
<td>1,3b</td>
<td>3b</td>
<td>3b,5</td>
</tr>
<tr>
<td>Opaques</td>
<td>1</td>
<td>1</td>
<td>1,4c</td>
<td>1,4c</td>
<td>1,4c,5</td>
</tr>
</tbody>
</table>

(from Colman, 1982:19, Table 6)
Colman’s Notes as Addenda to Figures 8.1a & b:

Figure 8.1a:
(Table 2, Colman, 1982:5)

( ) in column 4 shows elements present in subordinate qnty.

* in 2b, 2c, 2e are alteration products of only part of the original mineral, usually along grain boundaries and fractures

Figure 8.1b:
(Table 6, Colman, 1982:19)

Column 1 "Mineral" includes mineraloids glass and some opaques

Column 2 "A / Fresh Mineral" may include products of deuteric alteration, e.g. Fe-oxides and iddingsite

One critical question raised by Colman’s Table 6 reproduced above as Figure 8.1b is that Colman has lumped all plagioclase (both Na and Ca) together in a sequence of stability which implies all plagioclase is more stable than all pyroxene when in fact he has suggested elsewhere that

Na plagioclase > Orthopyroxene > Ca plagioclase > Clinopyroxene

in terms of decreasing stability (Colman, 1982:22, 14-16). This may, however, have little bearing on his Table 6 as shown for mineral weathering stages. Furthermore, the usefulness of his Table 2 reproduced in a modified form above as Figure 8.1a, is without parallel in the literature. Application to archaeological material will be attempted in Chapter 10 of the present study.

The following sections present individual mineral weathering observations compiled from the literature. They are discussed where any potential contradictions or problems arise through comparison of these weathering observations.
8.2.1 Feldspar Weathering

Feldspar weathering has been addressed by many studies, both in general weathering and in weathering of basalts and andesites. Research shows that Ca-plagioclase anorthite leaches faster than Na-plagioclase albite (Colman, 1982:22; Ollier, 1984:62) while the K-feldspar orthoclase leached slowest (Winkler, 1975:146) and Ollier maintains the K-feldspar microcline is the most resistant feldspar (Ollier, 1984:62).

Ollier also makes other observations about feldspars: 1) they are almost as hard as quartz but a predisposition to cleavage allows rapid penetration and alteration by hydration; 2) feldspar weathering may be via etch pits along cleavages rather than any rounding; 3) feldspars ultimately alter to clay or allophane; 4) when physical weathering (e.g. rounding) is greater than chemical weathering, the feldspar probably derived from an arid climate (Ollier, 1984:62-3).

Colman makes the following observations about plagioclase feldspar (the most common in volcanic rock) not mentioned in the other studies examined: 1) plagioclase weathering is not only controlled by fractures and grain boundaries but also by chemical compositional zoning, 2) especially in andesites, zoning may be either normal (with calcic cores), reversed (with sodic cores), or oscillatory. Thus, altered plagioclase may often show depleted cores or frittered glass inclusions in the cores (Colman, 1982: 11-12).

Gill further suggests 1) reversed zoning (calcic rim, sodic core) (presumably with reversed alteration tendencies) occurs in only about 10% of andesite plagioclases, and that 2) oscillatory
zoning is characteristic for plagioclase in orogenic andesites (Gill, 1981:171-72).

Other feldspar weathering studies suggest the following. Visual turbidity or cloudiness in the phenocrysts is a feature of feldspar weathering (Colman and Dethier, 1986). Wollast and Chou suggest that albite dissolution involves a three-step process with the importance of pH noted: "1) rapid exchange of Na+ with H+, 2) buildup of a residual layer depleted in Na+ and also depleted in Al under acidic conditions, and 3) steady-state and congruent dissolution stage where the rate is controlled by a surface reaction between the residual layer and the solution."

Furthermore, Wollast and Chou state that the first reaction is a "large amount of alkali ions released to solution and an increase in pH, suggesting that the main process occurring during this initial stage is the exchange of alkali ions on the feldspar surface for protons" (Wollast and Chou, 1984:75-76 respectively). Applicability of their experiments seems to be mostly related to the importance of pH in short-term feldspar weathering models. Studies of Rosenbauer et al. with mid-oceanic ridge basalt (MORB) show that Ca-plagioclase anorthite can be albitized in the right conditions: "presence of NaCl, excess silica, an absence of strong acidity (dissolved Mg)" in the laboratory with environment factors of 350°C and 400 bars of pressure (Rosenbauer et al., 1988). The relevance of this study to volcanic weathering is apparently limited to marine environments with high salinity, as the authors suggest, in altered volcanic marine spilites.

In summary, the turbidity or clouding found in feldspar weathering by Eggleton and Busecke seems to be the best
suggestion for visual contrast of a generally lighter weathering rind to fresh or unweathered interior, but this needs verifying in both geological and archaeological weathering of basalt and andesite.

It is the research of Colman et al. which is most germane to the present study, particularly as it is mostly derived from basalt and andesite, and is optically verifiable by means of petrographic examination and SEM. Nonetheless, the other studies suggest much promise for understanding the processes involved in feldspar weathering.

8.2.2 Biotite Weathering

Biotite weathering has not been addressed by Colman et al. in their basalt and andesite studies but has been suggested by Eggleton and Banfield as involving expected K depletion (as it is in high concentration between biotite plates) and also Fe oxidation. With natural hydrolysis as a major weathering feature, a hydrobiotite-like phase leads to gross plate exfoliation and biotite ultimately alters to chlorite (Eggleton and Banfield, 1985:31-33 & ff.). Winkler observes that ferrous-ferric iron is leached from biotite at the beginning of weathering since iron is "loosely built" into a ferromagnesian crystal lattice and that "iron almost immediately precipitates as a natural rust halo near the biotite flakes" (Winkler, 1975:164). Over a short (in geological terms) period exposed biotite may diffuse out to cover a whole rock with an ochre Fe stain (ibid, p. 164). This could also be an observable characterization for archaeological material of the present study where biotite is a component, e.g. Huaccoto material (Peru). For purposes of relative comparison,
release of Fe from mica is around 500 times greater under the same conditions than other ferromagnesian silicates according to Winkler's synthesis of other studies (Winkler, 1975:164). This might slightly contradict other trends showing overall biotite stability greater than pyroxenes and amphiboles (Ollier, 1984:69) and elemental mobilities (stability of Fe > K > Mg) (Colman, 1982:1) except that the stability of the mineral itself appears intact overall and that higher mobility of K and Mg may not have such visible release as Fe in biotite. These points will be discussed again in Chapter 9 on new studies in weathering of archaeological material.

8.2.3 Pyroxene Weathering

Colman makes the following observations regarding alteration of pyroxenes: 1) as stated, pyroxenes are more stable than glass or olivine and possibly calcic feldspar and generally less stable than sodic feldspar and amphibole (Colman, 1982:22); 2) pyroxene weathering can be either "throughout the grain or progressively inward from grain edges and fractures" (Colman, 1982:11); 3) pyroxenes which are weathered along edges and fractures evidence "concordant local decreases of Ca, Mg, and Si abundance" but not for Fe, which still maintains some stability relative to these others lost on grain fractures and edges; but 4) the internal pyroxene grain evidences little or no localized depletion of Ca, Mg, Si, or Fe; and 5) pyroxene alters initially to chlorophaeite and ultimately to amorphous allophane with its characteristic XES spectra for Si, Al, Fe (and possibly Ti) as Ca and Mg have been long leached out (Colman, 1982:5, 11). The
relative stabilities of pyroxenes appear to be: orthopyroxene, most stable; and clinopyroxene, least stable (Colman, 1982:22).

Ollier offers the following observations regarding pyroxene weathering: 1) the crystals have good cleavage (hence relatively rapid weathering); 2) augite is both the most common pyroxene and 3) augite weathers by ion exchange and alteration of the crystal lattice; 4) augite alters initially to intermediate minerals and ultimately to clay; 5) pyroxene evidences etch pits along its cleavages rather than "general surface attack with consequent rounding" (Ollier, 1984:62-63); and 6) in accord with Colman, titanaugite is most resistant to weathering, followed by augite and the other orthopyroxenes and then the clinopyroxenes (Ollier, 1984:62); 7) pyroxenes are magnesium rich (e.g. enstatite), iron-rich (e.g. hypersthene), calcium-rich (e.g. diopside) or rich in all three (Mg, Fe, Ca) like augite (Ollier, 1984:62).

Other observations about pyroxene weathering come from Schott and Berner: 1) "dissolution is strictly a surface process" which occurs "by a surficial H+ (or H O+) exchange reaction" (Schott and Berner, 1985:35); and 2) weathering by surface etch pits is consistent with Ollier (Schott and Berner, 1985:39; Ollier, 1984:62-63).

8.2.4 **Olivine Weathering**

Olivine weathering, like biotite weathering, is also noted as being immediately apparent, as stated earlier in the observations of Colman (Colman, 1982:1, 11, 14, 16, 19, 22), being with glass "the least stable mineral" in the basalts and andesites examined. Also as ferromagnesian (like biotite), olivine was described by Colman et al. as contributing to early weathering in that "early
stages of rind development are largely defined by oxidation colours produced by the alteration of...these minerals [olivine and glass]," as stated earlier in this section (Colman, 1982:1).

Empirical formulae of olivines (Mg,Fe) SiO show either iron in high concentration or magnesium in high concentration. Either the variant forsterite (Mg rich) or the variant fayalite (Fe rich) usually dominates depending on pre-depositing conditions of magmatic crystallization, although both contain significant percentages of Fe and Mg (MacKenzie and Guilford, 1980:1-2).

The rusty iron oxide stain of many olivine basalts (e.g. Huaran-Golan, Israel or in the Druze area of northeastern Jordan) is attributable to olivine Fe depletion. Alteration of olivine to iddingsite is also frequent in geological weathering. Iddingsite forms in the olivine grain fractures or as a deuteritic alteration rim caused by hydration and oxidation (MacKenzie et al., 1982:19; Colman, 1982:11) (see Plate 7.3 of Chapter 7).

8.2.5 Amphibole weathering

Colman makes these observations about amphibole weathering:
1) amphiboles are relatively meta-stable: more stable than the clinopyroxenes and ultimately stable beyond the orthopyroxenes; and roughly equivalent to the plagioclase range in stability; (Colman, 1982:22); 2) amphibole phenocrysts "have reaction rims of fine-grained opaques, presumably iron oxide" (Colman, 1982:13); 3) weathering rims thicken on amphiboles [with time] (Colman, 1982:13); and 4) amphiboles possibly alter intermediately to amorphous palagonite (which has XES spectra of Si,Al,Fe with residual Ca,Mg) (Colman, 1982:5).

Colman remarks that amphiboles were rare in the Western
U.S. basalts and andesites of his studies, and therefore his generalizations regarding weathering stages were "tentative at best" (Colman, 1982:13).

Ollier suggests the following characteristics of amphibole weathering: 1) amphiboles have good cleavage [and therefore rapid weathering rates, relatively speaking]; 2) "also alter by ion exchange and lattice alteration (like pyroxene)"; 3) amphiboles are "usually more resistant to alteration than pyroxenes;" 4) hornblende is more resistant than other amphiboles; 5) the hornblende common in volcanic rock, "oxyhornblende", is "more resistant in acid conditions than common hornblende;" 6) amphibole etching along cleavage "is dominant, not general surface attack with consequent rounding;" and 7) amphiboles alter "to chlorite and other clay minerals." (Ollier, 1984:62-63).

Other amphibole weathering observations, specifically for hornblende, suggest relative short-term dating by the use of hornblende surface etching for materials with 10 ages (Hall and Michaud, 1988). Their studies of hornblende etching are claimed to be more reliable than the clast weathering and their hornblende etching description is consistent with other descriptions (Ollier, 1984:63).

8.2.6 Glass weathering

Glass alters faster than any mineral in basalts and andesites according to Colman (1982:10, 22) and is specifically linked (with olivine) in the studies of Colman to the discolouration which marks the early stages of weathering rinds of basalts and andesites: "in weathering rinds from young deposits (about
20,000 yr old or less), alteration of glass and olivine is primarily responsible for the discolouration that defines the weathering rind" (Colman, 1982:10).

Initial weathering of glass includes staining of glass that is clear yellow and green at the outset to a speckly and fibrous yellow-orange and finally to red (but still translucent) before ultimate alteration to amorphous allophane (Colman, 1982:11). Colman also notes intermediate stages of loss of silica and loss of Mg, Ca, Na, and K but with a concentration of iron (Colman, 1982:11), suggesting perhaps that Fe is dominant in this stage of weathering (also evidenced by the red colour?). In the XES spectra for this weathering stage of altered glass, Colman shows Fe peak height in greatest abundance (above Si and Al) (Colman, 1982:12, Fig. 8c).

On a larger scale, weathering of glass is shown by either or both of two visible characteristics: one may be the lighter colour caused by loss of translucence of glass (also seen in turbidity of some feldspar weathering); another may be the resistance to polish as noted in weathering rind contrast to fresh unweathered interior of rock (see Chapters 9 & 10).

These studies in some cases were fundamental to Colman et al. and in other cases postdate the research of Colman et al., but are in accord with Colman et al. on mineral stability in nearly all details.

8.3 Elemental Mobilities and Stability

Colman also offers information on chemical trends as weathering indices during formation of weathering rinds, showing large loss of bases (Ca, Mg, Na, and K), oxidation of iron, and
overall hydration or water incorporation. Within minerals from weathering rinds of basalt or andesite, Colman's research points to the following relative elemental mobility:

\[ \text{Ca > Na > Mg > Si > Al > K > Fe > Ti} \]

where rate of loss apparently decreases with time (Colman, 1982:1). These observations of Colman on relative elemental mobility are reinforced by Dorn and al. who studied Na, K, Ca, Mg cation leaching (Dorn et al., 1982, 1984). Both studies used Ti or TiO as a stability referent (Colman, 1982:34; Dorn et al., 1984:309).

Other studies of mineral and elemental weathering include general mineral depletion and alteration, and specific volcanic phenocryst alteration. In general silicate weathering, Winkler states "oxidation of ferrous iron is the earliest evidence of incipient weathering, followed by the removal of Na, Ca, and Mg" (Winkler, 1975: 147). Synthesizing prior research, Winkler describes crystal lattices with the cations Ca, Na, K, Mg and others being leached by hydration with high charge and small ionic radius H ions having easy penetration into mineral surfaces. Describing elemental leaching, Winkler states "loss of ions in igneous rocks during incipient weathering is a maximum for calcium and a minimum for aluminium" (1975:146).

Also, iron oxide formation itself is intensely variable in view of environmental parameters even though it is an obvious (and perhaps most common) weathering result (Schwertmann, 1984). If the variability of iron oxide formation is indicative of other secondary mineral formation or alteration, the complexity of
mineral weathering scenarios is immediately apparent. Some of the variable factors are discussed in the next section.

8.4 Variables Affecting Rates of Weathering

As already stated in a preceding section on weathering rinds, two factors influencing the weathering of basalt and andesite have been suggested in the prior literature as primary: time and parent material; and several others as secondary: environmental factors such as climate, topography, and organisms (e.g. lichens) (Colman and Pierce, 1981:4 & ff.). The observations of Colman et al. are dealt with first as theirs comprise the major research on factors of weathering for basalt and andesite. These will be followed by observations of Winkler, Ollier, and others on weathering factors for stone in general.

8.4.1 Variable of Time

The following observations of Colman et al. are offered for weathering of basalt and andesite as related to time: 1) if rock types (lithologies) and climate are equal (or uniform), the effect of time is much greater than any other factor (Colman and Pierce, 1981:15); 2) variations in lithology affect weathering rates (Colman, 1982:20); 3) inter-regional and intra-regional contrast of weathering rates is likely (Colman and Pierce, 1981:27); 4) weathering rates are probably not constant over time due to climatic changes (ibid., p. 24); 5) the relationship between weathering rind thickness and time can be expressed by either a linear function (d = rind thickness; t = time; and k = other factor; and n = unspecified exponent):
\[ d = kt \quad [ \text{so} \quad d_1/d_2 = t_1/t_2 ] \]

or a logarithmic function:

\[ d = k \log t \quad [ \text{so} \quad d_1/d_2 = \log t_1/\log t_2 ] \]

or a power function:

\[ d = kt^n \quad [ \text{so} \quad d_1/d_2 = (t_1/t_2)^n ] \]

where \( k \) is a weathering rate constant only for the linear equation (Colman and Pierce, 1981:24); and 6) transitions between weathering stages should not be assumed to represent the same durations or equal weathering intensities (Colman, 1982:20).

The conclusion of Colman et al. is that rind thickness is not developed as a linear function of time but as a logarithmic one (Colman, 1982:20; Colman and Pierce, 1981:25-28, 37).

The observations of Winkler and Ollier on time in general are as follows: 1) weathering rates are exponential with regard to time for silicate rocks (Winkler, 1975:150) or probably all rocks (Ollier, 1984:212); 2) weathering rates may vary with time (due to accumulation and then dissolution of weathered products in differential conditions or because supply of weatherable material is limited) (Ollier, 1984:212); 3) glacial history alone suggests vast differences of conditions through Quaternary time so direct applicability of present to past processes is doubtful (ibid., p. 220 & ff.).

On the whole, the observations of Colman et al. on time as an exponential weathering factor and all the evidence for complex rates of weathering are in accord with Winkler, Ollier, and other researchers.
8.4.2 Variable of Parent Material

The observations of Colman et al. on parent material as a factor affecting basalt and andesite weathering are as follows: 1) the greater the similarity in lithologies, the less variation between rind thicknesses if other factors are similar (Colman and Pierce, 1981:10); and conversely 2) that the less similar the lithology, the more variation in rind thickness (by extension) except that one might find distinctly different rocks which happened for a combination of reasons to have similar weathering rates (Griffiths, 1990, pers. comm.); thus 3) the basalts and andesites in the study of Colman et al. have different rates of rind development (Colman and Pierce, 1981:10); with a tendency that 4) basalt forms rinds somewhat faster than andesite (Colman and Pierce, 1981:10); 5) which agrees with prior accepted conclusions that mafic rocks tend to weather more rapidly than felsic (Colman and Pierce, 1981: 10); 6) mineral lithology seems to be a greater influence than climate (Colman and Pierce, 1981:12); 7) rock texture is important in weathering rate in that coarse-grained rocks appear to have thicker rinds than fine-grained rocks [all else being equal?] (Colman and Pierce, 1981: 12); and 8) of factors besides time, parent material (lithology) appears to have most important effect (Colman and Pierce, 1981: 15). The question of why coarse-grained rocks appear to have thicker rinds than fine-grained rocks is probably related to the grain-by-grain weathering: density of groundmass with far fewer phenocrysts characterises fine-grained texture whereas the matrix of coarse-grained rocks is more granular and phenocrysts are far more abundant (Colman and Pierce, 1981:12). Thus, allowing for
phenocryst cleavage and fracture which provide a readier access for solution penetration in greater surface area on weaker crystal lattices (especially along fractures), weathering can develop deeper (although not necessarily faster - see Table 8.2.1 on crystal size) rinds on coarse-grained rocks. The fact that weathering will be grain-by-grain on larger grains appears to have controlling influence over this phenomenon, but it will also depend on which mineral is in the phenocrysts.

Observations of Ollier on parent material as a factor for weathering of igneous rock are: 1) extrapolating from the Bowen reaction series, i.e. the sequences of mineral crystallization from magma (Bowen, 1956), it can be explained that early-formed minerals (e.g. olivine...Ca-plagioclase...clinopyroxene) in the crystallization melt use up most of the bases and later-formed minerals (e.g. Na-plagioclase...amphibole...biotite) use less as less are available (Ollier, 1984:68); so that 2) "the more cations there are that can be replaced by hydrogen, the more weatherable" is the material (Ollier, 1984:68). Thus, basalts being more basic (the ratio of other cations to silica) than andesites, basalt weathers faster (in accord with Colman and Pierce, 1981:10 and prior literature cited there).

However, the application of crystallization sequence to infer instability in atmospheric weathering may be oversimplifying for several reasons: a) stabilizing layers may form on rock surfaces as results of initial leaching which slow down weathering rates (Winkler, 1975:150-01); and b) "K silicate glass is less stable than Na or Ca silicate glass of comparable composition (Griffiths, 1990, pers, comm.) despite the crystallization
sequence of Ca > Na > K feldspars from the magma or the elemental mobilities sequence of Ca > Na > K of Colman et al. discussed earlier in this chapter. Both of these sequences should be seen as relative, "regularity" as opposed to "rigidity" in particular is used in describing the Bowen reaction series (Read and Watson, 1973:402).

In summary, olivine basalts, for example, ought to weather faster than orthopyroxene basalts, and coarse-grained material faster than fine-grained material, all else being equal. Factors such as plagioclases being either at the more resistant albitic (Ab) Na rich end or the less resistant anorthitic (An) Ca rich end of the Ab-An range must be considered. Generalizations for comparison of weathering rates for many basalts and andesites may not be possible from the prior literature. Thus it is suggested that lithology as a weathering factor be extrapolated with caution from the mineral weathering data.

The factors of time and parent material are considered here as primary factors; discussion of the environmental factors of weathering follow.

8.4.3 Variable of Climate

The observations of Colman et al. on climate as a variable factor in the weathering of basalts and andesites are as follows: 1) climate is well understood to be a major influence on weathering processes (Colman and Pierce, 1981:13); 2) climate can be understood as complex of interrelated sub-variables such as temperature and precipitation tied to microclimate variations (Colman and Pierce, 1981:13-14); 3) weathering rind development rates increase with precipitation increases [possibly doubling
from 0.78 mm to 1.57 mm with a 20% precipitation increase from 55 to 65 cm comparing data from different sampling areas in the Western U.S. in studies of Colman et al. (ibid., p. 14)]; also 4) increases of temperature should increase rate of rind development by increasing the rates of chemical reactions (ibid., p. 14); 5) precipitation appears to be dominant over temperature as a control on rind development (ibid., p. 14); 6) rind development appears inhibited in arid climates (ibid., p. 14); especially 7) with high calcium carbonate soils [e.g. burial of basalt in a Levant archaeological site where the CaCO in soil would retard weathering rinds, see Ch. 9] (ibid., p. 14); and 8) since climate can change dramatically over short distances with important effects on weathering rind development, geographical proximity may not be as important as other factors [e.g. common mean annual precipitation/mean annual temperature (MAP/MAT)] (ibid., p. 13).

The observations of Winkler on climate as a factor for general weathering are as follows: 1) Winkler cites evidence (but not specifically for basalt and andesite) which is contrary to Colman et al. in that "temperature and relative humidity of the immediate environment play a more important role than the actual mineral composition of the rock" in above-surface stone weathering [two comments here: one, Colman et al. studied mostly slightly sub-surface basalts and andesites - which are comparable to many buried archaeological basalt and andesite artefacts or monuments; and two, Winkler does not specify basalt and andesite whereas Colman et al. do] (Winkler, 1975:147); 2) an application of weathering rates of iron oxides [as in
leaching products from mafic minerals] to metal corrosion rates could mean that a dry inland Egyptian location would have an average loss of 0.16 grams (according to Winkler) per year for metallic iron or a relative corrosiveness of 1 whereas a tropical marine Southeast Asian location would have an average loss of 1.36 grams (according to Winkler) per year for metallic iron or a relative corrosiveness of 9 (Winkler, 1975:99); also 3) Winkler cites research that with each increase temperature of 10 C an estimated weathering rate increase occurs in multiples of 2.0 - 2.5 such that a tropical moist climate would have 20-40 times more solubilisation and hydrolysis weathering than a temperate climate (Strakhov, 1967 in Winkler, 1975:147). This last point seems exaggerated in that it should be more likely to have only 15-30 times more solubilisation and hydrolysis weathering.

The observations of Ollier on climate as a weathering variable are as follows: 1) "water is the most important reactant in almost all forms of weathering" (Ollier, 1984:123); 2) silica leaching should be higher in tropical weathering than temperate weathering (ibid., p. 125); 3) again, "10 C temperature increase will double or treble reaction rates" [agreeing with all other sources] (ibid., p. 124); however, in arid areas 4) "either hot or cold, there is likely to be less chemical weathering" (ibid., p. 127); 5) precipitation - evaporation studies show that with precipitation > evaporation = continued removal of weathered products; whereas with evaporation > precipitation = lack of removal of weathered products (ibid., p. 124); 6) also the prevailing wind and weather direction can be important for microclimate differences in weathering (ibid., p. 126); 7) with relative humidity as a more aggressive combination of MAP/MAT
(ibid., p. 123); 8) the amount of "slaking" (wet-dry or freeze-thaw frequency) also accelerates weathering (ibid., p. 127), supported by Torraca’s research (Torraca, 1988:41-43) and 9) microclimate may be a better gauge than "coarse" climatic data in considering climate as a weathering factor (ibid., p. 127).

In summary, significant weathering rate differences should exist between tropical and temperate regions, with water-related processes such as MAP, relative humidity, and wet-dry frequency all playing vital roles as weathering sub-factors. Microclimate differences will also be expected to offset overall regional similarities, all else being equal, with temperature change also affecting weathering rate inter-related with other climatic phenomena to make a complex whole. After time and parent material climate is probably the most influential weathering factor for basalt and andesite. Quantification of climate as a weathering constant, however, is likely to be impossible on a global basis for basalt and andesite weathering studies with present methods.

8.4.4 Variable of Topography

In some respects, the variable of topography may fall more naturally under the category of microclimate. However, if altitude is a determinant of microclimate (e.g. as in orographic precipitation) it might be just as logical to assume microclimate is a subcategory of overall topography.

The observations of Colman et al. on topography as a variable for basalt and andesite weathering are as follows: 1) "minor differences in topography may have an appreciable effect on weathering rinds" (Colman and Pierce, 1981:10); 2) variation in
soil-drainage profiles and vegetation may be derivative of topography [which should be dependent on regional tectonics and degradation or erosional forces], which will affect weathering in a microclimate (ibid., pp. 9-10); and 3) in general relief a broad flat moraine area may weather less than a sharp moraine crest [maybe not due to erosion, as Colman and Pierce suggest, but due to prevailing weather concentrating precipitation, but see Ollier’s observation 1) for contrast)(ibid., p. 10).

Observations of Ollier on topography (or "aspect" in his discussion) as a weathering variable are as follows. 1) As a part of microclimate variations, frost may occur in an open area with regularity but not nearby in a protected or sheltered area (Ollier, 1984:125). 2) In general, south-facing slopes will be more likely to receive either more sunshine or greater variation in temperature (Ollier, 1984:126). This would be true unless they have more vegetation, which could also be equally true for a north-facing slope depending on the geographical region, e.g. which global hemisphere, steep mountain or shallow valley, primary direction of wind and climatic influence. In any case, one side of a valley is often more wooded than the other, which will either buffer weathering extremes or not allow penetrating warm sunshine. A further observation of Ollier on topography is 3) that wind exposure may also be significant, either in drying or as a concentrating force for precipitation (ibid., p. 127).

In summary, it is clearly seen how interrelated topography and microclimate are: assumptions regarding pervasiveness of a regional climate may be invalid in accommodating or predicting local weathering variations; topography must be studied closely as well as major relief (e.g. altitude) and major climatic data.
8.4.5 Variable of Organisms

Biotic agents as a weathering variable for basalt and andesite play a role in weathering as well, being mainly lichens, mosses and algae living on rock surfaces. Lichen fungal hyphae, for example, penetrate cleavage planes and accelerate mineral breakage (Ollier, 1984:55) and chemotropic bacteria ("one of the most important weathering" biotic agents) may discharge "wastes" high in sulphuric acid or other acids) (ibid., p. 54). Winkler states "the [bacterial] population on the volcanic rock of Borobudur appears to be exceptionally high" [which might be a significant weathering factor in conjunction with tropical climate as well as being derivative of it] (Winkler, 1975:155).

Torraca maintains crustaceous lichens "extend their growth several millimetres inside masonry material and decompose it to some extent by means of the production of organic acids (e.g. oxalic acid)" (Torraca, 1988:51), which may explain why Colman and Pierce found weathering rinds were 2-3 times thicker under lichen cover than where no lichen presence was noted (all else being equal) (Colman and Pierce, 1981:7).

Thus, organisms do contribute to weathering, although except in clear examples as shown by Colman and Pierce and suggested by Winkler (at the archaeological site of Borobudur) the net effect will be difficult to quantify.

Summary

Overall, integration of all variables into a cohesive whole with repeatable predictive frequency for individual contexts one
could encounter is likely to be overwhelming: these variables or weathering factors of time, parent material, and environment are sufficiently complex and interrelated to preclude any certain priority or to weight such weathering variables as factors having the mathematical value of constants. However, the literature suggests an implicit scale for prioritizing multiple influences of these factors in such an order:

\[
\text{time > parent material > climate > topography > organisms}
\]

such that any combination of two preceding factors should almost always be greater in force than any next-sequence variable alone:

\[
\text{time + parent material > climate}
\]
\[
\text{or}
\]
\[
\text{parent material + climate > topography}
\]

and that all else being equal between two samples, differences in one variable alone should account for significant weathering differences. Qualifications are suggested by the following points: Since climate is itself made up of subfactors, parent material plus MAT should have a greater effect on weathering than MAP alone (Colman and Pierce, 1981:11); since basalt usually weathers faster than andesite, andesite plus greater MAP could be comparable to basalt with lesser MAP (ibid., p. 10-11); or, by extension, coarse-grained basalts in a temperate climate could be comparable in weathering to fine-grained andesites in a tropical climate; etc., with many permutations and possible combinations. Furthermore, topography may not be a variable in any way other than as an influence contributing to climate (thus, like the MAP and MAT of Colman et al., better factored as a subvariable). In
consideration, any such prioritizing will still be likely to produce only a relative scale for weathering comparisons.

8.5 Archaeological Weathering of Basalt and Andesite

Apparently little or no prior literature exists for weathering studies of archaeological basalts and andesites. Where some prior literature does exist (as in the case of Cernohouz and Solc), it may be fraught with potential problems. Therefore, beyond the evaluation of that prior literature, much of the material in this section and following in Chs. 9 & 10 is either a) derived from observations of this researcher; or is b) synthesized here as an application from geological weathering of basalt and andesite in short-term consideration (which may actually introduce new variables, e.g. stoneworking).

Colman and Pierce suggest for basalt and andesite weathering that "in younger deposits, weathering may not reach the depths sampled in this study [1981], and rinds developed on surface stones may be more useful for deposits in the $10^3$ yr-old range" (Colman and Pierce, 1981:8), rather than those in the 12,000 to 250,000 (or greater) year old range of their study.

The implications for archaeological weathering are obvious, hence the considerable reliance on the studies of Colman et al. in applications for archaeological material. As will be elaborated in this section, it is important at the outset of this section to note that such expected features as weathering rinds found on geological material may not be found on archaeological material for a variety of reasons. Although their research was probably not intended to be strictly geological or archaeological
in application, Cernohouz and Solc (1966) provided the primary weathering study of basalt crusts on Bohemian castles which formed an integral part of Winkler’s assessments (1975) as well as the work of Colman et al. (1977, 1981, 1982, 1986) on the short-term geological weathering of basalt and andesite.

Although studies of geological weathering may be applied to archaeological contexts, potential problems may be associated with the application of what could be termed "archaeological" weathering into geological contexts as Colman et al. have done. This will be addressed in a following section and in Chapter 8. Dorn et al. and Miller’s archaeological suggestions will be noted first and the research of Cernohouz and Solc will follow with some discussion.

8.5.1 The research of Dorn et al.

The work of Dorn et al. (1982, 1984) could in some sense be concerned with andesite and basalt weathering phenomena except that desert varnish has been shown to be mostly aeolian deposits accumulated on the surface and integrated with Mn and Fe oxides.

The work of Dorn et al. is in accord with Colman’s relative elemental mobilities. Dorn et al. suggest a somewhat similar relative age system based on a cation mobility scale for accrued desert varnish on andesites and basalts of the Cobo Mtns. in east California. The cation ratio of $K + Ca : Ti$ is based on the idea that mobile cations (or bases) such as Na, K, Ca, Mg are more easily leached out of desert varnish than less mobile Ti cations. (Dorn and Oberlander, 1982:341; Dorn and Whitley, 1984:309). Dorn et al. have used cation ratios to date desert varnish by gauging reductions in the ratio of mobile $(K + Ca)$ to immobile $(Ti)$
cations and calibrating these with K-Ar ages of known volcanics in order "to establish an empirical cation-leaching curve useful in the chronometric age determination of rock varnishes." (Dorn and Whitley, 1984:309). The analytical method used by Dorn et al. was particle-induced X-ray emission (PIXE) for bulk chemical analysis and SEM + EDS for imaging and semiquantitative analysis (Dorn and Oberlander, 1982:327; Dorn and Whitley, 1984:309).

One criticism of the approach of Dorn et al. could be that although K-Ar may provide the age of the volcanic deposition, the youngest in the study Dorn et al. being 39,000 B.P. (Dorn and Whitley, 1984:309), this deposition date may be very different from the date desert varnish begins to form, however calibrated.

The general comparability of Colman's and Dorn's relative elemental mobilities suggests a reliable chemical trend for elemental stability even though applications and actual chemical actions and directions differ (i.e. external and some internal leaching in Colman's observations vs. external surface deposition in observations of Dorn et al.). Dorn et al. have applied their chronometric age determination system to rock petroglyphs in the Great Basin style (rectilinear, curvilinear natural, and abstract motif styles) on andesites and basalts in the Midwest and West of North America by Native Americans. Their datings of petroglyphs based on desert varnish accumulation range from 580 B.P. to about 6400 B.P. Their standard deviations and error margins suggest an approximate age determination to within 20%.

However, as desert varnish appears to accumulate from external sources rather than internal leaching, its applicability to the present study in gauging weathering mechanisms is limited.
8.5.2 Research of Miller

While his work is related more to associated human remains in young basalt contexts, the work of Miller is concerned with an application of K-Ar dating to basalts of greater than 2 million years of age, and is thus not directly applicable to this study (Miller, 1964).

One basic inapplicability with K-Ar basalt dating is that it holds little little use in weathering studies because its focus is on a longer term chronology rather than short term. Miller’s research is clearly geological, like that of Colman et al.

The main problem for application is that rather than provide information on the duration of weathering, it only gives the time of rock formation. Even where volcanic deposition may overlie archaeological contexts and be ideal for Miller’s research, K-Ar does not address the mechanisms of weathering.

8.5.3 Research of Cernhouz and Solc

Cernhouz and Solc suggested that "corrosion of basalt fragments follows a law, and it is possible to determine their age in a range from 500 to 10 million yrs" (Cernhouz and Solc, 1966:806). They maintained that these crusts have "characteristic colour" (as distinguished from interior) and that time is the factor responsible for weathering basalt.

Their analytical results for at least seven different basalt deposit samples in Czechoslovakia suggest an exponential rate of weathering. The equation used is

\[ d = A \log (1 + Bt) \]
where \( d = \text{crust thickness}; \ t = \text{time}; \ \) constants \((A = 4.64 + 0.05\) for lengths in mm; \(B = 0.010 + 0.001\) for time in millenia) worked for Bohemian archaeology and geology by their claims. Their data appear to suggest a slowing of weathering rates after initial rapid weathering, probably explained by a protective weathered mineral front where chemical equilibrium has been approached (in that the rate would ultimately become too slow to identify in short geological time). Their samples can be plotted thusly as in the rate curve in Table 8.4 below.

Table 8.4 BASALT WEATHERING RATE OF CERNOHOUZ AND SOLC

<table>
<thead>
<tr>
<th>Rind Thickness in mm</th>
<th>1.0</th>
<th>0.8</th>
<th>0.6</th>
<th>0.4</th>
<th>0.2</th>
<th>0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time in millennia</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>80</td>
<td>100</td>
<td>120</td>
</tr>
</tbody>
</table>

(Kamenec, nr. Turnov: c. 180,000 yrs B.P.)
(Skokovy, nr. Zelejov Early Wurm: c. 75,000 yrs B.P.)
(Zelejov valley, Wurm period: c. 18,000 B.P.)
(Trosky Castle, 600 yrs B.P.)

The work of Cernohouz and Solc has been often referenced and quoted in geological studies (e.g. Winkler, 1975:148; Colman and Pierce, 1981:26-28; Ollier, 1984:211). Colman and Pierce hold
that differences between their exponential rate curve for West
Yellowstone Quaternary basalts \( d = \log (0.73 + 0.038 \ t) \) and the
Bohemian basalt exponential rate curve (and thus weathering rind
development rate) are based on differences between the variables
of climate, mineral lithologies, and other (unspecified) factors
between the two areas; otherwise they suggest the validity of
each study (Cernohouz and Solc, 1966 : Colman and Pierce, 1981).
Cernohouz and Solc also claimed their method was accurate to
within 10-20%.

Colman et al. make several important qualifications for their
use of the Cernohouz and Solc model: 1) very thin rinds (0.1 mm)
at a 12,000 yr old context in the U.S.A. "suggest that the early
stages of rind formation are very slow at depths sampled (i.e.
below ground level -- not on surfaces exposed directly to the
atmosphere where they expect faster rates, see the comment of
Colman and Pierce, 1981:8); 2) inflected curves (exponential "S"
curves) with slow to exponentially fast to exponentially slow
rates are reasonable; and 3) "The fact that distributions of
weathering rind measurements [both Colman & Pierce and Cernohouz
& Solc] tend to log normal supports the logarithmic form of the
curve" (Colman and Pierce, 1982:27). Colman and Pierce have
postulated a reverse rate curve (with opposite asymptotes) for
the earliest weathering stage (slow to exponentially faster)
(Colman and Pierce, 1981:27).

Some potential problems are seen with the application of the
Cernohouz and Solc first datum (Trosky Castle 0.02 mm at 600 yrs)
which is apparently "archaeological" into a geological logarithm.
These are elaborated in the following section and in Chapter 10.
8.5.4 Potential Problems in Research of Cernhouz and Sole

First, unfortunately little or no calibration or supporting data exist in archaeological contexts other than the Bohemian basalt castles. Whether or not the archaeological weathering will in fact agree with the Cernhouz and Sole model depends on the other factors already noted which may be much more influential over the short archaeological term than time itself. It is the opinion of this researcher that any rate reversal in logarithmic forms may well be due to the other variables being eventually "overtaken" by the variable of time beyond the initial weathering period. That is, the parent material and environment may cease to be as influential as time once weathering has progressed to a certain point. Archaeological weathering may then be impossible to quantify if the other variables (which differ so much from context to context) are more influential at this early stage of basalt and andesite weathering. This will be elaborated in conjunction with the findings of this study of basalt and andesite in the selected archaeological contexts of Chapter 10.

Second, how important is the castle topography itself as a microenvironmental factor for influencing the weathering? The study of Cernhouz and Sole is not detailed enough to support extrapolations for prevailing weather direction in relation to direction in which the weathered basalts of Trosky castle face.

Third, how old was the stone (and how weathered) before its emplacement? Winkler suggests "The Bohemian basalts may have been slightly weathered when the mediaeval builders took the stone from the quarries; columnar jointing accelerated quarrying operations, but also granted access to weathering. Weathering
penetrated quickly after the first centuries of exposure, but slowed down as the weathered layer may have given some protection to the unweathered stone beneath" (Winkler, 1975:151). In reality, Winkler's astute suggestion cannot be ascertained with the data given by Cernohouz and Solc and an absence of comparison with the geological source of the basalt.

Fourth, was any unweathered basalt exposed in the shaping of the basalt in order to ensure good emplacement? This factor has only recently been articulated for building stone and could be enormously important in archaeological weathering development, as will be suggested in the next chapter.

On the other hand, the general agreement in weathering rate curves between the studies of Cernohouz and Solc and those of Colman et al. suggest that, aside from one documented incipient weathering evidence at 600 yrs exposure, the exponential curves appear reasonably close (in the opinion of Colman and Pierce, 1981:26). The problem is, as has been stated, that only one context less than 20,000 yrs is provided, which makes any such assumptions (about what happens prior to 20,000 yrs in weathering rates of basalt and andesite) potentially invalid. One aim of the present study is to examine such available short term weathering contexts and attempt to provide some understanding of the processes involved. These will be elaborated in Chapter 10.

In summary, the work of Dorn et al. and Miller do not bear directly on archaeological basalt and andesite weathering. More important for archaeological considerations, the dependence of Cernohouz and Solc on time as the only variable in their logarithmic rate of basalt weathering in one context
is fraught with potential problems. Any actual rate of basalt (and andesite weathering) as Winkler, Colman et al., and Ollier surmise, is probably complex for geological material over a long time and probably even more complex for archaeological weathering of basalt and andesite over a short time (e.g. 600 yrs), particularly if the material has received mechanical stress due to stoneworking.

8.6 Conclusions

In summary, exponential or logarithmic rates of weathering through time are expected. However, variations in lithologies and the environmental conditions between different weathering samples complicate the time factor for basalt and andesite weathering to such a degree that little relative sequencing of different geological material is likely outside the parameters of research followed by Colman et al. Applicability of their research is best expected for a small geographical region of similar lithology (both similar to their lithology and similar from rock to rock) but chronologically wide-ranging material.

Furthermore, weathering rinds may not be expected on archaeological material or, if defined in accord with the studies of Colman et al., may exhibit optical differences with geological material. Incipient weathering rind development (e.g. some Fe staining) is likely to be the most identifiable element.

As some justification for studying weathering of basalt and andesite in archaeological contexts, particularly by petrographic analysis, the work of Colman et al. indicated a surprising regularity in the weathering of geological basalt and andesite. Thus, perhaps the most applicable element after weathering rind
characterization in research to date is the mineral alteration stage description (Colman, 1982:5, 19 [and as Tables 2, 3 & 6]), reproduced in this chapter as Figure 8.1. According to Colman, stage A represents fresh rock and stage E an estimated age of 140,000 yrs by extrapolation from heavy mineral alteration.

Thus with Colman's mineral alteration stages A - E, it might be expected for archaeological weathering that only A (for all pyroxene, plagioclase, hornblende and biotite) and a fraction of B (for glass and olivine where Colman et al. postulate 10,000 yr relative age) be exhibited in datable archaeological contexts of basalts and andesites over a few millenia. These principles of mineral alteration and stages should be similar despite some differences (e.g. sampling methods: surface vs. subsurface; time: short-term vs. long-term; and environment: global vs. regional) in that much of the data compiled in this chapter are from general mineralogy rather than drawn only from Colman et al.

The prior work as shown by the literature review seems to justify more detailed investigation of shorter term weathering phenomena and an assessment of their potential use in relative dating of basaltic and andesitic archaeological material. These are precisely some of the lacunae the present study aims to fill. The applicability of weathering rinds and mineral alteration will be examined more closely in Chapters 9 and 10. Finally, the lack of prior discussion of stoneworking stress and its weathering effects poses a major question of applying geological data to material in archaeological contexts. It is likely that deduction of new principles for archaeological weathering will need at least tentative articulation.
Chapter Nine

STONEWORKING AND ITS ACCELERATION OF ARCHAEOLOGICAL WEATHERING

9.1 Introduction

A weathering factor apparently not considered by Cernohouz and Solc or Colman et al., is that stoneworking itself can cause acceleration of weathering. This has been suggested by Torraca in relation to stone receiving mechanical stress:

"Mechanical abuse of the surface of building materials can take place in the course of preparation for use...This has particular importance in the case of stone which might be fissured when it is quarried...or when its surface is carved (bush hammer or chisel work)...causing mechanical damage on the surfaces. An increase in the number of microscopic cracks always produces acceleration of weathering rates." (Torraca, 1988:30).

In all fairness, since only the youngest material considered by Cernohouz and Solc was from Bohemian basalt used in a medieval castle, i.e. an archaeological context, and since none of the material considered by Colman et al. would have had modification by human technology, it should not be surprising that possible acceleration by stoneworking was omitted from prior geological studies concerned with natural weathering. Contemporary accounts from the building industry also acknowledge the potential damage to stone in varying intensities by various stoneworking methods: "The extraction method used for quarrying material can sometimes be a cause of its alteration" (Amoroso and Fassina, 1984:7).

According to some geologists not associated with the building stone industry or short-term weathering of stone, possible acceleration of weathering by stoneworking has been suspected for some time but not confirmed (R. Mason, 1988; pers. comm.). The present study suggests that this acceleration is found on basalts and andesites which have been worked according to certain
stoneworking methods to be discussed shortly. The following sections synthesize a preliminary model of basalt and andesite microfracture, amalgamated from several sources as it is not found in the basalt and andesite literature as a whole but may be extrapolated from certain texts (Witthoft, 1974; Protzen, 1985 & 1986; Torraca, 1988; Wilke, 1988).

A brief discussion of elastic and plastic behavior and stress and strain is appropriate here. Elasticity is the ability of a material to return to its original size or shape when the external forces producing distortion are removed (Williams et al., 1980:142). In reality, no such ideal entirely elastic material appears to exist. The external forces can vary in degree or intensity, area of concentration, i.e. over a broad area or at a relative "point" but not elsewhere on the same plane surface, and in other ways. Plasticity is the lack of ability to return its original size or shape after external forces are removed, such that irreversible deformation takes place. When material has reached its elastic limit, it is on the verge of becoming permanently deformed (Williams et al., 1980:142).

Stress could be defined as the distorting force per unit area whereas strain would be the relative amount of deformation produced in a body under stress (Williams, 1980: 142, 651). Simple equations for stress and strain (stress = force/area; strain = extension/original length [in this case elongation strain]) can be combined in Hooke's Law: within certain limits strain is directly proportional to stress. Applying Young's Modulus (Y) a numerical value can be assigned to Y, depending on the material, for expressing the change (delta or d), i.e. the deformation:
stress
\[ \frac{f/a}{strain} \] or \[ \frac{Y}{dl/1} \]

While no coefficients or numerical values for Young's Modulus have been apparently calculated for all stone materials such that they would be applicable here and any quantitative assessments of force as used in stoneworking would be difficult to achieve, some background on potential sources and causes of stone stress and strength would be helpful, although full discussion of the stresses which stone in general can receive is outside the domain of the present study. Torraca, for example, describes some of the properties of stone thusly. Stone shows both elastic and plastic behavior and is a brittle material. Building stones are heterogenous in that they are composed of many different crystals "held together by joints with variable strength. Some elements, or joints, start breaking before the others, causing irreversible deformations" (Torraca, 1988:19-21). Although Witthoft states "We can only study or measure [stone] strain by its consequences," (Witthoft, 1974:51), he could be interpreted: that in the large complex of interrelated features such as hardness, elasticity, tensile strength, plasticity, brittleness, and in the sources and forces of stress, assessments of strain in stone deformation are very difficult to make except after the accumulation of irreversible changes through time. Thus, that any discussion of stoneworking damage risks dangers of oversimplification.

Some discussion of the stone properties of hardness and brittleness is appropriate here. Winkler states:

"The hardness of a mineral or rock is its resistance to permanent deformation and therefore an important factor for evaluating the workability of a stone in quarry and mill and its resistance to mechanical wear." (1975:30)
and he discusses several hardness parameters: scratch hardness, indentation hardness, abrasion hardness, rebound hardness and impact hardness (Winkler, 1975:30-35). While these different expressions of hardness are assessed in different tests, the scratch [Mohs], indentation [Vickers or Knoop], and abrasion [Kessler] hardnesses are all consistent for minerals assessed by Mohs (Winkler, 1975:38).

In these mineral tests from which Winkler infers rock hardness and strength, basalt is nearly always tested between limestone and quartzite (Winkler, 1975:32 [Fig.27], 33 [Fig.28], 34 [Fig.30], 36 [Fig.33], and 37 [Fig.35], and 40 [Fig.39]). Indentation hardness is the only one recorded by Winkler where basalt may be rated higher than quartzite (Winkler, 1975: 33 [Fig.28], but as only 1 of 5 parameters of hardness is anomalous to the others, perhaps the following explanation can suffice: 1) Winkler has related this parameter of indentation hardness to the maximum grain diameter of each rock; and 2) as grain diameter of basalts would be variable between fine-grained basalts and coarse grained or porphyritic basalts, with porphyritic basalts being coarse-grained; and as 3) Winkler’s data also show overlap between the two, where the fine-grained quartzites (e.g the hammerstones and chisels of the present study) are rated as being harder than the coarse-grained basalts (e.g the material of the present study), then it can be suggested that quartzites applicable to this study are consistently harder than basalts applicable to this study.

Rock brittleness is very complex (with minerals categorised as either plastic, plastic-brittle, or brittle) and is apparently
best assessed as being composed of several hardness parameters such as abrasion and indentation hardness. The brittleness of a rock may be suggested as that of its component minerals (Winkler, 1975:35). As basalt is compared to limestone, for example, basalt is quasi-elastic and limestone non-elastic (ibid., p. 43) as calcite, the component mineral of limestone, is considered to be brittle (ibid., p.35). Comparing the elasticity, plasticity and brittleness of quartzite and basalt (applicable to stoneworking discussed in this chapter) is more complicated. Since the coarse-grained rocks are less elastic than fine-grained rocks and since this is compounded with porosity (ibid., p. 43), thus if basalt is compared to quartzite, for example, quartzite being more fine-grained than basalt (again, the porphyritic basalts studied in this thesis) and also less porous, it is suggested that quartzite would be more elastic than basalt. This is perhaps debateable, but certainly in terms of Mohs hardness and strength classification (based on compressive strength), quartzite is both harder and stronger than basalt (Winkler, 1975:31-32, 40).

The following discussions will focus on stoneworking methods as these relate to the materials and tools applicable to this thesis. It must be clarified that the appraisals of stoneworking and the potential of accelerated weathering are limited to the materials discussed here, although application to other materials and stoneworking methods are possible.

9.2 Stoneworking Methods

Stoneworking causes irreversible deformation in several ways depending on stonedressing methods. Table 9.1 below lists some common stoneworking methods, not of all of which apply to
Table 9.1 SOME COMMON STONEWORKING METHODS

<table>
<thead>
<tr>
<th>Type</th>
<th>Probable Tool</th>
<th>Material Worked</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. FLAKING:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>quartzite</td>
<td>Wilke, 1988:55</td>
</tr>
<tr>
<td>b. Retouch</td>
<td>quartzite</td>
<td>flint, quartzite</td>
<td>Semenov, 1964:39, 44</td>
</tr>
<tr>
<td>c. Pressure</td>
<td>antler, obsidian,</td>
<td>quartzite</td>
<td>Semenov, 1964:44-55</td>
</tr>
<tr>
<td></td>
<td>chert</td>
<td>metal (flint, agate, chalcedony)</td>
<td></td>
</tr>
<tr>
<td>2. POUNDING:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Pecking</td>
<td>quartzite</td>
<td>quartzite</td>
<td>Semenov, 1964:66</td>
</tr>
<tr>
<td></td>
<td>basalt</td>
<td>basalt, limestone</td>
<td>Dorrell, 1983</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wilke, 1988:55</td>
</tr>
<tr>
<td>b. Battering</td>
<td>* dolerite</td>
<td>quartzite andesite</td>
<td>Lucas, 1962:64</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Protzen, 1986:85</td>
</tr>
<tr>
<td>3. GRINDING:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Rubbing</td>
<td>pumice, (granite,</td>
<td>marble, limestone</td>
<td>Lucas, 1962:70 &amp; ff</td>
</tr>
<tr>
<td></td>
<td>diorite, emery, sand</td>
<td></td>
<td>Wilke, 1988:55</td>
</tr>
<tr>
<td>b. Grinding</td>
<td>basalt</td>
<td>sandstone, diorite, limestone</td>
<td>Semenov, 1964:68-69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(limestone, marble)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>quartzite</td>
<td>obsidian</td>
<td>Semenov, 1964:19</td>
</tr>
<tr>
<td></td>
<td>stone (?)</td>
<td></td>
<td>Aldenderfer et al. 1989:54-55</td>
</tr>
<tr>
<td>5. BORING/</td>
<td>metal</td>
<td>flint, chalcedony, (bone)</td>
<td>Lucas, 1962:64-65</td>
</tr>
<tr>
<td>DRILLING</td>
<td>agate, quartzite</td>
<td></td>
<td>Semenov, 1964:78</td>
</tr>
<tr>
<td></td>
<td>(stone?)</td>
<td>(limestone, marble)</td>
<td></td>
</tr>
<tr>
<td>6. CHISELLING</td>
<td>metal</td>
<td>marbles, limestone</td>
<td>Ward-Perkins, 1972:</td>
</tr>
<tr>
<td></td>
<td>basalt</td>
<td></td>
<td>Yeivin, 1987</td>
</tr>
<tr>
<td></td>
<td>indeterminate</td>
<td>marbles</td>
<td>Torraca, 1988</td>
</tr>
<tr>
<td></td>
<td>marble</td>
<td></td>
<td>Rockwell, 1988</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bustamente, 1989</td>
</tr>
</tbody>
</table>

Notes:
1a-b-c differ mostly in tool and scale
2a-b differ mostly in tool and workpiece contact area
3a-b differ mostly in grade and type of abrasive
Some of these distinctions will be noted in the discussions.

* Battering is a combination of pounding and flaking action.

The tool in column 2 is not necessarily what was used to work the material in the adjacent level of column 3 (material worked)

( ) Parantheses usually mean material worked or the tool material was not necessarily given in the literature, although sometimes both tool material and worked material are given; these in ( ) may instead be extrapolated from other sources not given here for brevity. The exception to this is found in 1c where ( ) mean subcategories of "chert" (i.e. flint, agate, chalcedony as varieties of microcrystalline silica but not technical geological terms).
the present study. Definitions will be provided for applicable stoneworking methods in discussions; the other methods will be defined only as they relate to the applicable methods on which this chapter is focussed. Table 9.1 is not comprehensive for all stoneworking methods, tools, or materials worked.

Stoneworking methods have been discussed in some detail, most notably in the studies by Protzen (1985, 1986) for andesite in Inca contexts, by Lucas (1962) and Ward-Perkins (1972) on ancient Egyptian and Classical Greco-Roman contents respectively, and by Semenov (1957) for various methods and stones used since the Paleolithic period, although two weaknesses in Semenov’s studies include the dated nature of his discussions and ambiguities and technical lacunae in discussions coupled with probable excess of imagination from too little evidence on Paleolithic technology. The work of Lucas (1962) has been revised and updated from the original (1934) version and Ward-Perkins has used excellent ancient sources such as Vitruvius combined with field observation of ancient quarrying (1972) and is well regarded for his understanding of Classical stone technology and engineering (White, 1986) and Classical architecture (W.B. Dinsmoor, 1984, Architect, American School of Classical Studies, Athens, pers. comm.). With the exception of Torraca, none of the above studies discuss stoneworking damage as a factor of weathering.

Torraca has discussed the increase in microporosity and the increase in capillary action of aqueous solutions as results of stoneworking (Torraca, 1988:30 & ff) although his studies were mostly on carbonates, especially limestone and marble, rather than on the silicates (in this case basalt and andesite). Winkler
defines porosity as the "volume of pore space to its volume in per cent" (Winkler, 1975:28), listing the high porosity of andesite as between 10-15% (relative to quartzite at less than 1%; most (fine-grained?) basalt at 1%; and marble at 2%), with only shale exceeding andesite (10-30%) although limestone and sandstone have a porosity range up to 20% and 25% respectively (Winkler, 1975:29). Regarding porosity, Amoroso and Fassina state "Building materials with a high porosity have considerable space for water and, provided their pores are interconnected, they will have a high moisture content when saturated (Amoroso and Fassina, 1984:10-11). Winkler discusses capillary action in an exponential curve greatly influenced by the atmospheric relative humidity: "the higher the RH of the air in contact with the stone, the greater the capillary condensation" (Winkler, 1975:104-06). Amoroso and Fassini agree on the inescapable problem of humidity:

"Among the various agencies harmful to stone, humidity of different origins is one of the most important. In fact, in the absence of water there would be no chemical reaction of stone constituents...therefore the attack on stone would be reduced." (Amoroso and Fassina, 1984:12)

Thus, as prior studies affirmed for both parent lithic material and environment, the property of porosity combined with climatic features can greatly influence stone weathering. When compounded by stoneworking factors, weathering rates for stone such as basalt or andesite may be altered considerably.

Basalt and andesite in particular can also be listed as stone media on which a variety of these methods listed in Table 9.1 are directly applicable. This is shown in Table 9.2 as volcanic stone being recipients only of stoneworking, regardless of tools used.
Table 9.2 BASALT AND ANDESITE AS RECIPIENTS OF STONWORKING

<table>
<thead>
<tr>
<th>Method</th>
<th>Material</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. battering</td>
<td>andesite</td>
<td>(Protzen, 1985, 1986)</td>
</tr>
<tr>
<td>2. flaking</td>
<td>andesite</td>
<td>(Protzen, 1985, 1986)</td>
</tr>
<tr>
<td>2. pecking</td>
<td>basalt</td>
<td>(Dorrell, 1983 *)</td>
</tr>
<tr>
<td>3. grinding</td>
<td>andesite, basalt</td>
<td>(Semenov, 1964:69)</td>
</tr>
<tr>
<td>4. sawing</td>
<td>basalt</td>
<td>(Lucas, 1934:65)</td>
</tr>
<tr>
<td>5. boring</td>
<td>basalt</td>
<td>(Lucas, 1934:64)</td>
</tr>
<tr>
<td>6. chiselling</td>
<td>basaltic andesite</td>
<td>(Bustamente, 1989)</td>
</tr>
</tbody>
</table>

* also in Semenov, 1964:66

These methods will be discussed in following subsections in some detail. Other brief discussions of various methods include battering (pounding and flaking) as a preliminary roughing out method and pecking, abrading, and polishing for final finish (Wilke, 1988:55), or chipping, pecking, grinding, and polishing with a call to study their various mechanical principles by experiment and observation (Witthoft, 1974:50), although these may not necessarily apply to basalt and andesite. Percussion is often a general term; its application to working basalt and andesite needs to be carefully distinguished from other uses in the literature, and battering (as used here to mean pounding and flaking) also needs to be distinguished from pounding alone. Pounding and flaking leave very different remains on the worked surface, with flaking removing much of the intensely fractured regions around points of impact (Griffiths, 1990, pers. comm.). Percussion, as the term is used in many studies (where only percussion flaking may be implied), may be mostly related to the
working of flint and quartzite for tool production, or, when basalt has been used, these studies focus on basalt tool percussion wear rather than on the stoneworking damage to such artefacts as architectural ashlars or monumental sculptures. Of the work presented in this thesis, only investigation of wear on the Levant basalt tools would be applicable to such studies as, for example, edge damage on Hawaiian basalt scrapers (Price Beggerly, 1974).

Perhaps the best experimentally-derived discussion to date of the percussion and flaking stoneworking method of "battering" is that described by Protzen for Inca ashlars (Protzen, 1986:84-8). Another such discussion of stonedressing method is seen in the studies of Rockwell on stone chiselling since antiquity, which shows the effects of ancient and modern stone chiselling tools (Rockwell, 1988). Since the discussion of Protzen is focused on andesite specifically and is evidenced by many hammerstone finds (Protzen, 1986:99-100), many of quartzite, it is most applicable by reason of like hammerstone finds in other archaeological contexts of the present study. Although it is possible that chiselling causes even greater stone damage than battering by focussing the force of a blow unto a smaller area, this may not be verifiable. It is not only what proportion of impact energy from a blow is dissipated in plastic deformation and microfracture, but also in what proportion of the damaged material remains on the stone surface, particularly as flakes of stone may remove the microfractures caused by the previous blow (Griffiths, 1990, pers. comm.). Battering, chiselling, and grinding are the most applicable stoneworking methods to the
present study and will be examined in more detail in subsequent sections (9.3-5), including tools (e.g. hammerstones and chisels identified) from the different cultural contexts.

9.3 **Battering As A Stoneworking Method**

As stated earlier, Protzen's description of battering shows it to be a percussive technique, but specifically meant here to combine directed pounding and flaking. Semenov maintains that percussive methods are the oldest in stoneworking (Semenov, 1964: 39), with the primary percussive or hammerstone material also being stone. Another percussive term is pounding, but while it could have been both directed and have used degrees of force to include flaking, pounding as used in the literature will not be strictly assumed to be the same as battering (directed pounding and flaking with variable force applied) as defined here. Lucas also lists pounding first as a primary stoneworking method in earliest Egypt (Lucas, 1962 [1934]:64).

Protzen's experiments with andesite suggest the following probable Inca stoneworking technique. A hammerstone was held in both hands and directed at the surface of a rough andesite block, with angles of strike depending on the intended directed fracture and the pre-working shape of the block (Plates 9.1 and 9.2).

The typical hammerstones used by Inca stonemasons for rough work were quartzite cobbles weighing about 4 kg (Plate 9.3). Although the typical hammerstones for stoneworking were estimated by Protzen to have a Mohs hardness of 5.5, slightly more durable than the andesite being worked only by virtue of a greater resistance to cleavage (Protzen, 1986:99), quartzite hammerstones should have a Mohs hardness of about 7 (Winkler, 310
RUMIQOLQA QUARRY experiment with J.P. Protzen modelling hypothetical Inca stonework used to produce ashlar s as also shown below in Plate 9.2. The hammerstone being used is a relict Inca tool made of quartzite and the ashlar stone being dressed (for which Protzen also did all the rough shaping) is Rumiqolqa andesite. Time needed for the full process is approximately 90 min.

INCA "BATTERING" MODEL:
The illustration shows a hand-held hammerstone being used to remove large flakes first, and gravity - induced blows and angles are directed by wrist action as the large 4 kg hammerstone is dropped and guided in frames 1, 2, 3 & 5. In frame 4 a smaller 1.5 kg hammerstone is used for finer stone stonedingressing surfaces. Frame 6 shows results with a parabolic edge (not always produced). [from Protzen, 1986].
1975:32) and therefore significantly harder than the andesite. Protzen's experimental and artefact smaller hammerstones for stone finishing were usually around 1.5 kg (Protzen, 1986:99).

Protzen's hammerstone blows were actually mostly allowed to fall, powered by gravity, and directed with a wrist twisting just before impact for fracture angles. They were allowed to rebound before being caught, after which the process would be repeated blow after blow. The balance of the hammerstone was critical for directing fracture angle and consistency of strike. Each hammerstone shown to this researcher was roughly elliptical with parabolic curvature on the hammer ends and a higher density (being usually quartzite) than the andesite being worked into an ashlar shape (Protzen, 1986:96-99). Rough stoneding of a block about 25 by 25 by 30 cm was effected in 90 minutes using the above technique (Protzen, 1986: 99-100).

An ingenious amendment to Protzen's experimental stoneworking successes is suggested by Lee with architectural templates using scribing, plumb-and-bob, raised platforms, and counterweights for a one-step precision process matching of Saqsaywaman "cyclopean" boulders. Although much of the Saqsaywaman complex is constructed with limestone, Rumiqolqa (and possibly Huaccoto) andesite is found there, especially in the Myukmurka sections, which could be finally dressed by an arrangement as suggested above (Lee, 1990).

The immediate results of hammerstone blows are described by Protzen as small whitish scars at point of impact where the rock has been sheared away in typical conchoidal flakes. The whitish scars show localised crushing and compression of the stone. In his studies, Protzen also suggests that the pressure and
resulting friction of a hammer strike may produce sufficient heat which can partially metamorphosize limestone (Protzen, 1985:175), so the same pressure and heat of friction might be surmised for andesite on a different scale.

Ward-Perkins also refers to dolerite balls in quarrying, describing the pounding of granite surfaces in Pharaonic Egypt to free blocks from parent material, which would have much the same effect as it is comparable to battering (Ward-Perkins, 1972:4).

Pecking is somewhat intermediate between both battering and chiselling but is more related to battering than to chiselling, hence it is included in the discussion on battering. Pecking is evidenced on Neolithic material from Jericho (Dorrell, 1983 and 1990, pers. comm.). As an action it "punches" the stone surface with a stone tool having a pointed end. From the Early Bronze Age onward, the tools could be metal (bronze and eventually iron by the Iron Age) although in the Jericho Neolithic contexts, tools would be stone. In regard to Egyptian metal tools, Lucas rightly maintains the inability of copper and bronze to work harder stone such as diorite, granite, and schist (Lucas, 1962 [1934]:65). Pecking has been evidenced since the Neolithic (Semenov, 1964:66) with assumed hand-held pointed tools (like a geological hammer); probably delivering amounts of stress nearly equal to battering, with a primary difference being the stress concentrated in a smaller area like chiselling but with less control than chiselling because the chisel is stationary. Some of the differences suggested here may be arbitrary since pecking overlaps into both battering and chiselling. Other mention of pecking as a method can be identified through the literature (Witthoft, 1974: 50; Wilke, 1988: 55).
Plates 9.3 & 9.8

(Plate 9.3 [above]) INCA QUARTZITE HAMMERSTONES found at the Llama Pit of Rumigolqa Quarry; (Plate 9.8 [below]) a closeup of the left INCA HAMMERSTONE showing old fracture most likely from Inca use with new white scars from stoneworking for this study.
Both battering and the related pecking methods induce stresses in all directions in the stone being worked, although many of these will be vertical stresses which will also result in tendencies toward microfractures developing vertically (or perpendicular to the horizontal surface stone being struck). Naturally, where a conchoidal flake is produced, a shallow microfracture which was roughly parallel to the surface of the stone being struck creates a new surface edge, but the vertical microfractures still remain in the stone which has been struck.

9.4 Chiselling As A Stoneworking Method

Discussions of chisel stoneworking in the literature include those concentrating on ancient technology prior to metals or when the stone to be worked is harder than the metals produced by a contemporary technology (Lucas, 1934:65; Semenov, 1964:71). Thus stone chisels are required to be made out of a material like dolerite or quartzite for work on stones like basalt or andesite. Therefore, caution must be exercised when assumptions regarding a culture's level of technology maintain that lack of metal working is to be equated with a primitive society or low technology.

Chiselling as a stoneworking method would be similar to the battering method except for several factors. 1) Rather than stone being struck directly by a hammerstone, a chisel acts as an intermediate agent to absorb and redirect the force of a blow. 2) This redirected force is channeled down a blade length which acts to collect or constrict the force within the narrow area of the chisel's shank. Although the focus here is more with resistance to brittle fracture and not indentation, it is the stress, i.e. 315
ratio of internal force that occurs when a substance is deformed in any way to the area over which the force acts (Williams et al. 1980:142) that appears to be different between battering and chiselling specifically in the area affected, such that 3) finally the redirected force is released on a narrow point at a blade tip (rather than distributed over an area as broad as a hammerstone end). If the stone chisel is not significantly tougher than the stone being shaped, a high likelihood of breakage is probable, but some loss by breakage will occur even when stone chisels are much tougher than the stone being shaped. Chiselling also leaves white scars, as can be evidenced not only from basalt and andesite but also in a high volume of marble sculptures. In fact, many classical sculptures from the Greek and Roman period still show the chisel scars remaining after abrasive sanding and millenia of wear even though carbonate stone weathers at a much faster rate than basalt and andesite (Winkler, 1975:152; Hunt, 1989). The depth of microfracture by chisel action may depend greatly on the blade tip shape. The less acute-angled tip will have shallower penetration but greater local compression and probably greater durability; the more acute-angled tip will have deeper penetration but less local compression and probably less durability (Rockwell, 1988). These depths of microfracture may be to some degree also dependent on the contrast in hardness between the chisel and the medium being worked as well as the brittleness or ratios of elasticity to plasticity of each in comparison to each other, particularly as the ratios of stress to strain can provide comparisons of elasticity of various solids (Williams et al, 1980:144).

Ward-Perkins also describes some of the stone chiselling
tools and methods. He names axes or adzes for soft volcanic tufas of Central Italy, no doubt from northern Alban Hills quarries of Marino, Ariccia, and other Lazio tufas below Monte Porzio well-described elsewhere (Hibbert, 1985:316-17). Ward-Perkins also lists minimum stonedressing implements for finishing an ashlar block as a set-square, a template, and a broad-bladed axe. These broad-bladed metal axes work well for softer stone, but Ward-Perkins mentions coarse metal points or punches of iron or bronze and wooden mallets for harder stone. To quote him here:

"The remarkable thing is how much of the finest Greek classical sculpture was in fact not only roughed out but actually carved almost to its finished form with these very simple tools." (Ward-Perkins, 1972:4)

Coarse points (with less-acute point angles) and fine points (with more-acute point angles) as well as claw chisels are also noted by Ward-Perkins in the same passage. Most of the stone used in these classical contexts was carbonate like limestone and marble, usually estimated at 3 on a Mohs scale as inferred from calcite (Winkler, 1975:32), in contrast to the hardness of basalt and andesite, usually estimated at 5 to 6 Mohs hardness (Winkler, 1975:31-32).

Although Protzen mentions bronze pry bars used in some Inca quarries (Protzen, 1985: 184) he found no metal implements. This researcher has seen some small bronze axe blades (8 cm width) in Cuzco collections which might have sufficed for some stonework like the pry bars or might even have been used in stonedressing except that the andesite is too hard for bronze. Protzen's discussion of battering with quartzite appears more plausible as the primary stoneworking technique for battering the andesite. Furthermore, in a different context entirely at
the (Olmec) Museum of Santiago Tuxtla in Mexico, this researcher
was shown stone axes or chisels in 1989 by the museum director,
Dr. Bustamente. Made by Olmec craftsmen, the tools were purported
by Bustamente to have been used for Olmec sculpture. The stone
tools examined microscopically with a portable field laboratory
microscope, Swift FM-31 (see Ch. 4 of this thesis). They were
quartzite and dolerite with fine blade tips, sufficiently hard
(7 on Mohs scale) and very dense for the chiselling and dressing
of local basalts (at 5.5 on Mohs scale) from the Tuxtla Mtns.

Regardless of how many new stone chisels break from the
stress which they as secondary recipients are unable to channel
completely into a tertiary recipient, the net result on the stone
which is being shaped or dressed is that deeper microfractures
may result from impact concentrated by chiselling than from
battering with a broader area of impact, although this may be
debatable. Like battering, chiselling also induces a vertical
stress into the stone being worked, probably resulting in deeper
microfractures due to the concentrated stress on place of impact,
although again flakes will be removed along microfractures which
are roughly parallel to the surface being struck, with many
microfractures which are roughly perpendicular to the surface
being struck remaining in the stone surface.

9.5 Grinding As A Stoneworking Method

Grinding as a stoneworking method has not been considered
as a major method in the prior literature except secondarily as a
method of abrasion when making cuts with a sand and water slurry
or comparable agents (Lucas, 1934:64, 70 & ff; Semenov, 1964:68 &
Semenov notes that little evidence of grinding has survived from Paleolithic times and cautiously suggests it is a later development in relation to percussion and other methods (Semenov, 1964:68), although this is too artificial a hierarchic or tiered history of stone use in the opinion of this researcher. The fineness of finish achieved on many ancient sculptures, however, was produced by a polishing action for smoothing out surface deformities. Certainly grinding action is the exact method by which mortars, pestles, metates and querns operate in general on a softer substance and is probably also a primary shaping method for these very tools as well, especially in Neolithic contexts of Jericho basalts (Dorrell, 1990, pers. comm.) and by extension to many other stone tools.

For the finer stoneworking contexts, advantages of grinding over other methods are suggested by the following points: 1) smaller (i.e. finer) areas of surface can be shaped by grinding than by battering or by chiselling; 2) grinding removes material at the grain level without deep fracture below the surface; 3) one can achieve greater control over surface shaping by grinding than by battering (partly due to the necessary striking distance of a hand-held hammerstone from the surface being worked); 4) the optimum aim and result of grinding is the production of a smooth surface, generally with desirable flattening or removal of both asperities or depressions.

Examples of grinding as a stoneworking method may be seen on some of the archaeological material examined in this study: some Jericho Neolithic material, J 2025 for example, and possibly on Inca ashlars if "dragging" could be included when it produced deliberate results. However, Protzen has refuted grinding as
a final emplacement method for Inca ashlars to ensure tightness of fit (Protzen, 1986:86). Nonetheless, grinding action seems to necessitate the use of either a harder grinding surface or in some cases an equal hardness, i.e. same material, of surface, although it may be a matter of relative hardness which produces different rates of polish (Griffiths, 1990, pers. comm.).

Of the three major stoneworking methods discussed, grinding is probably the least damaging in terms of the internal stress and microfractures remnant in the finished stone. It is unlikely that grinding will result in significant microfracture. Thus, it is also probable that grinding will produce far less acceleration of weathering. Unlike battering (and pecking) or chiselling which produce internal stress, grinding results primarily not in flake loss (macro-scale) but only in grain loss (micro-scale).

9.6 Summary of Stoneworking Weathering Mechanisms

Because the prior literature lacks the detail suggested here, the mechanisms by which weathering is accelerated are suggested as follows. A (hammer or chisel) blow is received by the stone, which absorbs the force but the stone is brittle and insufficiently elastic or plastic to absorb all the stress. Thus the force of the blow is transmitted into the stone and causes fractures, some of which detach flakes and others of which remain in the stone surface as microfractures through the plastically-deformed region beneath the point of impact. As the thoroughly worked surface of the stone is then exposed to weathering agents, e.g. oxalic acid and carbonic acid (to name two natural ones) in aqueous solution, the microfractures act like capillaries and
increase surface area. Because both surface area and microporosity are greatly increased, the actual rate of weathering can be greatly accelerated on such a modified surface as presented by an archaeological monument or ashlar, compared to natural rates on unmodified geological material as suggested by Colman et al. on geological surfaces formed by large-scale fracture or grinding. As already suggested, this acceleration would be greatly reduced by grinding in that little additional surface area would result from mineral grain removal as opposed to vertical stress in battering and chiselling.

In summary, the fundamental difference between worked and unworked stone is that worked stone has more surface area for weathering (when one considers that microfractures act as pairs of surfaces susceptible to hydration. This will vary with the depth of microfracture and fineness. Microfractures are likely to be densely packed and convoluted; even shallow microfractures over the entire surface of an ashlar could easily increase the overall surface area by a considerable difference. That is, the exposed surface to weathering would be considerably greater, and weathering would be accelerated. Naturally, this will vary with the number and distribution of blows preferentially concentrated in some areas more than others.

The following specific qualifications apply. It must be clear that not all stone surface areas are equally worked. In the case of some Inca ashlars, drafted roughly parabolic edges receive the highest concentration of stoneworking in terms of received stress (and some edges or surfaces not in public view may receive very little finishing or not be at all parabolic). Because ashlar corners required an aesthetically-determined fit,
since Inca architects or masons appear to have given the greatest consideration per stone to these highly visible relief details, weathering should then be greatest at this focal point of stress. This should result in some measurable weathering differences as well as provide the most consistent gauge of weathering per stone since one can guarantee a parabolic drafted edge is not a natural surface but a modified one, and this is equally true for finely finished ashlars with squared edges (Figure 9.1; also Plate 5.5 and Plate 10.11).

In summary, it could be argued that a considerably increased surface area arising from shaping artefacts could result in a significant acceleration of the initial rate of weathering. Much research is required beyond the scope of this preliminary study to ascertain and quantify such a finding.

Suggested evidence of accelerated weathering by mechanisms of stoneworking will be provided in examples compared from several contexts to be elaborated in Chapter 10. However, the following discussion of Ollantaytambo Inca material offers the clearest evidence of stoneworking-accelerated weathering from this study.

9.7 **Deterioration of Inca Ashlars at Ollantaytambo**

Ashlars 2 and 39 (sample numbers from this researcher’s fieldwork) at the Inca complex at Ollantaytambo, Peru (see Ch. 5) are notable for showing exceptional voids near the worked edge surfaces (Plates 9.4 & 9.5) as seen by SEM photomicrographs. Several parameters characterise these deteriorated areas, which appear to result from microfractures, increased surface area and resulting increased microporosity.
The suggested parameters are: 1) up to 2 mm of "honeycombed" texture which is 2) consistently contiguous with and 3) parallel
to the worked edge; 4) with pores easily visible on the ashlar surface edge (where they open to the outer surface). Furthermore, as the parent material is relatively free of vesicles, it cannot be suggested that these voids of honeycomb texture are merely due to high vesicularity, particularly since the area of voids stops at a rough distance of 2 mm from the worked edge.

The original context of these ashlars appears to be use as fountain stones for an Inca waterway or aqueduct (see Ch. 5, Ollantaytambo) i.e. stones over which water flowed for an indeterminate period of time. This suggests that some hydration would be associated with these biotite andesite ashlars which find their closest geological parallels in the Huaccoto sources (Chapter 5). While the factor of increased water action must also be considered here, indeed may be even more responsible than the stoneworking itself, it is the stoneworking which has provided the access to the stone adjacent to the surface. This appears underscored by the apparent unscathed aspect of the stone beyond the 2 mm edge.

No other Inca material exhibited comparable weathering (as discussed in Chapter 9), but no other material was identified as being from a fountain context. It is assumed, therefore, that if other Huaccoto material could be found with comparable stoneworking and in a water-associated use, it would exhibit like phenomena; conversely that if Rumiqolqa material could be found in similar water-related contexts it might not exhibit identical phenomena (but could approximate them) due to differences in parent material (mineralogy), as it will be seen in the next chapter that Huaccoto material appears to weather at a much faster rate than Rumiqolqa material. Further discussion of these
(Plate 9.4 [right]) shows SEM MICROPHOTOGRAPH of a vertical MICROFRACTURE probably induced by Inca stoneworking on the edge of a Rumigolga ashlar. Some microporosity has begun to widen the crack from its original planar cleavage through stone.

(Plate 9.5 [left]) shows a SEM MICROPHOTOGRAPH of a resulting large MICROPORE area and honeycombed area of leaching channels from capillary action. The Inca "fountain context" of this Ollantaytambo andesite has apparently accelerated the weathering here to a stage normally seen only on the geological material. The weathering rind is also of a lighter surface colour.
Ollantaytambo ashlar will be continued in Chapter 10 on rind colour, rind thickness, and chemical analyses.

9.8 Stoneworking and Porosity Experiments

Experiments undertaken by the present study confirm that the primary deformation in Huaccoto and Rumiqolqa andesite caused by hammerstone strike blows is a proliferation of microfractures on the stone surface. The experimental parameters and results are as follows.

The primary question asked was whether or not immediate stoneworking damage and increased porosity could be measured. The preliminary nature of these experiments suggest that the means set up to measure parameters of immediate damage and increased porosity would likely be insufficient to accurately reflect any quantitative results and perhaps only qualitative differences could be proposed at this time.

Stoneworking and porosity experiments were conducted at the Petrographic Laboratory, Trailer 11, U.S. Geologic Survey, Menlo Park, California, in 1989 and in the Petrology Laboratory of the Institute of Archaeology, University College, University of London, in 1990. Samples of fresh andesite were brought from both Rumiqolqa and Huaccoto quarries. These andesite samples had no evidence of stoneworking and were closely compared to fresh rock which was "worked" by this researcher at the Llama Pit of the Rumiqolqa quarry under the guidance of J.P. Protzen in 1988.
I. EXPERIMENTAL STONEWORKING

Problem: Can one immediately assess stoneworking damage?

A. Experimental Parameters of Stoneworking:

1) Andesite samples from Rumiqolqa and Huaccoto were "battered" i.e. percussed by gravity-induced pounding and flaking as per Protzen's instruction and written accounts (noted here in Ch.9). "Unworked" samples required that a fresh surface was obtained only by a blow not directly associated with that surface.

2) The hammerstone was an authentic Inca tool (collected by this researcher at Rumiqolqa in 1988) and was quartzite, with old endwear (see Plate 9.3). Its weight was 3.5 kg.

3) The number of andesite samples was 6 of Rumiqolqa and 5 of Huaccoto material. The number of blows attempted exceeded 25 per material. Hammerstone blows were always directed at a consistent edge location on each sample from the same distance.

B. Observations of Experimental Results:

Consistent results were obtained in the following ways:

1) there was always some white powder and small flakes of fresh grey andesite resulting from the blows;
2) the size of the white powder ranged from microscopic to F 300 carborundum powder;
   the grey flakes ranged from sand grain size to 12 mm;
3) the grey flakes were often conchoidal in shape and could be seen to fit comparable conchoidal "gouges" on the parent rock surface (although not even 50% of flakes were conchoidal, most were longitudinal);
4) compression "dents" often accompanied blows; many up to 0.3 mm
5) white scars nearly always resulted from each blow (although very small [0.1-0.2] when stone flakes flew off);
6) white scar depth range from 0.7 - 2.2 mm.
7) Huaccoto material white scar depth usually deeper or larger, longer flakes removed;
8) Rumiqolqa material white scar depth usually shallower or smaller, shorter flakes removed.

C. Tentative Experimental Conclusions of Stoneworking

1) Worked andesite shows white scars from fresh stoneworking.
2) White scars are assumed to be microfractures.
3) Examination first with magnifying lens and second with stereoscopic microscope (at 25 X) appears to confirm microfracture assumption.
4) Based on B 7) & 8), Huaccoto material appears softer than Rumiqolqa material.

Answer: Apparently Yes, but interpretation is not secure; preliminary only at this stage.

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II. EXPERIMENTS IN POROSITY

Problems: Can one immediately assess increase in porosity of recently damaged andesite compared to fresh or undamaged andesite? How best to test possible increase in porosity?

A. Experimental Parameters of Testing Porosity

1. Andesite samples were assembled from Rumigolqa and Huaccoto, many were from freshly worked material in Experiment I.
2. Needle was fixed in place unto stone surface (worked or unworked) higher than the observed area (see 4).
3. Small (5ml) droplets or beads of water were placed at the top of a waxed needle (waxed to slow down flow of water and to control volume of drop) and...
4. Water was allowed to descend by gravity to spot above and higher on the observed surface (which was held at 45 degree angle so water would reach observed surface in a few seconds).
5. This was repeated with methylated spirits (m.s.).
6. A 15 x magnifying lens was used for observation with a stopwatch for timing rate of flow across surface.
7. All repeated (except 2) using a glass pipette (eye dropper) with a rubber water-filled bulb (manually squeezed) and aperture of 1 mm in diameter.

B. Observations of Experimental Results

1) Speed of flow of m.s. across worked stone was too rapid to compare with unworked stone;
2) Speed of flow of water over freshly worked white scar appeared sometimes faster, sometimes the same, but more often there was a tendency to a slower rate than on unworked stone in 40% of times tried (approximately 20 out of 50 x). Average overall time of each time 0.75 seconds with stopwatch.
3) No significant difference was noticed between Rumigolqa and Huaccoto material in terms of rate of flow.

C. Tentative Conclusions:

1) Worked andesite appears to have greater porosity than unworked andesite in that worked stone absorbed more water, slowing down surface flow. Premise: absorption is related to increased porosity.

Answer: Unknown, because premise could be mistaken. Rate of flow could be hampered by stoneworking detritus rather than slowed down due to absorption into "microfracture."

Solution: Better experimental parameters are required before any reliable conclusions are drawn.
Mercury porosimetry has been suggested as a more quantitative method to assess potential increases in porosity (T. Keith, pers. comm., 1989). Evaluation of experimental premises and method or sequences employed may show them to be problematic, but as a simple and repeatable reconstruction of probable Inca stoneworking results, the above experiment on stoneworking microfracture may offer some reasonable (albeit very tentative) explanations for observable Inca surface damage on ashlars, especially as this study is the first assessment of stoneworking as a weathering factor on Inca material and the first comparative study of Inca andesite ashlar weathering. The porosity experiment has both premises and elements which are not satisfactory to date in the opinion of this researcher. Both experiments need to be repeated multiple times and be significantly refined to have any significance other than as catalysts or trial and error methods to initiate thinking on the questions which need to be asked. One suggested improvement of the stoneworking experiment might be to attempt a variety of stoneworking methods (battering, chiselling, grinding, etc.) on one material (basalt), then one stoneworking method (e.g. battering) on a variety of different stone materials (andesite, basalt, sandstone, marble, limestone, quartzite, etc.) in order to assess microfracture depths per stone per method. One suggested improvement of the porosity experiment might be to use the stopwatch and a stereo microscope to time the flow of water across the field of view at a given magnification. A second improvement of the porosity experiment might be to soak a stone whose surface has not been worked in a measured quantity of water for a given period of time and at a given temperature and then assess how much of the water has been absorbed from the
measured water volume into the stone as a standard porosity index (Winkler, 1975:29) and then to repeat the process with a freshly worked stone of the same material, volume and weight to determine if any noticeable change in absorption has occurred.

Preliminary experimental results suggest at least two possible explanations for the whitish stoneworking scars noted by Protzen and also this researcher (Plates 9.6 to 9.8, note Plate 9.8 is with Plate 9.3 for white scars on a hammerstone). 1) These scars produced by stoneworking are likely to be the optical result of compression and pulverizing (although only part washes off in water, which brings the fullness of this explanation under question). Although the white scars on andesite may be explained by heat friction (as Protzen suggested with limestone and its partial metamorphosis, 1985:175), this is dubious. At least one reason for this not to be likely is that insufficient heat would be produced under the conditions of impact. Mechanisms of metamorphosis require intense heat and pressure at plutonic depth over long geological time or their equivalents in laboratory conditions of simulation and acceleration (Mason, 1978).

In the opinion of this researcher, 2) a better explanation is that proliferated microfractures (which can remain white after washing with water) decrease translucency of the stone. The white scar appears to remain through early weathering until the many localised microfractures are hydrated. This could take several years or longer depending on all the factors and their weathering "aggressiveness" such as found in tropical climates. The fact that weathering rinds are softer than the subsurface fresh stone (easily crushed with a hammer) may also suggest that the
compressible nature of microfractures after significant weathering has given a "honeycomb" texture to the weathered area. This was also observed by Colman et al. on particularly old geological material (Colman and Pierce, 1981:4) where no microfractures would occur but long term leaching could result in a comparable microporosity. 3) It is also likely that some combination of 1) and 2) is responsible: compression and some pulverizing along with loss of translucency due to the fine network of microfractures.

It is also to be noted that some of the whitish scars remain on Protzen’s original experimental andesite surfaces in Peru after more than 5-7 years of weathering exposure have elapsed (Protzen, 1986:80-88). However, none of the relict worked Inca ashlar blocks in the same Rumigolqa quarries show any such whitish scars after 500+ yrs of exposure to weathering factors; all such probable scars have apparently weathered to have the same appearance as the ashlar faces in superficial appearance, even though there may be subsurface weathering rinds. If indeed accelerated weathering took place on these surfaces, one could expect these original Inca scars to have weathered.

The experiments attempted to repeat Protzen’s methods but with an added assessment of immediate microfracture damage and increased porosity. The tentative conclusions support the premise that stoneworking damage can be immediately assessed. If the premise (in the porosity experiment) that "rate of flow is slower due to absorption of water from the worked stone surface" can be proven to be reliable, then a significant assessment of increased porosity due to stoneworking has been initiated.

The implications of this new research raise questions about
(Plate 9.6 [right]) FRESH STONEWORKING EXPERIMENTS shows the experimentally-derived white scars from "battering" the unworked Rumigolqa andesite. This surface has been washed with water with the white scar still remaining.

(Plate 9.7 [left]) shows FRESH STONEWORKING results with white scar derived from "battering" Huaccoto andesite. Even though the scale on Huaccoto stone is slightly larger, the depth of scar (microfractures?) appears greater here, thus reinforcing the opinion of this researcher that most Huaccoto stone is softer than the Rumigolqa stone.
incipient weathering of basalt suggested by Cernohouz and Solc, particularly if basalts employed in Bohemian castles received such mechanical stress in the dressing or shaping of stones. Unfortunately, their study did not provide such information. Any dependence, therefore, on their exponential weathering rates for early basalt weathering may prove problematic.

9.9 Conclusions

Accelerated weathering of stone in general by stoneworking has been suggested (Toracca, 1988) but apparently not applied in the prior research on basalt and andesite weathering (Cernohouz and Solc, 1966; Colman and Pierce, 1981). The present study has compared three relevant stoneworking methods: battering, chiselling, and grinding, and has suggested that battering and chiselling cause the greatest depth of microfracture while grinding appears to cause little microfracture damage. Chiselling appears to focus greater concentration of stress on a small locus of stone surface where battering appears to distribute the stress over a broader area.

Both battering and chiselling appear to induce vertical stress on stone, resulting in microfracture plus flake loss on a large scale whereas grinding appears to induce less flaking and no apparent microfracture but only grain loss on a small scale.

Furthermore, worked stone analysed by this researcher showed a probable average microfracture depth of 1-2 mm for Inca ashlar material presumably caused by battering (see Plate 9.4) and a probable deeper microfracture level caused by chiselling (> 2 mm) in other archaeological material at Tres Zapotes. Finally, worked stone appears to have a greater porosity than unworked stone due
to microfractures produced by working the stone. The fundamental increase in weathering seems to result from the greater surface area caused by microfractures. These appear to be the factors which accelerate weathering in archaeological andesite or basalt which has been worked or dressed by various methods. It is vital, then, that any subsequent study of basalt and andesite weathering (if not stone in general) must consider possible acceleration of weathering with the stoneworking method used. Finally, it cannot be iterated too strongly how the contributions of this chapter (particularly the application of evidence from the building stone industry to the questions of accelerated weathering for archaeological stone, the evidence for accelerated weathering in some Inca andesite ashlars, and the experimental assessment of immediate stoneworking damage and increased porosity in andesite) are original and necessary, requiring integration into the literature on basalt and andesite weathering in archaeological contexts.
Chapter Ten

NEW STUDIES IN THE WEATHERING OF ARCHAEOLOGICAL BASALT AND ANDESITE

10.1 Archaeological: Geological Weathering Contrasts

The same factors which result in geological weathering should also cause weathering in archaeological material, but with at least five differences. 1) The duration of time considered will usually be far smaller for archaeological material (except some Paleolithic contexts). Therefore 2) the weathering of basalt and andesite in archaeological contexts may be much less measurable, which may complicate assessment or, in fact, 3) may exhibit different phenomena not observed by Colman and prior stone researchers. 4) To distinguish between geological and archaeological weathering (or natural and unnatural weathering), certain features of human contact with the stone must be observed (e.g. reorientation as in cairns, fieldstone walls, etc.) which allow for both initial geological weathering before human contact and archaeological weathering after human contact. This was anticipated in part by Winkler in his assessment of Cernhouz and Solo with their weathering study of basalts from Bohemian castles although there was no distinction raised between archaeological and geological weathering rates (Winkler, 1975:151). 5) The stone as used in an archaeological context (e.g. architecture) may be modified to a greater or lesser degree by stoneworking and dressing with tools (which introduces factors not considered in the research of Colman et al.), as elaborated in Chapter 8. Also, 6) on ashlars in Colonial Cuzco, effects of continuing human use may mean that stones worked in the past may undergo further accelerating action (Colonial walls in Cuzco which lack the

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majesty of Pre-Conquest Inca walls are used as public urinals by the Quechua descendants of the Incas). Other weathering differences may also be involved which were not encountered in the present research.

It must also be considered that the aggregate of factors assessed by prior studies with regional focus (e.g. the temperate Western U.S. intermontane zones of Colman et al. or the temperate Bohemian intermontane zone of Cernohouz and Solc) and different sampling microclimates (up to 30 cm subsurface with Colman et al. or above surface on castle walls in Cernohouz and Solc) may pose considerable problems in applying their results to this research.

10.2 Weathering Colour Contrasts in Selected Archaeological Contexts

Synthesizing Colman’s and Winkler’s observations that early stages of rind development or mineral depletion can be largely defined by oxidation colours produced by mineral alteration of glass or of ferromagnesian minerals like olivine (Colman, 1982:10) or biotite (Winkler, 1975:164), Table 10.1 below identifies such minerals in their archaeological contexts, apparently without precedent in the prior literature. To the knowledge of this researcher, no other systematic or even preliminary comparison of selected weathering of andesite and basalt in archaeological contexts has been suggested with potential explanations. The rationale for examining surface stain is based on the hypothesis that two separate lines of evidence may be necessary: 1) short-term weathering of basalt and andesite may be identified by hue (oxide staining); and 2) long-term weathering may be identified (and separated from short-term thusly) by the development of
weathering rinds. However, where both long-term (geological) and short-term (archaeological) weathering exists in archaeological contexts, their surface and rind depth contexts must be examined separately as well as in calibration with each other. Finally, it is likely that some material will exist (but not necessarily the oldest) where a combination of both geologic and archaeologic weathering may be evidenced.

Table 10.1 WEATHERING COLOURS ON ARCHAEOLOGICAL SURFACES OF SELECTED BASALT AND ANDESITE CONTEXTS

<table>
<thead>
<tr>
<th>Context</th>
<th>Weathering Colour</th>
<th>Estimated Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Colonial Spanish ashlars, Cuzco</td>
<td>total rusty red (A biotite ++)</td>
<td>350 + yrs (1550 A.D.)</td>
</tr>
<tr>
<td>2. Inca ashlars: Korikancha Cuzco, Peru</td>
<td>partial rusty red (A hornblende +)</td>
<td>450 + yrs (1450 A.D.)</td>
</tr>
<tr>
<td>3. Inca ashlars: Intiwatana Pisaq, Peru</td>
<td>pale cream to pink (A augite ^)</td>
<td>450 + yrs (1450 A.D.)</td>
</tr>
<tr>
<td>4. Inca ashlar: Pisaq Quarry Pisaq, Peru</td>
<td>pale cream to pink (A augite ^)</td>
<td>550 + yrs (1350 A.D.)</td>
</tr>
<tr>
<td>5. Aztec frieze: Pl.Srp.Pyr. Xochicalco, Mexico</td>
<td>pink to ochre (A augite ^)</td>
<td>600 + yrs (1300 A.D.)</td>
</tr>
<tr>
<td>6. Aztec sculpture: Xochipilli Mexico City, Mexico</td>
<td>ochre</td>
<td>600 + yrs (1300 A.D.)</td>
</tr>
<tr>
<td>7. Tiwanaku monuments Tiwanaku, Bolivia</td>
<td>pale rust beige (A hornblende +)</td>
<td>800 + yrs (1100 A.D.)</td>
</tr>
<tr>
<td>8. Tres Zapotes monuments Tres Zapotes, Mex.</td>
<td>pale green (BA Mg-clinopyrox. + &amp; Mg-forsterite +)</td>
<td>3000 + yrs (1000 B.C.)</td>
</tr>
<tr>
<td>9. Olompali Petroglyphs Burdell Mt., Calif.</td>
<td>pale pink to white (A augite ^)</td>
<td>4500 + yrs (2500 B.C.)</td>
</tr>
<tr>
<td>10. Canaanite mortars Hazor, Israel</td>
<td>dark grey (B olivine +)</td>
<td>3300 + yrs (1300 B.C.)</td>
</tr>
<tr>
<td>11. Cycladic ashlers Acrotiri, Santorini</td>
<td>grey to black (A augite ^)</td>
<td>3500 + yrs (1500 B.C.)</td>
</tr>
<tr>
<td>12. Jericho grinding tools</td>
<td>dark grey</td>
<td>10,000 + yrs (8000 B.C.)</td>
</tr>
</tbody>
</table>

B = basalt   A = andesite   BA = basaltic andesite
++ very high content > 20%
+ high content > 10%
^ moderate content > 5%

The next three subsections examine visible surface weathering.
hues as provided above in Table 10.1 for the purpose of comparing weathering factor influences as evaluated in Chapter 8. It is not to be underestimated how vital such noted comparisons should be in coming to a better understanding of both local and global weathering processes on archaeological material. Nor should it be omitted that this is the first-ever articulation of comparative archaeological weathering of basalt and andesite contexts.

10.2.1 Colour Contrasts between Intra-Cuzco Contexts

The first contrast considered examines material found in similar environments in Cuzco but with significant differences in parent material. The proximity between the Colonial Spanish wall sampled and the Inca Korikancha is less than 100 m distance and both contexts face in the same southwesterly direction. The fundamental question to be asked is how influential might parent material be when environmental contexts are so similar?

It should be noted from Table 10.1, for example, that the Colonial Cuzco material is biotite andesite from Huaccoto (Ch.5) and emplaced later than the Koricancha material, a hornblende andesite from Rumiqolqa. In applying assessments of biotite alteration (e.g. Winkler and Ollier, 1975 and 1984 respectively, neither of whom appear to have observed or discussed Huaccoto quarries source material or its in situ use in Cuzco) it is important that while the fresh Huaccoto parent material shows little oxidation colour (being often pale grey), and shows unaltered biotite phenocrysts in thin section (Plate 5.4), the Cuzco Spanish Colonial ashlars appear to be highly weathered although less than four centuries have elapsed since their emplacement. They are soft and easily crumbled as well as
thoroughly rust-red at least several centimetres below the surface, which Gregory also noticed in 1912 (Gregory, 1916:92 & ff). Possible explanations for this are listed below in Table 10.2 in order of probability. These tentative explanations are extrapolated from the observations of Colman et al., Ollier, Winkler, and others as provided in Chapter 8, especially section 8.2 on individual mineral grain weathering.

<table>
<thead>
<tr>
<th>Table 10.2 HUACCOTO : KORIKANCHA WEATHERING COLOUR CONTRASTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral Chemistry</td>
</tr>
<tr>
<td>Phenocryst Size</td>
</tr>
<tr>
<td>Phenocryst Shape and Cleavage</td>
</tr>
<tr>
<td>Phenocryst Perfection</td>
</tr>
<tr>
<td>Phenocryst Textural Volume</td>
</tr>
<tr>
<td>Stoneworking &amp; shaping</td>
</tr>
</tbody>
</table>
Furthermore, an additional factor sheds light on the state of the sampled Cuzco Colonial Spanish biotite andesite ashlars. As stated earlier, the current Quechua population (relict Inca) of Cuzco seems to use the sampled section of wall as a public urinal (perhaps in scorn of its inferior workmanship compared to the Inca ashlars, perhaps as a rejection of the Conquest, or perhaps only as a matter of convenience). Furthermore, SEM (with EDS) analysis of sample ashlar material showed high sulphur content in clusters throughout the thin sections which were anomalous to phenocryst, xenolith, or intergranular groundmass locations which SEM micrographs clearly show (see Plates 10.1 and 10.2). Although any such amount of sulphur is foreign to the geological material from Huaccoto, such presence of sulphur in stone ashlars is possible at an elevated level as a concentrated byproduct of metabolites through bacterial colonisation in the urine deposited on the stone (Noble, 1991, pers. comm.) as found in the SEM analyses of Cuzco Colonial walls. Thus this could be such a human modification of a stone surface which would be in addition to actual stoneworking. Not only this, but no such use of imperial Inca ashlars as a public urinal appear to exist in Cuzco to this researcher's knowledge, even though it appears many could serve equally well for convenience.

Although this is only a suggestion, it might be possible that this crude Spanish Colonial masonry carved and emplaced here in Post-Conquest edifices elicits such a derogatory attitude from Quechua descendants of the Inca who are rightfully proud of the superior stoneworking of their ancestors. What is probably more certain, it is suggested here that early Inca use
Plate 10.1 shows SEM MICROPHOTOGRAPH of CUZCO COLONIAL material with large pits (lower left) associated with a corroded stone appearance. Uric acid in urine is relatively corrosive of materials including stone (Noble, 1991).

Plate 10.2 shows a SEM MICROPHOTOGRAPH of a DOT MAPPING of SULPHUR by EDS analysis, with the elevated level of sulphur occurring in the corroded pits of this COLONIAL CUZCO wall surface. As stated in the text, such anomalous sulphur presence can be found with bacterial growth in urine deposits on and in the Cuzco stone wall, also accelerating weathering by such human modification.
of Huaccoto quarries may have indeed found rapid deterioration of the biotite andesite and even an undesirable staining after a few generations of emplacement (which could also suggest some minor chronometric deductions). This in itself might have led to development of the Rumiqolqa quarries in looking for a more suitable masonry material than the Huaccoto biotite andesite which had been proven unsatisfactory by experience. In this case it appears as suggested in Chapter 9 and some prior literature that, all else being equal:

\[
\text{parent material} > \text{climate} \\
\text{and} \\
\text{parent material} > \text{time}
\]

as the most influential weathering factor of the three for these archaeological andesite contexts in Cuzco.

In summary, this evidences that difference in parent material can account for tremendous weathering differences when nearly all other weathering factors appear equal. Assuming that a century of time could be significant, it is the younger context which has weathered more (despite the fact that the Huaccoto geological material appears fresher in unworked quarry andesite and is most likely younger in geological age). Aside from the added pollution of accessible Colonial walls for a public urinal, all of the Huaccoto material above the urinal height appears equally red with iron oxide stains. Given that other environmental contexts (with a difference of less than 100 m between the two contexts and an identical southwesterly direction of placement) and that stoneworking methods would be roughly equal, the factor of parent material as a determinant of weathering cannot be underestimated.
10.2.2 Colour Similarity between Levant Neolithic and Canaanite Contexts

The second example for which explanation is offered is a comparison between contexts of uniform parent material but from widely different duration of weathering periods. This should be, in terms of potential for relative dating, an ideal gauge of time alone as a weathering factor, all else being equal.

The factors in common are noted first. First, stated in Ch.7, Jericho—Great Rift Valley Cover Basalt material distributed over an area greater than 500 sq.mi. has a uniform chemical character and mineralogy (Schulman, 1967:104; Williams-Thorpe et al., 1990b) as olivine basalts. This certainly applies in both the Neolithic material sampled from Jericho and that from Canaanite Hazor. Second, the general climate in both sample areas is semi-arid: although Hazor may have up to 100% greater MAP than Jericho at 400 mm compared to 200 mm, little difference exists in MAT at roughly 20°C for Hazor and 23°C for Jericho (Rosenan, 1970). Third, both materials examined in these two contexts sampled exhibited comparable stoneworking contexts as probable tools with use wear visible on their bluntly-rounded ends.

Possible explanations for similar weathering colour despite differences in time of exposure are as follows below (Table 10.3) extrapolated from the mineral weathering review from Chapter 8:

Table 10.3 HAZOR: JERICHO SIMILARITY OF WEATHERING COLOUR

<table>
<thead>
<tr>
<th>Parent</th>
<th>Environment</th>
<th>Possible Explanations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material:</td>
<td>1. If the younger material is sufficiently coarser-grained and the and the older material was sufficiently finer-grained, some equalised weathering could occur (Colman and Pierce, 1981:12).</td>
<td></td>
</tr>
<tr>
<td>(grain size)</td>
<td>2. Comparable weathering could occur if the soil depth of the younger was shallower and soil depth of the older was deeper; or because the soil depth of both was below a weathering</td>
<td></td>
</tr>
</tbody>
</table>
Table 10.3, cont.

(soil depth)          front in the stratigraphy (Colman and Pierce, 1981:7). In fact, stratigraphic contexts were such that the Jericho material was the deeper of the two contexts: Jericho Neolithic > 5 m; Hazor Canaanite 1-2 m.

Parent Material
Deposition Age

3. If the younger material was of a sufficiently higher porosity than the older material, the younger material could have an accelerated weathering (or the older material a retarded weathering due to surface area differences (Ollier, 1984:60-62). In fact, stone porosity variations between the basalts were not consistent (although at least one very porous Neolithic sample is noted, e.g. J 2025).

4. Although the archaeological age of Jericho material could be older, its geological age (and therefore pre-worked weathering) could be younger. In fact, deposition age appears impossible to gauge at this point since no determination of provenance has been made for either archaeological material. On the other hand, some of the Hazor material appears more fresh than some Jericho material, which might suggest a younger age for the Hazor material.

Although three of the above circumstances are unverifiable, the second possible scenario was indeed verifiable based on the stratigraphic records of both Jericho and Hazor excavations. Much of the Jericho Pre-Pottery Neolithic material has a depth of stratigraphy of greater than 5 m subsurface (compared to Hazor depths of 1-2 m for sampled material), which may be the most significant weathering factor as discussed above (along with some difference in MAP) despite the greater archaeological age of the Jericho material by more than 5 millenia (Dorrell, 1983). The question remains whether this alone could account for all of the apparently similar weathering hue between Hazor material whose archaeological age is from c. 15th to 13th c. B.C. compared to the Jericho Neolithic material whose archaeological age is from
c. 8500 B.C. Applying the stratigraphic differences between the sampling of Colman and Pierce and that of the present study, it is possible that characterisation of weathering may be difficult to assess given such sampling depth dissimilarity. Several such interpretations of the influence of these factors follow:

\[
\begin{align*}
\text{environmental differences in stratigraphic depth} & > \text{differences in archaeological time} \\
\text{geological age of deposition} & > \text{archaeological age of context}
\end{align*}
\]

It should be obvious that a pre-use longer geological weathering of younger archaeological material could be greater than a post-use longer archaeological weathering of younger geological material if stoneworking methods were identical.

On the other hand, the results could show that differences in stratigraphy are no more important than time, which itself may not be a significant factor, if weathering colour is identical. Without more sampling and more data on the other three apparently "equalising" factors, a more complete assessment is unlikely.

In summary, this scenario does not contradict Colman et al. or exponential weathering rates of Cernohouz and Solc with time as the most influential weathering factor. The questions it raises in regard to stratigraphic depth as a weathering factor perhaps best associated with microclimate could be significant in other archaeological contexts, particularly where these stratigraphic depths contrast with continual surface exposure.

10.2.3 Colour Contrasts between Olmec and Canaanite Contexts

The third surface weathering contrast to be noted examines...
two somewhat similar but not identical parent materials which have greatly different climatic contexts and great contrast in surface weathering colour. The fundamental question to be asked is how influential might climate be as a weathering factor when compounded with some contrast in parent material?

The third example for which explanation is offered is the Olmec colossal heads, tenons and other sculpture from the area of Tres Zapotes, which have weathering hues of a uniform pale green on pyroxene-olivine basaltic andesite, compared to the dark grey hue of the Golan Cover basalt of the Jordan River valley olivine basalt. Common and contrastive features are noted as follows.

First, the common features: compared to the olivine basalt from the Levant, especially Jordan River-Golan basalt, the Tres Zapotes-Cerro El Vigia material has nearly equal SiO content at 49-51 wt % with olivine and pyroxene in both. Also the fresh-looking olivine basalt of Jordan River Valley (e.g. both Qarne Hittim and Tiberias-Poriyya) has a similar petrographic texture compared to the Tres Zapotes-Cerro El Vigia basalt material, especially in plagioclase feldspar matrix and relative amount of olivine iddingsitized. Another common factor is that both have been buried for some millenia in comparable stratigraphic depths, especially the Hazor archaeological material) of between 1-2 m subsurface (Yadin, 1958).

However, the Jordan River Valley olivine basalt looks darker on its weathering surface than the pale Tres Zapotes material. What factors might account for such obvious weathering difference between the two basalts? (see Plates 6.4 and 7.4 for petrographic texture). Possible explanations are listed below in Table 10.4.
### Table 10.4 TRES ZAPOTES: JORDAN VALLEY WEATHERING COLOUR CONTRASTS

<table>
<thead>
<tr>
<th>Parent Material</th>
<th>1. Tres Zapotes material is basaltic andesite (or andesitic basalt) whereas Jordan Valley material is mostly basalt).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithology</td>
<td>Tres Zapotes material is doubly Mg-rich with high Mg-clinopyroxene (15 wt % Mg) and high Mg-rich Mineralogy Olivine (forsterite: 39 wt % Mg) whereas the Jordan material is Fe rich (10 - 16 wt % in pyroxenes and in olivines (fayalite: Fe rich).</td>
</tr>
<tr>
<td>Texture</td>
<td>Tres Zapotes has giant clinopyroxene phenocrysts up to 5 mm in size with a textural volume of 28% whereas the Jordan Valley material phenocrysts average 1 mm with a textural volume of 10-18%.</td>
</tr>
<tr>
<td>Climate: MAP</td>
<td>Tres Zapotes is tropical with estimated MAP at 2400-2700 mm whereas the Jordan Valley is semi-arid to arid at less than 400 mm MAP.</td>
</tr>
<tr>
<td>Climate: RH</td>
<td>Tres Zapotes is tropical with estimated relative humidity at 80%; Jordan Valley is arid at 25-30%.</td>
</tr>
<tr>
<td>Climate: MAT</td>
<td>Tres Zapotes is tropical with estimated MAT at 23 C whereas the Jordan Valley is semi-arid to arid at 20 C.</td>
</tr>
</tbody>
</table>

Factors 2-5 listed here are probably most responsible for colour.

The pale green surface hue of the Mexican material is common for Mg rich andesite in a tropical climate with considerable leaching or hydrolysis rates accelerated by such high precipitation and temperatures. The leaching colour (pale green) most likely reflects both the fact that Mg is still quite high and that Fe volume was low at the outset (in contrast to the iron oxide stain on certain Jordan Valley olivine basalts).

In this case, it appears that, all else being in common:

greater contrast > some contrast in climate in parent material

such that:
climate + parent material
or
parent material + climate
or
climate + parent material
or
parent material + climate
> time
> all other factors combined

for the most influence in weathering colour for these two basalts in the archaeological contexts noted above.

In summary, the contrasts between Mexican and Levant basalts, whose parent material is sufficiently different (even though their petrographic textural appearance is somewhat similar) but whose environmental contexts are greatly different, evidences how significant climate is as a weathering factor compounded with some significant mineralogical differences in parent material. Also since there is an apparent time difference of less than half a millenium between the Canaanite and Olmec contexts noted, the factor of time alone appears far less influential than climatic factors compounded with some parent material factors as the Jericho-Golan material appears much less oxidized due to a semi-arid or arid climate (especially in any contexts around Jericho) than the tropical climate of Olmec material. This suggests that the environmental factors should not be underestimated nor should the time factor be overestimated in rates of weathering.

It must be emphasized that when the present research was undertaken, the literature (especially the study of Cernohouz and Solc and subsequent research building on that study, e.g Colman et al.), presented strong indications that the weathering of andesite was an orderly process and that it was worth investigating as a potential chronometer on the basis that time
seemed to be the dominant variable. Whether or not the short term weathering may suggest that time is not the dominant variable exactly because it is too short term, remains to be established.

While these attempts to explain weathering hue differences may seem simplistic, in the opinion of this researcher they best explain to date the above noted weathering contrasts on basalt and andesite in the archaeological contexts selected.

In summary, it is again iterated that the idea of examining weathering colour as an important factor in a potential chronometer for basalt and andesite was extrapolated from studies of Colman et al., as time spans of less than 20,000 yrs might be insufficient to develop actual weathering rinds on the surface whereas staining itself might have been a more sensitive indicator of age and incipient weathering (Colman, 1982:10). Thus, the present research has arbitrarily separated external weathering colour as an incipient or shorter term visible form of weathering from weathering rind development as a longer term visible form of weathering. Section 10.3 examines comparatively weathering rind thickness in archaeological contexts.

10.3 Weathering Rind Thickness on Selected Archaeological Material

As discussed in the previous chapter, weathering rinds are identifiable on geological material with a weathering exposure greater than 20,000 yrs, and may also be found on archaeological material with a weathering exposure of less than 10,000 yrs with some possible differences in characterisation. Extending the work of Colman et al., since basalt-andesite surface rinds in their study were often absent compared to those buried up to 30 cm
within a soil horizon (Colman and Pierce, 1982:7-8), it is possible that fewer, variable, or atypical weathering rinds (atypical when compared to geological weathering rinds) would be identifiable on archaeological material. This will also be complicated by the difficulty of sampling culturally-protected archaeological material considering the necessarily-destructive process of preparing polished sections for examination.

The potential problems of taking weathering influences into account, complications such as acceleration of weathering by stoneworking, and questions arising from comparison of different contexts will be discussed in this section. Cultures discussed will include Pre-Pottery Neolithic in the Jordan Valley, Levant; Canaanite in the Jordan Valley, Levant; Olmec in the State of

### Table 10.5 WEATHERING RINDS ON ARCHAEOLOGICAL MATERIAL

<table>
<thead>
<tr>
<th>Context</th>
<th>Material</th>
<th>Assumed Date</th>
<th>Rind Colour: Exterior Colour</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Neolithic</td>
<td>olivine</td>
<td>c. 8500 B.C.</td>
<td>black: grey</td>
<td>4.9 mm</td>
</tr>
<tr>
<td>(Jericho 2025)</td>
<td>basalt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Neolithic</td>
<td>olivine</td>
<td>c. 8500 B.C.</td>
<td>black: grey</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>(Jericho 2025)</td>
<td>basalt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Canaanite</td>
<td>olivine</td>
<td>c. 1500 B.C.</td>
<td>black: grey</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>(Hazor)</td>
<td>basalt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Olmec</td>
<td>pyroxene</td>
<td>c. 1000 B.C.</td>
<td>pale grey-green: dark grey</td>
<td>6.2 mm</td>
</tr>
<tr>
<td>(Tres Zapotes)</td>
<td>basalt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Inca</td>
<td>biotite</td>
<td>1450 A.D.</td>
<td>white: grey</td>
<td>2.6 mm</td>
</tr>
<tr>
<td>(Ollanta 39)</td>
<td>andesite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Inca</td>
<td>hornblende</td>
<td>1450 A.D.</td>
<td>dark pink: light pink</td>
<td>3.8 mm</td>
</tr>
<tr>
<td>(Saqsaywaman 2)</td>
<td>andesite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Inca</td>
<td>hornblende</td>
<td>1450 A.D.</td>
<td>dark pink: light pink</td>
<td>2.8 mm</td>
</tr>
<tr>
<td>(Rumigolqa 6)</td>
<td>andesite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Inca</td>
<td>hornblende</td>
<td>1450 A.D.</td>
<td>black: grey</td>
<td>2.2 mm</td>
</tr>
<tr>
<td>(Rumigolqa 2)</td>
<td>andesite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Inca</td>
<td>hornblende</td>
<td>1450 A.D.</td>
<td>black: grey</td>
<td>2.3 mm</td>
</tr>
<tr>
<td>(Rumigolqa 3)</td>
<td>andesite</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Veracruz, Mexico; and Inca in the Cuzco Province of Peru. Others will also be discussed briefly which might have a bearing on the present research. Table 10.5 above presents these contexts.

It is notable that only examples #4 & 5 listed in Table 10.5 exhibit a weathering rind hue comparable to that defined by prior literature (Colman and Pierce, 1981:3-4 & ff): lighter rind contrasted with a darker interior. That is, all the above archaeological contexts of weathering are the opposite of that expected from the prior studies, having exterior rinds which are darker than the immediate interior area. This will be further elaborated in the discussions of Olmec material in section 10.32 and of Inca material in section 10.33.

The most significant common feature of observed archaeological weathering rinds, excluding #4 & 5 above, is that there is a reversal of geological rind hue contrast (as suggested by Colman and Pierce, 1981: 3 & ff; light rind on dark interior) with andesite artefacts exhibiting a darker rind on the surface and a lighter interior. This may be the primary characteristic feature of short term weathering on archaeological as opposed to geological basalt or andesite. This will be discussed further in the following subsections.

The actual chemical characterisation of a darker rind seems mainly due to some hydration remaining even after heating above 100°C; apparently held within a network of microfractures caused by stoneworking; or 2) a possible concentration or migration of Fe oxides which seem to be in higher concentration here than in the interior from which they are leached. This information is deduced from SEM with EDS profiles as seen in Figure 10.3 following the discussion of Inca weathering rinds.
A. Jericho Weathering Rind Data

As shown above in Table 10.5, # 2 & 3, the Neolithic basalt tool noted in Chapter 6 as J 2025 has actually two weathering rinds (see Plates 10.3 to 10.5). One is on the circumference of an original archaeological surface and the other is found both on the flattened bottom and the V-groove on top as shown below in Figure 10.1. Interpretation as an archaeological surface is not without assumptions, i.e. it could be a geological weathering rind. The evidence, however, suggests an archaeological surface due to the "baetyl" or conical shape of the object. This outer first rind suggests secondary use as follows: 1) in its first Neolithic context, the stone was shaped into a cylindrical tool, possibly as a hammerstone or comparable utensil, but it appears to have suffered breakage on the striking end surface an indefinite time after usage began; 2) in its second Neolithic context (an unknown time later) the broken tool appears to have been converted into what Dorrell has suggested as an straightener for arrow shafts or a similar tool (Dorrell, 1990; pers. comm.). The many hammerstone finds at Jericho are documented by Dorrell in the excavation reports with obvious wear and tip shattering from repeated blows (Dorrell, 1983:101 & ff).

Thus the first black (unpolishable) weathering rind of 4.9 mm can be possibly explained as a) stoneworking via grinding method; b) representing the early stage of weathering (archaeological weathering only) since the exterior of the rind is darker than the interior; c) the factor of time is the most influential
factor in the thicker rind on this stone. These three causes are parts of each other, i.e. complementary. Likewise, the second thinner black weathering rind of 1.5 mm is possibly explained as a) stoneworking via grinding method; b) representing the early stage of weathering (archaeological weathering only) since the exterior of the rind is darker than the interior; c) the factor of shorter time causing the thinner rind (as compared to the possible longer time duration resulting in the thicker rind). These three causes are also complementary or related.

Figure 10.1 PROBABLE NEOLITHIC REUSE OF JERICHO BASALT 2025

1st cylindrical surface
- dark weathering rind 1 (4.9 mm) (most likely earlier grinding)
- 2nd surface (reuse) V-groove for "straightening arrows"
- dark weathering rind 2 (1.5 mm) (most likely later grinding)

2nd surface: (reuse) flat bottom for stability
- dark weathering rind 2 (1.5 mm) (most likely later grinding)

Having two weathering rind surfaces, comparable in dark colour (and therefore suggesting archaeological rather than geological weathering) but which contrast in rind thickness, could be a result if the tool had been buried after the second Neolithic use and only excavated in the last 50 yrs, thereby halting further weathering by a burial context of greater than
(Plate 10.3 [above]) JERICHO 2025 CROSS SECTION showing three separate stoneworking surfaces: 1) rounded, 2) v-cut groove, and 3) flattened base. Unfortunately no photograph has yet succeeded in showing the 1.5 weathering rind on 2) & 3); Plate 10.4 [below] also JERICHO 2025 shows the unpolishable 4.9 mm weathering rind.
5 m depth. That is, if the tool had not been buried for a great length of time, it would also display a thick weathering rind.

The difference between the two J 2025 weathering rinds would only suggest the result of time if the following situations were deducible: 1) that grinding was the stoneworking method used in both the 4.9 mm and 1.5 mm rinds; and 2) if sufficient time had elapsed between the two different usages. Strong evidence for grinding could be suggested in the symmetry of the 4.9 mm rind. The contours of the surface are so perfectly matched in the rind that some weight could be attached to this observation. In this case the thicker rind would actually represent the time factor of weathering (which could be inhibited by the depth of burial when it might actually be much thicker had it been on or near the surface), also assuming not much acceleration of weathering by the stoneworking method of grinding. How much time lapse has occurred between the starting of the two weathering rinds is not deducible, but it is evident that the second usage cut a notch through the first usage and flattened the bottom of what was probably a discarded tool. The Jericho excavations do show that prior occupation occurred before the Pre-Pottery Neolithic, going as far back as Proto-Neolithic and even into Mesolithic (Dorrell, 1983:489-90). Whether or not the first rind reflects such early usage is not susceptible to resolution by the above arguments.

An alternative picture could, however, be constructed. While this may complicate the picture, it is possible that not as much time difference as environmental contrast occurred: original use took place under conditions favouring the initial 3.8 mm weathering whereas burial after second usage only allowed a further 1.5 mm weathering rind development under the more stable
conditions of a 5 m + stratigraphy where oxidation and hydrolysis would be minimal. Stability at this depth has not been addressed by prior studies on basalt and andesite weathering.

The weight of evidence against time alone as the responsible factor rests mostly on the data reported by Cernohouz and Solc: if their interpretation applies to all basalt weathering, time alone might account for an initial rate of only 0.1 mm per half a millenium, unless of course, as Winkler speculated, the process may start at a high rate before slowing down again exponentially. By the account of Cernohouz and Solc, a time span of 10,000 yrs. should result in a geological rind between 0.2-0.3 mm, or a 4.9 mm rind should develop only after 1 million yrs based on the regional model of Bohemian basalt, which may not be applicable (Cernohouz and Solc, 1966:806-07).

Comparably, a time span of 10,000 yrs in the study of Colman and Pierce should result in a rind of less than 0.2 mm: a 4.9 mm rind would only develop after 1 million yrs within the subsurface and environmental conditions of their regional study, which also may not be applicable (Colman and Pierce, 1981:26-27). On the other hand, if the data of both Cernohouz and Solc and Colman and Pierce are not applicable to this study, this rind may best represent mostly the time factor of weathering in the Levant.

Other Neolithic samples from Jericho (e.g. J 2509 in Ch. 7) also in collections of the Institute of Archaeology display very indistinct weathering, that is, it cannot be yet determined if rinds are present. A more representative sampling is required as J 2025 exhibits the most observable weathering of more than 30 Neolithic basalt stone tools examined superficially. Of the 30+
tools, 26+ were examined superficially whereas only 4 were
were sectioned and polished as further sectioning and polishing
was not permissible at that time. Extended sampling will be
difficult considering the necessary removal of material for
analysis (representative polished sections and thin sections) of
artefacts and other archaeological material.

Thus, the J 2025 rinds seem to reflect either 1) two distinct
time stages of weathering and/or 2) two different weathering rate
developments arising from different environmental conditions. In
the opinion of this researcher, the second alternative mentioned
is favoured in that both stone modifications may have resulted
from grinding as described earlier in this chapter but that the
first stone modification took place at a significantly earlier
date and under different environmental conditions while the
second stone modification may have resulted from grinding action
plus an inhibited rate of rind development due to deep burial
under successive Chalcolithic and Early Bronze occupation levels.

For a tentative appraisal, this could be expressed thus:

\[
\begin{align*}
greater & & \text{original} & & \text{lesser} & & \text{deeper} \\
time & & \text{environment} & & \text{time} & & \text{stratigraphic} \\
& & \text{factor} & & \text{factor} & & \text{factor}
\end{align*}
\]

(Neolithic Rind 1) (Neolithic Rind 2)

It is notable that the second Neolithic rind has a mitigating
element due to its deep burial when compared to the original
environment in which the first rind developed, which would also
have an effect in the following possible scenario.

It is also important to note that measurements of weathering
rind thickness were made on Vernier Scale calipers (to 0.01 mm).
(Plate 10.5 [above]) JERICHO 2025 unpolishable 4.9 mm WEATHERING RIND severed by secondary stonework: a polishable v-cut groove; (Plate 10.6 [below]) CANAANITE HAZOR basalt "Baetyl [?]" found in Hazor Late Bronze III cultic context of Canaanite Holy of Holies (with material removed for thin and polished section preparation).
B. Hazor Canaanite Weathering Rind Data

The Hazor Canaanite olivine basalt tool (example 3 on Table 10.5 above and as discussed in Chapter 7) also has a rind whose black exterior contrasts with a grey interior. Its rind thickness of 0.8 mm also appears more the result of stratigraphy rather than time, although a combination of greater environmental influence (with slightly higher MAP) compounded with burial depth could increase weathering in the Hazor material to roughly one-half that of the second stage of the Jericho Neolithic material (Plates 10.6 & 10.7).

Thus, the factor of time compounded with environment may be responsible for the difference of 0.7 mm between the second Jericho Neolithic rind (1.5 mm) and the Hazor Canaanite rind (0.8 mm). Rough calculation immediately shows the 2nd Neolithic rind thickness to be nearly double the Canaanite rind thickness when the time difference is nearly trebled. This may suggest the following relationship between weathering influences:

<table>
<thead>
<tr>
<th>greater</th>
<th>deeper</th>
<th>shallower</th>
<th>higher</th>
</tr>
</thead>
<tbody>
<tr>
<td>time</td>
<td>stratigraphy</td>
<td>stratigraphy</td>
<td>MAP</td>
</tr>
<tr>
<td>factor</td>
<td>factor</td>
<td>factor</td>
<td>factor</td>
</tr>
</tbody>
</table>

(Neolithic rind 2)  (Hazor rind)

As discussed in section 10.22 on environmental factors, the weathering influences apparently exhibited on the Neolithic 1st rind thickness of 4.9 mm when compared to the 0.8 mm rind thickness on the Hazor material appear to be time and original environment (rather than a factor of time only) as the most influential weathering factors. This could be expressed thus:
Several other possible alternatives should not be omitted from possible scenarios. While it is difficult to establish if the ancient environment was different from the present, i.e. the climate in the Neolithic was significantly wetter than the present or recent environment, it might be that palynological and other evidence may show the Neolithic period indeed had an environment which favored a more rapid weathering than the arid climate it now experiences. This could account for a higher contrast in rind thickness between the first and second Neolithic rinds and the Canaanite Hazor rind. On the other hand, as suggested earlier, burial after the Neolithic reuse with subsequent stratigraphy accumulating quickly (especially in the active Early Bronze period) could account for the higher contrast between two Neolithic contexts than between the second Jericho Neolithic context and the Hazor Canaanite context. Either scenario is difficult to assess given the paucity of palaeoenvironmental data for this area. Even so, it would still require a considerable time lapse between the two uses for such a thick rind to develop after the first usage.

Lastly, is it possible that the thickest rind (4.9 mm) might reflect an earlier Mesolithic use rather than Neolithic use? That is, the thickness of the first rind could suggest Mesolithic use with the second rind suggesting Neolithic reuse, compared to the Canaanite material suggesting the more or less expected least
developed rind of the three:

Mesolithic rind  >  Neolithic rind  >  Canaanite rind

4.9 mm  1.5 mm  0.8 mm

This interpretation of rind thicknesses could only be realistic:

a) if time is the most significant weathering influence; b) if parent materials are roughly comparable; c) if environments have remained stable over a long period (Mesolithic to the present or at least to the Canaanite period); and d) if depth of burial has been a minimal factor all along.

The fact that rind thickness as tentatively characterised here for archaeological weathering (darker exterior rind than interior stone and thicker because possibly accelerated by stoneworking) contrasts with the studies of Cernohouz and Solc (1966) and Colman et al. (1977, 1981, 1982, & 1986) cannot be resolved at this point other than to suggest differences between geological and archaeological weathering not envisioned by the prior studies. If further sampling can be done on known Mesolithic material which also displays comparable rind thickness (4.9 mm), it would greatly facilitate a less tentative weathering profile and affirm the representative sampling and interpretation as suggested in this last paragraph.

C. Jericho and Hazor Individual Mineral Grain Weathering

Within the Weathering Rinds

A comparison of individual mineral grain weathering between the Neolithic and Canaanite samples is inconclusive. As seen in Plates 7.4 and 7.5, both materials show iddingsite alteration of olivine phenocrysts to a similar level, which would be consistent
(Plate 10.7 [above]) HAZOR CANAANITE "BAETYL [?]" closeup showing 0.8 mm dark weathering rind, best seen just under mm marker edge; (Plate 10.8 [below]) TRES ZAPOTES COLOSSAL HEAD (Monument A) with past mutilation as weathering contrast. Note 4.5 cm compass as scale on upper right. Tres Zapotes Archaeological Museum, Mexico.
with predictions of the instability of olivine relative to other more stable minerals (Colman, 1982:11). Accordingly, pyroxenes of both Jericho 2025 and Hazor material appear similar without any noticeable alteration or discoluration by FeO (Colman, 1982:11). Little contrast in individual mineral grain weathering can be suggested for either of the two materials. It is perhaps likely that the semi-arid to arid environments of these contexts have not allowed more than olivine alteration to Colman’s Stage 2 for that mineral alone (Colman, 1982:5), with the other more stable minerals seeming to be still at Stage 1 in their fresh appearance as per Colman’s Tables 2 & 6 (Figure 8.1). That is, insufficient hydration, oxidation, and low relative humidity of the Levant material (with Levant climate being much drier than the Pacific Northwest of the U.S.) compounded with a shorter time period (archaeological time rather than geological time) even though the Levant weathering rinds themselves are thicker (accelerated due to stoneworking), could explain why the Levant olivine phenocrysts show comparable iddingsite alteration. Unfortunately, no relative time data can be inferred from Colman’s studies (as a relative sequence of time to know when olivine alters) for Stage 1–2 weathering (olivine-only alteration) other than Colman’s observations that olivine alteration will occur early. Comparable olivine alteration in this case in this case could occur for both Jericho contexts in a 10,000 yr period for the deeper Neolithic stratigraphy of > 5 m and only 3,500 yrs for shallower Canaanite stratigraphy at Hazor of 1–2 m as well as the Stage 1–2 (or A & B) olivine basalts in Colman’s evidence of earliest weathering of geological material (Colman, 1982:5,13,14,
and 19), thicker rind and rind colour contrasts notwithstanding due to stoneworking. The same comparison of olivine alteration is possible for potential Mesolithic, Neolithic, and Canaanite material with earliest weathering of geological material as noted by Colman (ibid.), i.e. partial alteration to iddingsite at Stage 1-2 (or A & B), again other contrasts of rind thickness and rind colour notwithstanding due to stoneworking.

In summary, the scenarios suggested above are perhaps the only assessment discussed to date of observed weathering in these Levant contexts discussed (Jericho Neolithic and Hazor Canaanite) which seem to share similar parent material (olivine basalt) and type of stoneworking (by grinding). Of factors discussed, time should not be underestimated as influential, particularly as the Neolithic (or Mesolithic + Neolithic) Jericho 2025 has the thickest rind and has been verified as being in the oldest stratigraphic context, at least Pre-Pottery Neolithic (Dorrell, 1983:101 & ff; as well as Dorrell, 1990, pers. comm.).

The importance of time as a factor in weathering is further reinforced in a quotation by C. Epstein on Golan dolmens from the time boundary between the Late Chalcolithic and the Early Bronze period (c. 2250 B.C.):

"Stones and boulders which have been not been moved for thousands of years are covered with a distinctive patina due to weathering and lichens, which makes later disturbances easy to detect." (Epstein, 1985:28)

Whether or not the biologic weathering acceleration by lichens contributes here to a measurable rind is difficult to assess since quantitative measurements are not provided in the text. The term "patina" may only refer to a superficial staining instead of a weathering rind. Nonetheless, this Jordan-Great Rift Valley
olivine basalt weathering even in an area classified as semi-arid suggests some weathering influence for the factor of time.

10.3.2 Olmec Weathering Rinds at Tres Zapotes

A. Colossal Head - Monument A Rind

As shown above in Table 10.5, 4, the Olmec basalt monument at Tres Zapotes museum, the Colossal Head (Monument A) has the most clear evidence of a weathering rind, fortuitously made visible by a mutilation of the left eye, nostrils, left upper lip and right centre of the headgear (see last paragraph of section 6.1, Chapter 6, for discussion of mutilation chronology).

The weathering rind thickness of 6.2 mm on the Tres Zapotes colossal head is a consistent measurement, but some variation exists on mutilated surfaces (up to 0.7 mm in either direction). As stated in Tables 10.2 and 10.5, the external weathering colour of pale green-grey contrasts especially with the subsurface mutilation colour with its darker grey interior exposed (Plates 10.8 & 10.9).

Monument A was described by Stirling in 1943 as the most striking single object from Tres Zapotes (which opinion may be superseded now by the importance of Stela C with its Cycle 7 date calendric hieroglyphs), excavated from a stratigraphic depth of around 2 m before 1940 (Stirling, 1943:16-17 and his Pl. 4a & b). Monument A is in the Tres Zapotes Archaeological Museum near the village and site of Tres Zapotes.

As discussed earlier in Chapter 9 on stoneworking methods, Olmec stone chisels were shown to this researcher by Dr. Fernando Bustamente of the Santiago Tuxtla Museum in 1989 (being one of two local museums where Tres Zapotes material is collected, only
(Plate 10.9 [above]) TRES ZAPOTES COLOSSAL HEAD (Monument A) CLOSEUP showing past mutilation weathering contrast with 6.2 mm weathering rind best seen on right nostril and right eye socket; (Plate 10.10 [below]) SAQSAWAMAN ASHLAR 2 edge with 3.8 mm rind
15 miles from the site of Tres Zapotes; the other museum being the Tres Zapotes Museum itself near the village of Tres Zapotes). These chisels were examined by portable field microscope (Ch. 4). Examination suggests them to be dolerite and quartzite and best associated with the monumental basalt sculpture stoneworking, specifically purported to have been used in working Cerro El Vigia stone at Tres Zapotes, although they were out of context at the Santiago Tuxtla Museum for this researcher’s appraisal. These stone tools support a stoneworking method of chiselling with Mohs hardness estimated at 7, alleged Olmec context, and blade edges (4-5 cm width) tapering to strong fine points of 90 degrees on finely-worked tips. Also as suggested earlier in Chapter 9, chiselling may be more destructive in accelerating weathering than battering as a stoneworking method. This is plausible in that a chisel point (despite how many new ones are used, broken, and discarded) concentrates the force, giving higher stress, into a smaller area on a stone surface than a bluntly-rounded hammerstone, as suggested earlier. Thus, weathering could be even more accelerated here than on hammerstone-worked surfaces.

Some discussion about sculptural mutilation is appropriate at this point. Both Stirling (1943: 17) and Grove discuss the prevalence of monument mutilation along the Gulf Coast in which Olmec sites are predominantly found. Stirling maintained that mutilation happened in the pre-excavation context and Grove also postulates several possible theories for the mutilation, each of which would be roughly datable to a comparable Olmec period. In Grove’s analysis, ethnographic explanatory parallels are found in mutilation with the death of the person which the object depicts,
in this case probably an Olmec leader (Grove, 1981: 62 & ff). Although this Colossal Head (Monument A) could also represent a deity figure, Olmec deities appear most often in sculptures as were-jaguars or related hybrid feline-human figures (de la Fuente 1981:83). Change of dynasty, change of calendar, and conquest have all been suggested by Grove or others to explain mutilation, with the conquest explanation being the choice most likely to represent a greater length of time between carving and mutilation (Grove, 1981:62-64 & ff). The considerable thickness of the rind raises questions about Grove's theories of probable same culture mutilation (i.e. Olmec mutilation as well as Olmec carving) in that the depth of weathering, however accelerated by stoneworking and tropical environmental factors, would be unlikely to be so thick if the mutilations occurred relatively soon after the carving. On the other hand, the differences in weathering colour which is noticeable between the original carved surface, the mutilation, and fresh Cerro El Vigia stone suggest that some time has also transpired between the mutilation and the present. It is even possible that the mutilations could be "recent" (for example, around the immediately Pre-Hispanic period through the agency of a later conquest closer to the present, e.g. an Aztec conquest in the 13th - 14th c. A.D.). In this case, surficial discolouration could take place without much additional rind development (which cannot be gauged across the "newer" mutilated surface of an intermediate colour between Olmec carving and fresh stone).

Some debate also exists as to which Olmec period this Tres Zapotes head belongs. Stirling affirms its probable original context as a foundation platform and dated it to the early middle
Tres Zapotes occupation period based on colossal head form, style and ceramic context (Stirling, 1943:11, 31) which would be in the first quarter of the 1st millenium B.C. Grove maintains, without specifying the colossal head Monument A itself, that "most of which [Tres Zapotes monuments] are Late Formative" (Grove, 1981:62), placing them roughly in the mid-to-last third of the 1st millenium B.C., which is an accepted assumption that Tres Zapotes occupation is placed mostly after San Lorenzo (as early as 1250 B.C.) and La Venta (as late as 600 B.C.) (Diehl, 1981:77).

The above-mentioned Tres Zapotes Stela C Cycle-7 calendrical date appears to be 31 B.C. but it has been calibrated by radiocarbon to an earlier date (Pugh, 1981:6), again in the last third of the 1st millenium B.C. as well, which is extremely strong evidence for at least Stela C. There is, however, no need for all the other Olmec material here to have similar chronology (a point implicit in Grove's argument above).

In the opinion of this researcher, the colossal head form best represents an early Olmec phase. This is based not only on style of Olmec colossal heads and the fact that some San Lorenzo colossal heads are also traceable to Cerro El Vigia basalt along with Tres Zapotes monuments including Moment A (Williams and Heizer, 1976:4, 11) but also based on the fact that the primary material for colossal heads, regardless of site, is Tuxtla Mtns. basalt (although the andesite of other monuments such as some tenons and frieze units appears to derive from the volcanic peaks near Teapa, 100 km south of Villahermosa according to Williams and Heizer, 1976) (Coe and Diehl, 1980: Appendix A). This suggests deliberate transmission of a common style and a
common material by a culture whose appropriation of both was also
collected, although this is not absolutely necessary when the
cultural tradition of deliberate archaizing can be evidenced.
The colossal heads from San Lorenzo and La Venta are in a depth
of stratigraphic sequence calibrated by radiocarbon dates
which supports their early manufacture in the tenth century B.C.
(Drucker, 1981: 42) Furthermore, Drucker maintains that the
colossal head cult seems mostly synchronous between San Lorenzo,
La Venta and Tres Zapotes (Drucker, ibid., p. 42).
Evidence for this could be found in the rind thickness of
6.2 mm on the Tres Zapotes colossal head under consideration
(Monument A) if other comparable rinds could be identified and
examined on San Lorenzo and La Venta basalt colossal heads, which
would lend support to Drucker's statement. On the other hand, if
Drucker is accurate in this proposed synchronicity, it might be a
reasonable springboard to use the Tres Zapotes rind thickness as
a calibrated means to suggest a 6.2 mm rind as representing a
10th c. B.C. date for this tropical climatic region and parent
material, but this is too circular an argument at present.
Without doubt, the thickness of the weathering rind here is in
part derived from the factor of time. What would be inconsistent
here (as stated in Table 9.4) given the high MAP of 2400-2700 mm,
the MAT of around 23°C and the mean annual relative humidity
of around 80%, as these are compounded with the time factor, is a
weathering rind of thickness less than the somewhat older
Canaanite Hazor basalt (by as much as half a millennium).
This again corroborates the earlier factoring of section 10.23
with modifications noted from Chapter 9 (on the stoneworking
method of chiselling) where it is again suggested that:
Thus, a hugely-porphyritic pyroxene-olivine basalt (Tres Zapotes archaeological material) weathering in a tropical climate where the weathering is also further accelerated by the more stressful chiselling stoneworking method ought to evidence a thicker rind than a less porphyritic olivine basalt (Hazor or even Jericho archaeological material) weathering in a semi-arid/arid climate where the weathering is accelerated (but not as much) by the less stressful battering stoneworking method even when the latter is older (slightly, by less than half a millennium) than the former. This will be even more profoundly marked with the Jericho basalt tool, even considering the far greater Neolithic age, when buried assumably below a weathering zone, i.e. deeper than the 20-50 cm soil horizon of Colman (1982:2) in an arid climate. A weathering zone is the subsurface area of weathering mechanisms beneath which oxidation and hydrolysis are very limited, the 20-50 cm soil profile being most weathered [except for the surface] by the account of Colman (1982:2). In the case of the Jericho material, weathering time must be more tightly defined by exposure to weathering (which the Jericho Neolithic material may arguably be seen as having less real exposure by stratigraphic depth).

At this stage it is important to note two points where the research of Colman et al. must be applied. First, as noted in Table 9.5, the weathering hue contrast between outer and inner surfaces on the Tres Zapotes archaeological material is not reversed, i.e. dark rind over light interior, as found in nearly all other archaeological weathering rinds, but is in accord with
the normal lighter zone found on the exposed outer surface as noted by Colman et al. (Colman and Pierce, 1981:3). Second, the obvious depth of weathering of the Tres Zapotes archaeological material is in contrast to the geological weathering rind depths as described by Colman et al., with the thickest rind identified by these researchers measured as 3.5 mm (at Wingate Hill, Mt. Rainier andesite assumed to be older than 250,000 yrs) in contrast to the 6.2 mm weathering rind on the Tres Zapotes basalt colossal head. A tentative explanation offered for the difference between the archaeological materials (rind hue reversals) and the consonance between the geological and Tres Zapotes archaeological weathering hue is also offered with the contrast between the rind thickness of geological material and the rind thickness of the Tres Zapotes material (otherwise consonant with geological parameters). Preliminary observations are:

1) consistent rind colour = a suggestion of characterisation for archaeological weathering (dark rind, light interior)

2) consistently thicker rind = a suggestion of characterisation for accelerated weathering by stoneworking (than geological material) (average rind > 1 mm)

Furthermore, the concord between most archaeological samples (excluding Tres Zapotes) suggests the following points: 1) high correlation in rind thickness is unlikely to be explained solely as an evidence of depth of stoneworking damage alone; i.e. the rind contour is too close a parallel of the outer surface contour where stoneworking alone ought to show a more varied depth due to unequal distribution of stoneworking blows (this, however may
be more dependent on technique. 1) the consistent rind colour is unlikely to be anything other than an evidence of incipient (rather than advanced) weathering; i.e. all of the material evidencing the dark rind to light interior is obviously archaeological. That is, it may be expected that the darker rinds appear first and then become lighter. This may be due to the fact that greater microfractures in the worked area increases microporosity sufficiently to accelerate the mobilisation of MgO and FeO (darker oxides) to the fractured area of the stoneworking at an early stage (archaeological time), then as weathering advances through fractured zones it mobilizes some MgO and FeO totally out of the stone, but over time (geological weathering). This will be examined again via the data of chemical analyses.

Two caveats, though, must be acknowledged. One, it could be possible that the dark area does not signify archaeological weathering at all, merely increased microfractures. The problem with this potential explanation is that the immediately observed stoneworking result appears to be white scars (Chapter 9) rather than dark areas, although how long this white scar remains is unknown. The second concern is that increased hydration (also a result of stoneworking) could account for the dark colour of the archaeological rind. The problem with this potential explanation is that the dark rind only becomes most visible after extensive polishing and heat drying above 150°C, which should drive off any water retention. Thus, the following facts emerge from Table 10.5 in light of the research by Colman et al. where geological weathering rinds are lighter in colour and thinner in depth:
all dark rind = archaeological

but not all archaeological = dark rind

(1 exception)

and

all archaeological = thick rinds

but not all thick rinds = archaeological

and

all geological = light rind

but not all light rinds = geological

(1 exception)

The one exception as noted above is the Tres Zapotes Olmec sculpture. Therefore it is suggested that the best explanation for the extra thick weathering and the geologically-similar hue are due to the aggressiveness of a tropical climate compounded with the aggressiveness of chiselled stoneworking. Simulation of geological weathering in rind hue and exacerbation of weathering by chiselling result in this visibly different weathering rind:

<table>
<thead>
<tr>
<th>tropical climate</th>
<th>chiselled stoneworking factor</th>
<th>combined archaeological and geological weathering</th>
</tr>
</thead>
</table>

in that features of both geological weathering (light rind, dark interior) and archaeological weathering (thickness of rind as due to stoneworking damage and tropical climate) are shown by this Tres Zapotes Olmec monument.

B. Tres Zapotes Archaeological Material, Great Mound Internal Weathering

The material already discussed in Chapter 6 as having been found in the excavation context of the Great Mound, Tres Zapotes, and generously given to this researcher for analysis by Dr. James Porter, is now considered for weathering information in the
following paragraphs. It will be compared with the geological sample material from Cerro El Vigia, its original source.

The basalt chips from the Great Mound are weathered both externally and internally, with no fresh surfaces prior to thin section preparation. They appear to derive their shape and size from the fact that they are most likely fragments from sculpting Tres Zapotes monuments of this basalt. As such, it is possible that they could be either early or late for Tres Zapotes, with a range from Early to Late Formative with almost a millenium of time difference. In any case, their archaeological context is undisputed even though their stratigraphic context is not retrievable.

The basalt chips from the Great Mound are unfortunately less than 1.5 cm in depth, which means that a comparison for rind depth will be irrelevant. Too much surface area will have allowed weathering to proceed inward from both directions of their outside surfaces, thus in all probability obscuring any zone delineating fresh from weathered stone in these samples.

On the other hand, these Great Mound stone chips are consistent with Monument A in both external weathering colour of a pale grey-green and an internal weathered zone of the same colour. That is, the whole amount of material sampled from the Great Mound could be stone chips from the weathering rind of boulders used for Olmec sculpture. On the other hand, the Great Mound stone chips could be small enough to be completely weathered. Whichever case is applicable, it is clear that the interior of the stone chips show no fresh contrast; being fully weathered through all 1.5 cm of depth. This contrasts with the sampled fresh Cerro El Vigia material in the following ways:
1. Cerro El Vigia material is darker on the surface and throughout; appearing similar to the interior (beneath the mutilation) of Monument A.

2. Tres Zapotes Great Mound material is lighter all the way through; appearing similar to the weathering rind hue of Monument A.

2. Cerro El Vigia material appears generally fresher throughout in hand specimen with its surface feldspars relatively unmarked.

2. Tres Zapotes Great Mound material appears generally etched (with tiny "pocks") on its surface feldspars in hand specimen.

At the present date, it is unknown if the surface of Monument A, the Colossal Head in the Tres Zapotes Museum near the site displays the feldspar etch pits, although some other Tres Zapotes archaeological artefacts do possess etch pits (see Ch.8, section 8.2.1).

Although the above differences are inconclusive, it would appear that Tres Zapotes Great Mound archaeological material may confirm the weathering of Monument A as representative at least in hue and in comparable depth of weathering (in excess of the models provided by Cernohouz and Solc and Colman and Pierce). It is impossible to ascertain whether the Great Mound basalt chips are products of stoneworking but there is no evidence to suggest that they are not so. In the opinion of this researcher, these basalt chips appear just as weathered as Monument A, which might evidence a comparable date in the 10th c. B.C.

C. Internal Individual Mineral Grain Weathering Comparison between Tres Zapotes and Cerro El Vigia Material

While it was impossible to sample the above Tres Zapotes Monument A Colossal Head for individual mineral grain weathering internally (which would require some removal of samples) it was possible to examine the above material of identical source in B.
from the Great Mound at Tres Zapotes (generously supplied by Dr. James Porter) and to compare individual grain weathering of this material with that of source material from Cerro El Vigia which was sampled by this researcher.

As can be seen in microphotographs (Plates 6.6 and 6.7), petrographic examination shows both archaeological material from Tres Zapotes Great Mound and geological material from Cerro El Vigia to have some olivine alteration to iddingsite. Although it may be minor, there appears to be slightly greater iddingsite alteration on the Tres Zapotes archaeological material than on the Cerro El Vigia fresh geological material. This may be due to the apparent fact that the archaeological material shows greater fracturing of both olivine and giant clinopyroxene phenocrysts. Many giant phenocrysts of clinopyroxene in the archaeological material from the Great Mound at Tres Zapotes do not last through thin section preparation, which may be a result of stoneworking with more microfractures, although there is no real external evidence yet for this. There is a consistent difference here, however, in the higher loss of the huge pyroxene phenocrysts from Tres Zapotes material than Cerro El Vigia material, which suggests that the Tres Zapotes material could have gone through greater stress.

In a curious twist, the Cerro El Vigia material should have a longer outside exposure, hence a probably greater time factor of weathering on its outer surface than on the Tres Zapotes archaeological material (which has been buried at some uncontexualised stratigraphic depth and thus somewhat protected from exposure). Yet, the interiors of both have been examined and
the Cerro El Vigia material is definitely fresher. Furthermore, no geological weathering rinds were found on the source material from Cerro El Vigia. This is not because of having sampled only recent exposures, because samples were from round boulders and large river cobbles comparable to Colossal Head dimensions. The external weathering, however, of Cerro El Vigia material was comparable in colour. It is possible that all weathering rinds on surface rocks in the tropical environment are lost by exposure to intense climatic conditions (Colman and Pierce, 1981:7-8) and also because the material is so coarse-grained (Colman and Pierce 1981:12) as a hugely-porphyritic basaltic andesite. As another possible explanation for the thick weathering rind on the Tres Zapotes archaeological material, as has been raised earlier, it might be that the Tres Zapotes archaeological material from the Great Mound (the stone chips analysed here) came from an already weathered zone on the stone boulders, and that further weathering has thickened the geological weathering rind which developed since the Plio-Pleistocene (or even from a later Quaternary flow) to which much of this area of the Tuxtla Mtns. dates (Coe and Diehl, 1980).

Some of these discussed differences between archaeological and geological material could be expressed thusly:

<table>
<thead>
<tr>
<th>equal</th>
<th>deeper</th>
<th>chiselling</th>
<th>geological</th>
</tr>
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<tbody>
<tr>
<td>time</td>
<td>stratigraphy</td>
<td>stoneworking</td>
<td>&gt; weathering</td>
</tr>
<tr>
<td>factor</td>
<td>factor</td>
<td>factor</td>
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<table>
<thead>
<tr>
<th>Tres Zapotes material:</th>
<th>(Cerro El Vigia)</th>
</tr>
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<tbody>
<tr>
<td>(Monument A &amp; Great Mound)</td>
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or

| geological & archaeological | chiselling | geological | |
|---------------------------|------------|------------|
| weathering | stoneworking | > weathering |
| factor | factor | |

<table>
<thead>
<tr>
<th>Tres Zapotes material:</th>
<th>(Cerro El Vigia)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Monument A &amp; Great Mound)</td>
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</table>

378
Two qualifications are necessary here. 1) The equal time factor means that over the last 3000 yrs only the archaeological material shows significant weathering rind development. That is, the geological age of both materials should be essentially the same, so even if some geological weathering had developed in all the material, it is possible that the archaeological material has had additional accelerating influences. 2) In chiselling, flakes from the stoneworking may be sufficiently large as to escape some of the intense microfractures which have remained on the stone surface. Thus, not all chiselling produces equal damage on all archaeological material.

In summary, these possible weathering explanations enlarge considerably upon the factoring of Colman et al., without which, however, it would have been impossible to build a cohesive and more complete weathering picture.

10.3.3 Inca Weathering Rinds

Weathering rinds identifiable on Incas ashlers are the most numerous in the present study. This is not only because sampling quantity of Inca material has been good: access to Inca quarries (e.g. Rumiqolqa) wherein many relict Inca ashlers can be sampled; but also because this material is not considered as sensitive a cultural property as the Inca structures themselves, resulting in greater ease of sampling archaeological surfaces at the quarry.

Nonetheless, out of perhaps eighty ashlers examined at the Llama Pit of Rumiqolqa quarry, nearly all of which appeared to have equal weathering exposure in terms of length of time left undisturbed in an archaeological context, less than 40% of these
showed complete stoneworking to what might be considered a finished state. Of the others sampled, weathering was nearly totally absent other than external hue or staining. That is, the andesite blocks sampled which had little stoneworking had correspondingly absent weathering rinds. This has greatly supported the factor of stoneworking as an accelerated weathering factor. Conversely, a total of less than ten Inca ashlars with drafted edges with the characteristic parabolic shape (see Figure 9.1, Ch. 9, and text on Inca "battering" stoneworking) were found to have identifiable weathering rinds. Of the other perhaps 240 blocks in the Llama Pit (from Protzen's count, although only about half could actually be considered ashlars) probably many of these might show the almost nonexistent 0.00-0.01 mm "crust" identified in the study of Cernohouz and Solc if they were broken up.

The following discussions address individual ashlars with weathering rinds, all of which, with one exception, exhibit the reverse rind hue (dark rind, light interior) which seems to characterize archaeological weathering compounded with stoneworking-accelerated contexts. It appears significant that they are all from Rumiqolqa, the best-preserved and largest identifiable Inca quarry location, also with one exception — the same exception noted above — which comes from Ollantaytambo but whose geologic origin is Huaccoto. It is also important to note that the Huaccoto material in Cuzco appears to have no rind development and also that the environmental differences between Huaccoto and Ollantaytambo are greater than those between Huaccoto and Cuzco. These points will be elaborated in succeeding
discussions.

The ideal features recommending these Inca contexts for a weathering study are 1) the regional nature of Rumigolqa source contexts, approximating the parameters of the studies of Colman et al. in having little variation, allowing greater statistical control; 2) the short term nature of the weathering, testing the time factor suggested by Cernohouz and Solc (500 yrs); 3) the greater representative sampling provided by the quarry contexts; and 4) the certainty of undisturbed contexts for a majority of relict ashlars at the Rumigolqa quarries -- the fact that the ashlars have remained in an undisturbed situation since manufacture should permit a more quantitative assessment of weathering on a small scale to be made.

The importance of the first feature listed above should not be minimized. The abandoned ashlars at the Rumigolqa quarry share the following common weathering parameters: approximate date of use, parent material, stoneworking method, and environmental conditions (including for the most part microclimate). Thus they should share weathering features as well.

In keeping with the need to examine visible microscopic (via individual mineral grains) as well as visible macroscopic (via weathering rinds) textures, petrographic observations will also be incorporated in the discussions of the following individual Inca ashlars (but not in separate sections as in rind discussions of Levant and Mexican material). Tentative explanations will also be provided which assess the similarities and contrasts between individual ashlars.
A. Saqsaywaman: Ashlar 2

The Saqsaywaman ashlar arbitrarily numbered here as # 2 is from the circular structure named Myukmurka (J. Rowe, pers. comm. in 1988). This structure is adjacent to the scarp above Cuzco, approximately 280 m higher than the city itself. Its chronology is not certain, but it is associated with Pachacuti's monumental building period beginning shortly after accession in 1438 A.D.

The ashlar, like many others from Myukmurka, is worked from Rumiqolqa red hornblende andesite which quarry observations and subsequent examination (T. Keith, 1988, pers. comm.) show to be hydrothermally altered. The argument suggested here is that the red Rumiqolqa stone was quarried before the grey stone, partially supported by the availability of hydrothermally-altered red andesite on the surface above the Rumiqolqa quarry (named by Protzen as the Llama Pit). Vents or vertical veins of this red stone have been mostly quarried out at the Llama Pit, leaving an abundance of grey stone remaining despite its also having been extensively quarried. Tentative evidence from the archaeological contexts in support of possible earlier use of the hydrothermally altered material is as follows.

This ashlar averages a 3.8 mm weathering rind on its drafted edge (Plate 10.10). This might tend to suggest a greater age than all other sampled rind-bearing ashlars given that it is the thickest rind. This may be corroborated by the fact that the lowest stratigraphic courses of andesite in Cuzco below the scarp of the Korikancha (on the southwest side) are also made from red hornblende andesite. How much earlier this is than the
Pachacuti building period is unknown. It appears that some of the green granodiorite from El Rodadero is also employed in the same basic levels of Korikancha stratigraphy. This granodiorite used in Cuzco structures differs greatly from the ashlars associated with Pachacuti. While the Pachacuti ashlars are squared and mostly rectangular and in what Agurto Calvo calls "sedimentary" courses of andesite (Agurto Calvo, 1987:158), these granodiorite emplacements are often cyclopean in size or in highly polygonal shapes, what Agurto Calvo calls "engastado" with irregular angles (Agurto Calvo, 1987:154-57; 172), as seen at the corners of the Calles (streets) Cabracaancha and Tullumumayo in Cuzco with highly-convex, bubble-like exteriors or in the artisan area northeast of the Cathedral respectively (Plate 10.11) and also in some Machu Picchu walls. If this use of granodiorite also predates Pachacuti (which is suggested by this researcher) as the observed low stratigraphic position below the Korikancha would allow, then the three observations of thicker weathering rind, lower Korikancha stratigraphic stone course, and quarry access at Rumiqolqa would mutually complement each other in supporting an early relative date for the Myukmurka structure.

However, the following caveat must also be mentioned as a potential counter-argument. It is possible that the hydrothermal alteration noted (happening long before quarrying at Rumiqolqa) which gives this material its "rosado" pink colour (Agurto Calvo, 1987:150) made this material softer and more easily fractured than unaltered grey andesite, thus both easier to remove in the quarry and also more deeply microfractured in its stoneworking. This could also result in the 3.8 mm rind.
Perhaps the best resolution would be to suggest that both of these situations are true: that it may well be slightly earlier (but without a fixed idea of time lapse); and that the altered state allowed an accelerated rind development. This could be expressed thusly for a 3.8 mm rind:

\[
\text{hydrothermal} + \text{stone-} + \text{equal time} > \text{stone-} + \text{equal time}
\]

\[
\text{alteration} \quad \text{working factor} \quad \text{working factor}
\]

Red Rumiqolqa material \quad Grey Rumiqolqa material

Additional supporting evidence for the importance of the factor of time can be seen in the following hydrothermally altered ashlar from Rumiqolqa, Ashlar 6.

B. Rumiqolqa: Ashlar 6

Again noted as hydrothermally-altered red ("rojizo" or "rosado" difference not always marked in Agurto-Calvo’s account), Ashlar 6 from the Llama Pit quarry at Rumiqolqa also has a dark red rind over pink interior. The rind on Rumiqolqa Ashlar 6 averages 2.8 mm in thickness, considerably thinner than the above-noted Rumiqolqa ashlar found at Sacsaywaman (Plate 10.12).

As seen in petrographic texture (Plate 10.13) the hornblende phenocrysts in this ashlar show a heavy relief and reaction rims of opaque material which appear to be expected in hornblende alteration as noted by Colman (1982:13). Also present is a change in colour throughout the stone in thin section which might be associated with alteration as these hornblende phenocrysts are
(Plate 10.11 [above]) INCA GRANODIORITE POLYGONAL WALL north-east of the Cuzco Cathedral, Plaza de Las Armas; (Plate 10.12 [below]) WEATHERING RIND of RUMIQOLQA ASHLAR 6 at 2.8 mm (difficult to see except along top edge, bottom right area is actually dark because it is broken off); scale of the ashlar fragment is 1.3 cm wide.
more orange to brown than other golden-orange hornblendes seen by this researcher. Such contrasts may be more likely as products of hydrothermal alteration than of time alone.

However, since environments are roughly comparable between Saqsaywaman and Rumiqolqqa, with little variation between exposure to MAP of about 1550 mm and MAT of about 16°C, it is important to try to account for the difference in weathering rind since the following factors appear in common: parent material (including hydrothermal alteration), environment, kind of stoneworking, and possibly time (although as stated, the Saqsaywaman ashlar may be older).

An average difference of 1.0 mm between Saqsaywaman 2 and Rumiqolqqa 6 could possibly be explained thusly. First, although the type of stoneworking appears comparable, it must be noted that Saqsaywaman 1 has much more finished dressing and is in its final emplaced context. On the other hand, Rumiqolqqa 6 is not in final dressing stage. It is possible that additional dressing at Rumiqolqqa (Protzen, 1986:88) to the finely-dressed state plus additional time could account for the difference, expressed thusly:

\[
\text{Additional stoneworking + time + in factors} > \text{in factors common factor common}
\]

(Saqsaywaman 1) (Rumiqolqqa 6)

The following discussions will examine other Rumiqolqqa ashlars with weathering rinds. As has been stated previously, measurement of weathering rinds has been by Vernier Scale caliper with multiple measurements to reduce possibility of error.
Plates 10.13 & 10.14

(Plate 10.13 [above]) RUMIQOLQA ASHLAR 6 PETROGRAPHIC texture w/
iron oxide rims on altered hornblende (note the characteristic
amphibole cleavage), plagioclase feldspar and groundmass; (Plate
10.14 [below]) RUMIQOLQA ASHLAR 2 with 2.2 mm weathering rind.
C. Rumiqolqa: Ashlar 2

Rumiqolqa ashlar 2 is also of hornblende andesite, but not in a hydrothermally-altered state. It is grey in hue with a black rind over a grey interior (Plate 10:14). The rind has an average thickness of 2.2 mm and the ashlar appeared mostly fine-dressed with a distinct parabolic drafted edge (see Figure 9.1, Ch. 9).

As its context in the Llama Pit quarry should suggest it is of the same approximate chronology as the previous ashlar, perhaps a little younger, the rind thickness difference between the red altered andesite of Rumiqolqa 6 and this grey andesite of Rumiqolqa 2, a difference of 0.6 mm, could be considered minimal (other than by Cernohouz and Solč's study). However, it should be noted that it is more finely-dressed than the previous ashlar with additional stoneworking, which may have increased its rind to a nearly comparable thickness. This could be expressed:

\[
\text{hydrothermal time} + \text{additional factor} > \text{stoneworking factor}
\]

(Rumiqolqa 6)                        (Rumiqolqa 2)

in that the hydrothermally-altered ashlar still possesses a thicker rind, but one which might have been much thicker if it had finer stonedressing.

D. Rumiqolqa: Ashlar 3

Rumiqolqa ashlar 3 is also of grey hornblende andesite, with a fine stonedressing comparable to the previous ashlar. Its rind colour is also black against grey interior, and rind thickness averages 2.3 mm. In all aspects it appears comparable to the
previous ashlar (Rumiqolqa 2). As such it is representative of about four other Rumiqolqa finely-dressed ashlars with notable parabolic drafted edges and comparable weathering rinds between 1.8-2.3 mm in average thickness (Plate 10.15).

Petrographic texture of Rumiqolqa ashlar 3 (Plate 10.16) shows a typical hornblende phenocryst with a thinner reaction rim than noted in the hydrothermally-altered (and possibly slightly older) Rumiqolqa 6 as well as having a lighter, yellower phenocryst hue as noted in the study of Colman (1981:13) on amphibole alteration in general. These two observations support the suggestion that the hornblende phenocryst appearance of Rumiqolqa 6 is due to the hydrothermal alteration noted. Thus, the closeness between the weathering rinds of the last two ashlars (and others equally-worked at Rumiqolqa from nearly-identical parent material, i.e. not hydrothermally-altered by a hot steam vent) could be suggested as perhaps only a slight difference in microclimate or otherwise equal. This could be expressed thusly:

\[
\text{similar weathering} = \text{similar parent} + \text{similar conditions} = \text{rind thickness}
\]

This overall similarity between Rumiqolqa material which has had essentially the same conditions in the abandoned quarry ashlars, particularly as noted here in Rumiqolqa 2, 3, and the other Rumiqolqa ashlars with a rind thickness range between 1.8 - 2.3, suggests that the significant variables may be among those chosen by this researcher, that is, the ones important for preliminary characterisation of archaeological weathering of a worked stone, particularly for Rumiqolqa quarry contexts.

This closeness of contexts could be important in supporting
(Plate 10.15 [above]) RUMIQOLQA ASHLAR 3 with 2.3 mm weathering rind; (Plate 10.16 [below]) RUMIQOLQA ASHLAR 3 PETROGRAPHIC texture with hornblende (less altered than in Rumigolqa Ashlar 6 and more altered than the hornblende in the Korikancha interior wall) and plagioclase feldspar as well as groundmass.
the deductive nature of observations made thus far in the present study regarding archaeological weathering rinds in general. As a further possible control feature, the following discussion is provided for a fragment of Rumiqolqa material which was not near a parabolic drafted edge.

E. Rumiqolqa: Control Sample 1-1

Rumiqolqa Control sample 1-1 is from a mostly-unworked rear edge of an ashlar which shows little stoneworking and certainly has no proximity to a parabolic drafted edge corner, unlike every other Inca ashlar mentioned thus far (Plate 10.17). It has very little rind development with a dark edge averaging about 0.4 mm. As such it is much closer to the model provided by Cernohouz and Solc (of a 0.2 mm rind after 500 yrs) assuming it to represent an Inca date around 1450 A.D., making its age around 550 yrs or close thereto. This alone might be very supportive of the data of Cernohouz and Solc, but with the following exceptions: 1) its rind is more than twice the thickness of that on Bohemian basalt according to Cernohouz and Solc (1966:806-07); 2) colour is still a reversal of expected colour being black rind on grey interior; and 3) it has had a minimum of stoneworking which is not known for the Cernohouz and Solc model.

Tentative explanations offered for these differences are: 1) the parent material differences are responsible (except that the (Bohemian) basalt should weather at a faster rate than the (Peruvian) andesite (Colman and Pierce, 1981:10) which is opposite to what has been observed here; 2) considerable regional differences in climate and environment (MAP, MAT, RH, etc.) may
be responsible; and 3) the amount of nominal stoneworking on the
Inca ashlar could suffice to accelerate additional weathering
acceleration. In the opinion of this researcher, it is likely
that no one explanation is responsible but some combination of
the above may effect the difference. On the other hand, it may
be possible that stoneworking itself is most responsible for
the rind colour reversal.

Petrographic texture of the Rumiqolqa Control Sample 1-1
shows a hornblende phenocryst very similar to the ones in the
above non-hydrothermally-altered ashlars, with very little opaque
reaction rim and fresh yellow-green colour. The closest parallel
to this unaltered hornblende (Stage I [or A], 1-2c of Colman,
1982:13,19) is to be seen in Plate 5.6 on an ashlar fragment from
the interior of Korikancha (the Inca Temple of the Sun) in Cuzco,
made from Rumiqolqa hornblende andesite. This finely-dressed
ashlar had not only been incorporated into the Iglesia Santo
Domingo complex since the 16th c. A.D. Colonial Spanish period
when it was apparently covered by a tile roof, but also exhibited
no weathering rind, and had the freshest appearance of all worked
material in petrographic thin section. The hornblende phenocrysts
have very little reaction rim and a yellow-green colour. They
appear to have been through very little weathering exposure,
perhaps no significant exposure if covered by an Inca roof
structure and re-covered permanently shortly after the 16th c.
Spanish Conquest or even occasionally exposed since that time
for very brief periods. This lack of alteration on an ashlar
which was on the protected interior of a structure would support
much of the weathering discussions in this chapter in that a
protected environment will limit weathering, particularly as contrasted to the very exposed Rumiqolqa quarry environment, regardless of stoneworking. It could even be suggested that such interior protection as found in the Korikancha context mentioned could in effect be considered a zero time factor (i.e. no age or close thereto) based on lack of alteration, which also supports the significance of time as a weathering factor for the exposed Rumiqolqa material.

In summary, Rumiqolqa weathering rinds on Inca ashlars may be best representative of stoneworking-accelerated weathering as measured against Rumiqolqa Control Sample 1-1 and the data of Cernohouz and Solc; the notable exception being the finely-worked ashlar from the Korikancha which appears to have very little rind development or mineralogic weathering.

As such, a relative dating technique may be calibrated as originally suggested by Cernohouz and Solc with another point placed for weathered andesite alongside the basalt context the prior researchers found, this one beginning at 0.4 mm for a comparable 500-600 yr period. Naturally, it is too early to ask more from the data: much further sampling and calibration will be necessary before such a relative dating technique can be realised (if ever given the range of parent material and diverse environmental factors) as discussed here and in the prior literature. On the other hand, Inca ashlars at Ollantaytambo from biotite andesite tentatively traced to Huaccoto contrast significantly with Rumiqolqa ashlars, as discussed in the next subsection.
Huaccoto biotite andesite appears to have been employed in Ollantaytambo, despite the transport difficulty mentioned in Ch. 5, judging by at least several Inca ashlars including the ashlars arbitrarily numbered Ollantaytambo 2 and 39. As stated earlier (in Chapter 9), the weathering of this Ollantaytambo material is in some ways not consistent with the weathering of Rumiqolqa material except for the depth of rind development, which may best support the depth of stoneworking damage in both source materials despite their mineralogic differences.

As noted at the outset of the discussion on weathering rinds, the Huaccoto andesite used for ashlars here has a normal [by the account of Colman and Pierce (1981:3 & ff)] rind colour of white rind over grey interior, being exceptions (with the Tres Zapotes basalt) to all other rinds on archaeological material, i.e. dark rinds on lighter interiors. Ollantaytambo 2 has an average rind thickness of 2.4 mm and Ollantaytambo 39 has an average rind thickness of 2.6 mm (Plate 10.18). As can be seen both by the unaided eye and more clearly in SEM micrograph, the porosity of these Ollantaytambo ashlar edges is in high contrast to the fresh interior (see Plate 9.4). This porosity and rind colour may be best considered as representative of stoneworking damage, with the softer Huaccoto biotite andesite in contrast to the harder Rumiqolqa hornblende andesite (a characteristic noted by this researcher).

Petrographic examination of Ollantaytambo ashlars clearly shows biotite phenocrysts (Plate 5.8) which are in high contrast to the biotite phenocrysts of fresh unworked Huaccoto material.
(Plate 10.17 [above]) RUMIQOLOQA CONTROL SAMPLE 1-1 with 0.4 mm WEATHERING RIND on mostly unworked surface; (Plate 10.18 [below]) OLLANTAYTAMBO ASHLAR 39 with 2.6 mm WEATHERING RIND. Note that the parabolic corner edge is transitional between dark and light, perhaps suggesting microfractures are becoming micropores.
Ollantaytambo biotites have opaque reaction rims which are possibly to be compared with long-term opaque FeO reaction rims found on the basalt and andesite material examined by Colman and posited by him as the mineral weathering stage 2c of Stage II (or B) (1981:5, 19) (see Figure 8.1 of this thesis for Colman's mineral weathering stages. Although Colman's studies did not include biotite, application of mineral stability proposed by Ollier and others suggests biotite would be in a sequence between hornblende and Na Plagioclase, i.e. albite (Ollier, 1984:69; Read and Watson, 1973:404-07). Furthermore, the colour of these Ollantaytambo biotite phenocrysts is clearly altered to a yellow-brown as opposed to fresh green biotites in unworked interiors of Huaccoto material, and may partially explain the rusty exterior colour due to rapid FeO staining as biotite is weathered (as noted in Ch.8) (Winkler, 1975:164).

These two visible contrasts (light rind and altered biotite) in Ollantaytambo andesite ashlars are the most dramatic seen in any of the archaeological material noted in this study which have verifiable stoneworking contexts.

As stated earlier, the Ollantaytambo material is also unusual in that these ashlars were exposed to a high volume of water in that they appear to be from fountain contexts (Protzen, 1988, pers. comm.) with much of the aqueduct apparatus still in place and partly operational. While it is unknown if all the andesite ashlars from Ollantaytambo have light weathering rinds and have also all been in water-related use, the probability of such is dubious. As seen in Plate 10.18, there is both dark and light rind development (mostly dark with patches of white) whereas in other ashlar edges much of the rind is nearly all of a lighter,
leached appearance. It is suggested here that ashlars 2 and 39 at Ollantaytambo have been in environments where moving water had removed surface iron from the biotite, limiting Fe oxide staining and also accelerated the weathering to the level of porosity now seen at the level of stoneworking depth (around 2.4-2.6 mm).

This could be expressed thusly:

\[
\text{stoneworking} + \text{aqueous (short = apparent)} \\
\text{factor} \quad \text{environment} \quad \text{time (span)} \quad \text{geological} \\
\text{weathering}
\]

If this is not the case, a better explanation will have to be provided for the type of weathering rind seen to date on what appears to be Huaccoto biotite andesite at Ollantaytambo. Another explanation could be that the Ollantaytambo ashlars do not date from Pachacuti's era of building (mid-15th c.) but are from an earlier period (see Ollantaytambo, Ch.5). This remains to be seen and is at odds with the traditional date for this section of Ollantaytambo (Protzen, 1988, pers. comm.).

Furthermore, this weathering at Ollantaytambo approximates the weathering rind thickness and rind colour of Tres Zapotes material, already noted in 10.3.2 wherein an unusually thick weathering rind is found with a light rind colour. Weathering of glass appears to be evidenced for Ollantaytambo ashlar 39 even beyond the porosity voids within the weathered zone as shown by silica loss at a 1.5 mm distance from the perimeter (discussed in the next section on chemical analyses). The accord between both the Tres Zapotes and Ollantaytambo contexts suggests that the factor of stoneworking (probably chiselling on the Olmec Tres Zapotes colossal head; probably battering on the softer Huaccoto andesite) is most likely responsible for the thickness of the
rind itself. In this case, it becomes a matter of terminology whether or not a true weathering rind has developed. More likely a dark rind can be better equated with archaeological weathering as shown by the Rumiqolqa Control Sample 1-1 which has a dark rind but minimal stoneworking and the Levant material (including both Jericho Neolithic rinds and Canaanite Hazor) all of which as examined by this researcher appear to have been produced by the method of grinding with little or no stoneworking damage.

Table 10.6 may present some of the most important findings of this research as partially filling in the gap between Cernohouz and Solc's short term archaeological and longer term geological weathering and the longer term geological weathering of Colman et al., but also presenting conflicting evidence as to the expected results because the data of the present study do not reinforce or fit in to the data of either prior study at the critical initial (i.e. early) weathering points.

Table 10.6 POSSIBLE TIME-FACTORED ARCHAEOLOGICAL WEATHERING

<table>
<thead>
<tr>
<th>Rind in mm</th>
<th>Jericho</th>
<th>Hazor</th>
<th>Rumiqolqa 1-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>* (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td></td>
<td>* (2)</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1000</td>
<td>2000</td>
<td>3000 4000 5000 6000 7000 8000 9000 10000</td>
</tr>
</tbody>
</table>

Therefore, conflicting with the conclusions of Cernohouz
and Solc, three weathering rinds whose growth has not been notably accelerated by stoneworking can be contrasted with the data on Bohemian basalt used in castle walls (also likely to be unmodified by stoneworking to any large degree if the present study is any indication). These are found as points (1) Rumiqolqa Control Sample 1-1 at around 500 years of weathering with a rind thickness of 0.5 mm; (2) Hazor Canaanite at around 3500 years of weathering with a rind depth of 0.8 mm; and (3) Jericho Neolithic 2 (secondary use) at around 10,000 years of weathering with rind thickness of 1.5 mm. An exponential curve (developing beyond the three points) may be connected to points in the studies of both Cernohouz and Solc and Colman and Pierce, however, with important differences. The suggestion of this study is that thick rinds can develop in a relatively short time, as can be seen in Cernohouz and Solc where a time period of 20,000 yrs. is required for a rind thickness of 0.3 mm as contrasted with only 500 yrs. required for a rind thickness of 0.4 mm in Rumiqolqa material which is mostly unworked. Thus the rate curve of the present study is greatly different than those suggested in prior studies. Furthermore, as has been shown in photographs, the rind colour is also in contrast with a dark rind as opposed to the light rind of the prior studies. These contrasts are not understood to be resolved by acceleration of weathering through stoneworking alone but at present no more important influence has been discussed. On the other hand, although it appears not to have been discussed in detail, the differences between the exponential rate curves of Cernohouz and Solc and that of Colman et al. is also to be noted, particularly where the strictly geological rate curve formulated by Colman et al. is significantly less accelerated than that of
Cernohouz and Solc. Whether or not this difference can be resolved via differences in parent material and environment is not clear, but the dramatic acceleration of weathering rind development of the rate curve in the present study suggests that these differences ought to be resolved by more than just the factor of time.

Even in the present study there is some disparity between the stratigraphic depths with one (1: Rumiqolqa) having surface exposure and (2: Hazor) having 1-2 m depth and (3: Jericho) having > 5 m depth suggests that the last two contexts could have significantly thicker rinds with higher stratigraphy. Also, the other factors of environment (climate as seen in MAP, MAT, RH) and parent material as variables urge caution in accepting this as the only interpretation of the data. One could resolve some disparity by noting that the Jericho Neolithic material had considerable surface exposure (as well as possibly having been pecked or battered in its first use) for an indeterminate time span nearer the surface -- which could be true if its stratigraphic depth would have been shallow for several millennia -- and also that all three of the above contexts have in common little or no stoneworking (2 and 3 by grinding). Thus, time as a weathering factor can be influential in rind depth development, suggesting that prior research is valid with the proviso that the material has not undergone stoneworking stresses which may accelerate weathering. The importance of this contribution in filling gaps of the prior studies should not be overlooked. Also, going beyond the focus and conclusions of the prior studies, the accumulated data on the potential of
weathering accelerated by stoneworking adds an important element not considered by the prior studies.

The darkness of the rinds found on most of the material and the probability that the Bohemian basalts noted in the study of Cernohouz and Solc were above the surface (unlike the material in the studies of Colman et al.) may call for a reappraisal of the rind colour data of Cernohouz and Solc.

Table 10.7 below suggests a different graph for stone which has undergone stoneworking (and/or climatic) acceleration. The multiple common-depth rinds from Rumigolqa as well as the material from Tres Zapotes and Jericho Neolithic 1 (all of which evidence stoneworking) are included in this table.

Table 10.7 ARCHAEOLOGICAL WEATHERING RINDS ACCELERATED BY STONEWORKING

<table>
<thead>
<tr>
<th>Rind</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0</td>
<td><em>(Tres Zapotes)</em></td>
</tr>
<tr>
<td>5.0</td>
<td><em>(Jericho Neolithic 1)</em></td>
</tr>
<tr>
<td>4.0</td>
<td><em>(Saqsaywaman)</em></td>
</tr>
<tr>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td><em>(Rumigolqa: four samples at around 2 mm; Ollantaytambo: 2 samples at around 2 mm)</em></td>
</tr>
<tr>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>1000 2000 3000 4000 5000 6000 7000 8000 9000 10000</td>
</tr>
</tbody>
</table>

(time in years)

As seen above in Table 10.7, no semblance of an exponential curve can be derived from the material with stoneworking damage. The tendency of Inca material to be for the most part damaged to a depth of 2 mm is in fact an evidence for the common method of battered stoneworking (except for the hydrothermally-altered or very soft Huaccoto material). On the other hand, the extreme
depth of rind of Tres Zapotes material is suggested by the chisel method of stoneworking plus tropical climate plus time as order of influence of weathering factors; equally the depth of rind of Jericho Neolithic 1 can be explained as a combination of pecking stoneworking plus time. Thus time cannot be removed as a factor of influence in weathering, particularly as the least-developed rinds with accessory stoneworking are seen in the youngest archaeological material whereas the most-developed rinds and accessory stoneworking are seen in the oldest archaeological material.

In summary, rind thickness may be best equated with the suggested destructive methods of stoneworking (such as chiselling and battering) where the material is known to have been worked. This is not to underestimate the factor of time as influential in the weathering of basalt and andesite in such archaeological contexts as selected here for study. The data as observed in the present study could also suggest that additional experimental work should be undertaken on different stones using on the one hand, the same stoneworking method as a control, and on the other hand, different stoneworking methods. Yet, as can be seen in material from both the Levant and from Inca contexts such as Rumigolqa Control Sample 1-1 and the protected Korikancha interior, the element of exposure is sufficiently capable of also distinguishing weathered from unweathered surfaces.

This suggests much potential application for chronometric examination and a relative dating technique if and when the other weathering factors can be calibrated with time as suggested for geological weathering by Colman and Pierce (1981:24-39). Ultimate application of relative dating of rind development is most
expected from continuing regional studies such as offered by the material at Rumiqolqa or a similar context with a volume of exposed material which have not been disturbed since emplacement or the cultural use. Any projected success of relative dating of basalt and andesite weathering of archaeological material seems to require stone not altered by results of stoneworking.

10.4 Chemical Analyses

The analyses of SEM with EDS on all the archaeological material of this thesis showed little evidence of the elemental mobility that might have been expected from the studies of long term geological basalt and andesite weathering by Colman and others (Colman, 1982:10-20; Ollier, 1984, esp. Chs. 3 & 11; Winkler, 1975, esp. Chs.7 & 9; Colman and Dethier, 1986, esp. Ch. 15, pp. 379-93) or experimental laboratory studies (Balitskii and Zubkova, 1982:160 & ff; Rosenbauer et al., 1988:237-43; Drever, 1985:211). The most likely explanation for this perceptibly low level of elemental mobility is that the archaeological material studied represents a relative chronology which is too short term to offer significant and measurable contrasts.

While it is likely that more detailed and quantitative analysis could suggest elemental mobilities for the Levant and Olmec materials due to their greater relative age, the factors of burial depth and lack of known geological sources in the Levant apparently resulted in a lack of consistency in EDS dot scan profiles across the material and limited the overall usefulness of the elemental results. Other factors limiting the consistency of EDS line profiles are possible but are not offered here.
The low volume of Levant and Olmec samples relative to the Inca material is probably also significant for being less representative of expected elemental tendencies.

The single group of archaeological samples which seemed to suggest minimal elemental mobilities was the Rumigolqa-Huaccoto-Pisaq material, probably due to a more representative sampling in the volume of Inca material as well as having in situ known source contexts, i.e. Rumigolqa, Huaccoto, and Pisaq quarries. For reasons not fully understood, SEM optical resolution of weathering rinds was not ideal, except in the case of the Ollantaytambo material where there was high visual contrast between weathered and unweathered areas in terms of gross changes in microporosity (see Plate 9.4). Although it is recommended that the Inca chemical weathering tendencies be taken for nothing more than tentative suggestions, these Inca contexts will receive the bulk of attention in chemical weathering data.

As suggested earlier in this thesis (Chs. 5, 6, 7: "Chemical Analyses") the primary analytical foci would be on 1) feldspar because it was the one phenocryst common to all material and 2) on the groundmass because glass there is perhaps the least stable component in all prior weathering studies (Colman, 1982:10-11 & ff). Where feldspar comparison were considered earlier in this study relative to chemical analysis in questions of provenance, groundmass material will be the primary focus of weathering analyses, noting the instability of glass in even the youngest of geological materials (Colman, 1982:10).

The primary method used to gauge elemental mobility on Inca material was by SEM with EDS line profiles run across perpendicular ashlar faces known and marked as Inca-modified
surfaces. The two possible EDS elemental profiles suggested here are Si loss from the weathered area in contrast to the unweathered area of Inca material and potential Fe mobilisation from the hornblende and biotite phenocrysts.

10.4.1 Potential Loss of Si

An important question to ask regarding elemental mobility is regarding the most likely change to occur over the shortest time, in archaeological rather than geological periods. The prime candidate for focus appears to be glass in the groundmass, because of its inherent instability (Colman, 1982:10,11, 12, 14).

Deterioration of glass can be gauged by Si depletion as probably the most consistent indicator of short term weathering (Colman, 1982:11). Furthermore, alteration of glass in the thin sections of many archaeological materials of this study showed the expected stage B (or II) as 2a-2d from Colman et al. for stained glass (Colman, 1982:5) by petrographic analysis (see Plates 5.7, 5.8, & 10.13 of the Inca material for Colonial Cuzco, Ollantaytambo, and Rumigolga Ashlar 6), thus correlating the petrographic and chemical analyses. Figure 10.2 below presents EDS analyses of potential Si loss.
Figure 10.2 INTERIOR SI INCREASE AS POSSIBLE EVIDENCE OF DETERIORATION OF GLASS IN GROUNDMASS

EDS

Count

Rate

Perimeter Depth in mm

Note: EDS analyses were by Link System 10-25S with all parameters in common: @ 20 kv; 100 seconds livetime; cobalt standard as reference; elevation was 31.46 and the means of analyses was by dot scan mode @ 3000 x. Because EDS detection count rates are not quantitative assessments, the above data are preliminary and are given only as tentative evidence. The above numbers associated with points represent the EDS count rates.

The 2 mm zone usually distinguishes weathered from unweathered material based on weathering rinds in Rumigolqa material (3 mm in Huaccoto material). The most dramatic indicator of Si loss in a weathered area is seen at Ollantaytambo (0-39, see Plate 9.4 which photomicrograph matches this particular detection sequence). Arrows indicate some stability has been reached at that point.
All EDS spectra showed a change in Si detection count rates with general Si rise as analyses progressed inward. Both Rumiqolqa 2 & 6 stop at 2 mm since no significant change occurred after that point (based on 87 spectra). Korikancha analyses are not recorded on this graph because no consistency or overall tendency for Si loss or gain was observed. The total number of EDS spectra analyses examined per context are: Rumiqolqa, 87 spectra on more 10 samples; Colonial Cuzco, 26 spectra on more than 5 samples; Huaccoto, 14 spectra on 5 samples; Ollantaytambo, 13 spectra on 4 samples; Korikancha, 8 spectra on 3 samples; Pisaq, 8 spectra on 4 samples. The spectra are reported in sequence from perimeter to interior for each context and are not an Si average of all the analyses but are representative of the total number of analyses, i.e. the progression shown for Ollantaytambo is similar to the majority of the groundmass analyses.

The probabilities of the Si being depleted from the glass are suggested by the following: 1) loss of Si from hornblende and biotite phenocrysts (on line profiles moving from perimeters to interiors) is lower and less consistent according to detection count rates on these two minerals respectively at all Inca contexts (only 1 EDS line profile on Ollantaytambo biotite and 1 line profile on Rumiqolqa hornblende were found out of over 40 analyses of spectra to suggest any Si loss from perimeter to interior); 2) the extensive microporosity differences in, for example, Ollantaytambo material appear to be not around phenocrysts but groundmass areas (Plate 10.19); which, if the microfractures followed phenocryst fractures, Si loss would be expected there; 3) also, the Ollantaytambo data was acquired not in voids created
by microfracture but in the leached areas between porosity voids; 4) as shown in EDS detection count rates, Si is the most mobile of all the detected major elements, being unstable compared to other elements, which would be expected in deterioration of glass (Colman, 1982:10-11); 5) the Si loss is not expected to be from plagioclase feldspars because these are as relatively stable as hornblende and biotite (Colman, 1982:22; Read and Watson, 1973:403-07) whereas, as has been mentioned often, glass is the least stable component in basalts and andesites (Colman, 1982:10-11, 12 through 14, and Tables 3, 5, & 6); 6) and most perhaps important of all, glass is abundant in petrographic examination of both Rumiqolqa and Huaccoto material (Chapter 5 of this thesis and Gregory, 1916:92, 100).

One immediate implication of this potential Si loss, possible for all basalt and andesite where glass is present in the groundmass, applies to the provenance studies found in Chs. 5 - 7 of this thesis. That is, could depletion of Si on a weathered surface, especially worked ashlars even from the source quarries, obscure the chemical boundaries between materials? This should not be the case for most of the Inca material where comparisons of only fresh material were made between samples, i.e. unworked quarry samples and even unweathered interiors of ashlars, nor should it affect the unweathered Korikancha material from protected interior walls of the roofed ashlar structure. However, in the site contexts of Ollantaytambo and especially Colonial Cuzco, nearly all samples were from superficial areas averaging 3 cm in depth. Thus, considering the suggestion that Huaccoto source material weathers rapidly (Gregory, 1916:92) and the fact that archaeological sampling itself is often limited to removing
the least destructive volume of material for analysis, comparison of 65.2 wt % SiO at Huaccoto to 64.8 wt % SiO at Colonial Cuzco (see Table 5.3) may suggest that Si depletion at Colonial Cuzco contexts could skew analyses which might otherwise easily evidence determination of provenance to Huaccoto by chemical analysis in accord with petrographic analysis.

This same question of potential Si loss should be applied to all studies of provenance of archaeological basalts and andesites where sampling may be limited to surficial material. Presumably, others are aware of this feature of glass weathering as glass is a common component of volcanic rock groundmass. Nonetheless, the provenance studies on millstones, querns, and related grinding tools where these are basalt or andesite should be reappraised for this possible skewing of chemical analyses through short term Si depletion in groundmass glass.

While this tendency towards Si loss is only suggested here, it is nonetheless displayed in sufficient examples (and more than any other elemental mobility) as summarized in Figure 10.2 to recommend its correlation with glass deterioration, although this warrants further study before it can be considered conclusive.

10.4.2 Potential Fe Mobilisation

As displayed on many archaeological surfaces worldwide, the rusty colour which so often stains basalt and andesite suggests some elemental mobility of iron. Characterisation of the iron mobility as suggested by prior studies (Colman et al., 1981, 1982 & 1986) has not been achieved at a comparable level in this study as might have been expected based on the prior work. This may be
INCA ASHLAR-OLLANTAYTAMBO BIOTITE <PERIMETER>

(Plate 10.19 [left]) SEM PHOTOMICROGRAPH of edge of Ollantaytambo ashlar 39 with a BIOTITE around which are at least six MICROPOROUS leached out probably of what were initially microfractures.

INCA ASHLAR-WORKED EDGE <INSIDE 14 MM> BIOTITE

(Plate 10.20 [right]) OLLANTAYTAMBO ASHLAR 2 BIOTITE phenocryst with multiple plate cleavages along which iron is easily mobilised out of the stone (Winkler, 1975:164).
partially because it has been difficult to obtain consistent EDS results in Levant and Olmec contexts based on less representative sampling, and, more important, probably because the short time factor in the Inca contexts is responsible for little evidence of elemental mobility. On the other hand, the Rumíqolqa and Huaccoto materials have provided perhaps the most representative results, may be seen with Huaccoto biotites on Cuzco surfaces. Elemental mobility in biotite was also suggested by biotite ease of cleavage (Ch.8) (also see Plate 10.20). Huaccoto material is apparently more easily damaged by stoneworking (for possible reasons offered in section 10.21 and Table 10.2), not the least of which are the large percentage of biotite phenocrysts in total volume (24%); the size of the biotite phenocrysts (many at 2 mm length), therefore more surface area (Ollier, 1984:60-61), and the platy nature of biotite which also results in more surface area, and with it susceptibility to weathering (Ollier, 1984:60-61). Winkler suggests the mobility of iron from the silicate lattice of biotite thusly:

"Biotite...loses its iron at the beginning of the weathering process because the iron is only loosely built into the lattice. Iron almost immediately precipitates as a natural rust halo nearby the biotite flakes. The presence of larger quantities of biotite flakes evenly distributed across the rock substance may spread an almost even ochre cast over the rock. The release of iron from mica is about 500 times greater in distilled water than from other ferromagnesian silicates leached under identical conditions... The presence of black mica [biotite] appears to be a source for the rapid release of iron." (Winkler, 1973:164)

Winkler also suggests the cleavages of certain minerals allow an increased porosity, which is the nature of biotite with "easy travel routes" along its parallel cleavage planes (Winkler, 1975:27) for microporosity.
This puts the all the observations regarding the rusty colour of Huaccoto source material in a clear light, particularly in Colonial Cuzco emplacements. Modern accounts of the ochre-red staining appear to begin with Gregory (1916:92-3) who noticed it almost a century ago, which suggests the iron staining has been noticeable for some time.

One question to be asked for Huaccoto biotite and Rumiqolqa hornblende (although Rumiqolqa staining nowhere approximates the Huaccoto staining in this researcher's observations), since these will be the foci of this section, is how best to measure iron mobilisation. Again, EDS detection rate counts, while not assumed to be quantitative, are used to support the petrographic evidence of biotite alteration mentioned earlier (Ch. 5 & Ch. 10) as well as in conjunction with appropriate SEM photomicrographs.

Figure 10.3 POTENTIAL FE CONCENTRATION IN FERROMAGNESIAN PHENOCRYSTS IN INCA CONTEXTS
Notes to Figure 10.3:

All EDS analyses were by Link System 10-25 S with all parameters in common: @ 20 kv; 100 seconds livetime; cobalt standard as reference; elevation was 31.46 and the means of analyses was by dot scan mode @ 3000 X. Because EDS detection count rates are not quantitative assessments, the above data are preliminary and are given only as tentative evidence. The above points associated with numbers represent EDS count rates.

The count rates represent single count rate profiles across the material rather than averages. They are, however, representative of a majority of the spectra acquired. Huaccoto analyses numbered over 18 on 4 samples; Colonial Cuzco analyses numbered over 13 on 4 samples; Ollantaytambo analyses numbered over 12 on 3 samples; Rumiqolqa analyses numbered over 21 on 6 samples.

The 2 mm zone usually distinguishes weathered from unweathered material based on weathering rinds in Rumiqolqa material (3mm in Huaccoto material). The o and dotted line represents Huaccoto as probable source and the x and single line represents Rumiqolqa material. Arrows indicate some stability has been reached at that point. See Plate 10.20 for biotite SEM photomicrograph.

Figure 10.3 above shows a possible tendency toward Fe concentration in biotite phenocrysts near ashlar edges of probable Huaccoto material, based on the EDS detection count rate as a profile. "Ashlar edge" is synonymous here with the term "perimeter." The apparent consistency of a similar Fe peak in all probable Huaccoto source material also supports the petrographic match between Huaccoto and Colonial Cuzco, and may suggest such a provenance identification. Ollantaytambo follows a similar Fe profile but is not as close to a Huaccoto profile as Colonial Cuzco material. It is also clear that the Fe in Rumiqolqa hornblende count rate profiles does not appear as consistent as the Huaccoto biotite appears. The yellow-brown colour of much Rumiqolqa hornblende as observed in petrographic analysis (Ch. 5) and the thick iron oxide rims of the hornblende, particularly as contrasted with the fresh Korikancha hornblendes which have the expected pale green colour and no iron oxide rims (Plate 5.5) are
evidence of some iron mobility, but as expected from Winkler's assessment of rapid Fe loss in biotite (Winkler, 1975:164). The Rumiqolqa hornblende Fe mobilisation does not suggest a tendency as does the Fe in Huaccoto source biotite to be concentrated on or near the ashlar edge. Winkler also notes that Fe in hornblende is released at a much slower rate than from biotite (Winkler, 1975:165), which also may account for less staining on Rumiqolqa ashlars in Cuzco contexts.

In summary, it must be iterated that while some tendencies may be suggested as to possible Si loss from groundmass glass on Inca ashlar faces with worked edges and possible Fe concentration in the environs of biotite phenocrysts also on Inca ashlar edges, the nature of EDS count rates as non-quantitative assessments must be considered. Therefore the possible elemental mobilities suggested here are of a preliminary nature only, requiring a more quantitative confirmation to be conclusive.

10.4.3 Dark Weathering Rind Colour

A possible hypothesis for the dark weathering rind colour of archaeological material is offered in this section. As found to contrast consistently with the light rind of geological material on the exterior over a darker exterior, the dark rind over a lighter interior offers a unique opportunity to suggest a sequence of weathering.

First, it is acknowledged that water is incorporated into weathering rinds (Colman, 1982:27) and that hydration of the rind is proportional to the weathered stage of the rind, i.e., that the more weathered the material, the higher the molecular percentage of water (Colman, 1982:27). Exposure to an environment
results in increased total porosity as new pores arise due to mineral cleavage (Amoroso and Fassina, 1984:10-11).

Second, if it can be accepted that stoneworking can increase the microporosity of material (Torraca, 1988:29-30) and Chapter 8 of this thesis), hence the increase in weathering surface, and that water content increases consistently from unaltered surface to weathered surface over a line profile of that surface (Colman, 1982:27), then the subsequent capillary action related to the volume of water passing through a stone surface cannot but help to both dissolve mineral constituents (Amoroso and Fassina, 1984:2) and replace minerals temporarily with hydrated minerals and ultimately with water (Colman, 1982:27).

Third, if only heat above 110°C can evaporate water in the weathered area (Colman, 1982:27, although he does not specify time length) and if weathering rinds on all material of the present study were best displayed after washing, polishing, washing, and drying by heat (regularly above 100°C but not likely to be consistently over 110°C for sufficient time) in laboratory settings, then the following weathering scenario could offer some explanation for the nature of a dark rind.

A) white scar + hydration + time = dark scar

(archaeological time)
then...

B) dark scar + hydration + time = light rind

(geological time)

The suggested weathering steps are: 1) Stoneworking causes microfractures which can be seen as an aggregate white scar on the stone surface; 2) the white scar can be understood as a loss
of optical translucency due to all the new microfractures; 3) the incorporation of water via new capillary channels turns the rock area affected into a dark region (which reflected light initially as a white scar) and this incorporation of water may change the unaided eye's perception of the refractive index of that area; 4) continued leaching over a long term geological period eventually turns the dark region light again as porosity reaches a stage where the large pores outnumber the original narrow, somewhat planar light-reflective microcracks.

Plate 10.18 of Ollantaytambo material may in some sense depict a stage transitional to solely darker and lighter areas; between A and B in that the white leached appearance has only partially developed in a mostly dark weathering rind. Thus, even this appearance (Plate 10.18) could suggest that weathering as an expression of time is still on the side of an archaeological age to this point (but the geological time and weathering are going to dominate shortly). As a chronometer, such a sequence would almost need all four stages: dark, dark and light, light and dark, light, or:

(a transitional weathering rind sequence)

<table>
<thead>
<tr>
<th></th>
<th>dark</th>
<th>dark and light</th>
<th>light and dark</th>
<th>light</th>
</tr>
</thead>
<tbody>
<tr>
<td>95%</td>
<td>70%</td>
<td>30%</td>
<td>30%</td>
<td>70%</td>
</tr>
</tbody>
</table>

but only as a gradual continuum rather than an obvious hiatus between each phase.

Although this suggestion of water content causing the darkness of an archaeological rind is very tenuous, it is offered
in lieu of a better-understood mechanism. It also suggests that
detailed elemental analyses are needed to investigate this
hypothesis with a rigorous experimental programme.

10.5 Conclusions

In summary, short-term archaeological weathering (even when
accelerated by factors like stoneworking) may not exhibit
comparable (or measurable by the methods used here) elemental
mobilities to those exhibited by long-term geological weathering
of basalt and andesite. Additionally, mineral alteration may be
difficult to assess except in contexts like Ollantaytambo biotite
which contrast with fresh parent material, but also which have
probably been in unusual weathering circumstances.

As seen in the observations on external weathering colour in
discussions of this chapter (10.2), especially where time factors
are too short for the development of a weathering rind or where
no apparent stoneworking accelerated weathering is present,
external colour may evidence short-term "staining" but is
unlikely to offer more data on relative dating of archaeological
material. Weathering colour may be more indicative of actual
mineralogic differences in parent material as shown by Cuzco
Colonial and Korikancha contrasts as well as the differences in
exposure (exposed at the Colonial Cuzco contexts and unexposed
in the Korikancha contexts) even though there is a proximity of
100 m between these two contexts examined in this study. These
contrasts may be visible to any observer but not necessarily
explained until the present study.

On the other hand, weathering of archaeological material
is in contrast to natural geological weathering by the following
respects. Archaeological weathering appears to have a reverse weathering rind colour (dark rind on light interior) possibly due to water content in the as-yet not fully leached weathering rind, thicker rind development, and is most likely to be accelerated by stoneworking. Exceptions to this may be found in tropical or aqueous contexts where a soft stone (like Huaccoto andesite) is exposed to a high volume of water (like fountain environment as an artificial microclimate or as in tropical climates with high MAP, MAT, and RH as in Tres Zapotes).

Possible short term indicators of weathering may be suggested by some incipient elemental mobility such as in depletion of Si in groundmass glass or the beginning of Fe concentration at the surface which may also account for the external staining.

Also, an important variable central to many archaeological contexts is introduced by the factor of depth of burial, although this would depend greatly on the age of the material and conditions of stratigraphy. As suggested by the Jericho Neolithic material, lack of weathering exposure probable after a second usage can complicate the weathering of what might be a commonplace occurrence in excavation contexts. This is highlighted by the lack of exposure of interior Korikancha ashlar material in contrast with the Rumiqolqa material which has been subject to continual exposure over the same period of time. This would also apply to studies of provenance where archaeological sampling is limited to surface material or data thereon as well as to burial of artefacts, especially applicable to weathering contrasts in artefacts where exposure of massive architectural elements on a surface would be much greater than individual sculptures of the
same material buried at some depth.

The following factors appear most responsible for archaeological weathering of basalt and andesite as understood in the present study for overall application:

(1) \( \text{time} + \text{environmental} \ > \ \text{than all others} \)
\( \text{factor} + \text{factor} \ > \ \text{combined} \)

using a model extrapolated from Colman et al. and which assumes parent material is minerallogically similar. This study has given new points on the time graph between the material studied by Cernohouz and Solc and the material studied by Colman et al. but has also contrasted their data with an accelerated rate curve. An exponential curve of time as most influential weathering factor is likely unless the element of stoneworking has been introduced, in which case the following is likely to be more applicable:

(2) \( \text{stoneworking} + \text{environmental} \ > \ \text{time} \)
\( \text{factor} + \text{factor} \ > \ \text{factor} \)

depending on the type of stoneworking employed in which case:

(3) \( \text{chiselling} > \text{battering} > \text{grinding} \)
\( \text{method} > \text{method} > \text{method} \)

in terms of accelerated weathering by microfracture damage and subsequent increased microporosity an agent of weathering, noting that grinding as a stoneworking method may not produce the above calibration suggested in (3) whereas chiselling and battering can result in such weathering rate development. In many cases, the following weathering statement may be true for both chiselled and battered stone in contrast to unworked stone, all else being equal:
Finally, it may be suggested that archaeological weathering of basalt and andesite is characterised by a dark and thicker rind as contrasted with the light and thinner rind found on geological material, if all other factors are equal. At present, the primary reason for the contrast in thickness appears to be stoneworking (as the primary reason for colour contrast may be hydrated rinds which have not yet been leached). Ultimately, the differences in weathering features may suggest that because the archaeological weathering is short term, time becomes the least important weathering factor (where parent material, stoneworking and environment are more important than time), unlike the very nature of long term geological weathering where that fact of time may eventually overshadow the other weathering variables, as some equilibrium is reached in the stone when the rate appears to slow down (Colman and Pierce, 1981:37; Colman, 1982:1).

Additional studies will be more likely to suggest better approaches to understanding weathering factors for archaeological basalts and andesites. Although much potential is suggested for a chronometric comparison of weathering rind development as a relative dating method, as can be intimated by the Rumiqolqa contexts, the potential appears to be mostly limited at present to studies which compare similar materials subjected to similar environments.

The explanations offered for weathering phenomena in this chapter are in some part applications from the literature and in part formulations which have yet to be confirmed by further
examination of archaeological material. The observations of this chapter are the first attempt at the systematic application of weathering to archaeological basalt and andesite in the selected contexts. It is hoped that more regional analyses like the Inca ashlar Rumiqolqa contexts can be integrated with broader studies worldwide so that a better understanding of archaeological basalt and andesite weathering can be developed in time.
CONCLUSIONS AND POTENTIAL APPLICATIONS OF RESEARCH

11.1 Conclusions of Research

From Chapter 1 of this thesis it can be maintained that the geological boundaries between basalt and andesite have been redefined (Le Maitre, 1989) such that what may have been classified as basalt in, for example, a prior archaeological context (Bandelier, 1911; Albright, 1929; Garstang, 1929; Murray, 1930; Lucas, 1934; Thompson, 1936; Childe, 1943; Semenov, 1964; Conduraci, 1971; Marinatos, 1976; and Stol, 1979, to name a few) may deserve reexamination. Prior studies which this thesis has reappraised, with the result that what was termed basalt should be reconsidered as andesite or basaltic andesite include Inca, and Olmec contexts (Gregory, 1916; Sterling, 1943; Williams and Heizer, 1976; and Coe and Diehl, 1980) with many others which have either derived from them or which have made reference to them. Geological studies as well (Freund et al., 1965; Schulman, 1966a & b; and Radulescu, 1968) could also be reappraised when rock extrusives which can pertain to Canaanite or Dacite cultures may also deserve reappraisal as basaltic andesite on the one hand or dacite on the other hand, particularly as the present study has found Canaanite and even Neolithic material which could be classified as basaltic andesite.

Chapter 2 has surveyed historical references to what may be considered basalt and andesite in antiquity, from Sumerian and Egyptian to Pliny in the Old World, and from Aztec to Inca and Pacific Islander in the New World. Chapter 2 has also presented a
brief global survey of basalt and andesite uses. More important, this thesis has examined potential stone criteria for the first time in a systematic fashion. The potential stone criteria which are suggested as recognizable in antiquity include availability, workability, durability, aesthetic appreciation, and philosophic or metaphysical associations, and specific applications have been made to Inca, Olmec, and Canaanite cultures, as well as general applications in other cultures, for example, ancient Egyptian and Roman, based on empirical experience, technologies and continued preferences for basalt and andesite which extend beyond mere tradition.

Chapter 3 has reviewed methods used to determine provenance, with special emphasis placed on optical petrology or petrography, particularly when the chemical analyses suggest such strong chemical similarities as are found among Levant basalts that the possibility of distinguishing materials may be best enabled by textural analysis. Chapter 3 has also examined instrumental sequences for determination of provenance with a rationale for the sequence and method employed in the present study.

Chapter 4 has explored the advantages for field research using a prototype portable field laboratory which has been experimentally successful for thin section preparation and field microscopy. A new mounting medium for stone thin section analysis has been pioneered and found satisfactory for stone, with limited application to ceramic petrology. Anticipated modifications have also been suggested based on the experimental use to date.

Chapter 5 has examined Inca andesite sources in the Cuzco region of Peru and has suggested provenance for certain Cuzco and outlying contexts based on fieldwork, petrographic, and chemical
analyses, in some cases dependent on new stone sources found through this study. Inca stone technology and potential criteria for stone selection have also been discussed in detail, with many observations on Inca technology and chronology of use which extend understanding of the Inca culture.

Chapter 6 has examined Olmec basaltic andesite sources in the Tuxtla Mtns. of Mexico, with particular attention to Tres Zapotes and a provenance reappraisal of Cerro El Vigia for that site, based on fieldwork, petrographic, and chemical analyses. The topic of Olmec preference for volcanic material has also been addressed, with hypotheses on Olmec culture which extend beyond the site of Tres Zapotes itself.

In Chapter 7, a pioneering survey of basalt use has been presented for selected Canaanite and Neolithic contexts in the Levant. While questions regarding provenance have been asked, the overall chemical similarity of Levant basaltic flows suggests the continuation of textural analysis by petrography as well as other analyses in order to provide a broader base for understanding potential Levant volcanic stone sources. Some petrographic and chemical analyses are presented to initiate and stimulate further needed research. Potential stone selection criteria in the Levant has been a major focus of this chapter, with many observations and suggestions presented for the first time.

Chapter 8 has reviewed basalt and andesite weathering from prior studies specific to that range of stone as well as mineral weathering in general. Both the geological studies, which are in preponderance, and the archaeological studies, which are in a distinct minority, have been integrated for potential application.
to the present study. One major conclusion of this chapter as well as this thesis in general is that archaeological weathering is to be distinguished from geological weathering, both for its short term nature and the potential of accelerated weathering by stoneworking. The work of Colman et al. has been examined in detail for applicability to the present study, despite the fact that its focus was geological rather than archaeological, and as some of the precedents of prior study have integrated what might be archaeological material, the validity of such prior studies has also been examined.

Chapter 9 extended Chapter 8 by examining stoneworking as it stresses stone in general and basalt and andesite in particular, reviewing prior applicable studies on stoneworking as they dealt with stone stress and strain, methods of stoneworking, microfracture, and microporosity. Also important to this chapter are experimental stoneworking observations which examine the potential of increased surface area and the nature of the damage done to stone visible on both short and long terms, with an attempt to characterise the damage effected by stoneworking.

Chapter 10 examined new archaeological weathering contexts in Inca, Olmec, and Levant materials. Weathering rind colours and thicknesses as well as individual mineral grains have been the focus of petrographic and chemical analyses. In many contexts explanations have been provided for the weathered colour of external surfaces of archaeological material. The potential of weathering factors such as time, parent material, and environment have been assessed for possible relative dating of archaeological basalt and andesite, and the conclusions of this study are that similar materials subjected to similar environments provide the

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optimum contexts for any such relative dating. The Rumiqolqa quarry contexts provided such material for this thesis, and new rind rate contexts may be added as well as contrasted to the time curves posited by the studies of Cernohouz and Solo as well as Colman et al. where it could be established that even minimal stoneworking appears to accelerate weathering. On the other hand, it also appeared that in numerous archaeological contexts, stoneworking may have greatly accelerated expected geological weathering rind development and/or mineral alteration. Some data on possible elemental mobilities and the hydration of weathering rinds was interpreted to suggest weathering colours which were either similar to or distinct from prior characterisations of basalt and andesite weathering. Another major conclusion of this thesis is that by its very nature of being short term, archaeological weathering (in which time may not be the most influential factor because other factors overshadowed it) may not exhibit the same phenomena as geological weathering (in which time became the most influential factor due to the very fact that it was long term).

However tentative and preliminary were many of the analyses and interpretations of this chapter and those chapters leading up to it, they were often the first to be attempted and are thus expected to be refined by future research.

11.2 Anticipated Applications of Research

Several research foci extend beyond the domain of the present study with potential for building on the regional nature of the contexts selected thus far. Naturally, in the first instance, any
other added regional studies will expand our present knowledge of weathering of basalt and andesite. However, it may reasonably be expected that it will become increasingly feasible, ultimately with a global data base, for the following applications to be realised: a reliable relative dating technique for archaeological basalt and andesite; increased effectiveness of provenance research on basalt and andesite monuments and artefacts; assistance in authenticating basalt and andesite artefacts; and possible climatic inferences from monitoring basalt and andesite on a short-term basis. The following subsections suggest the potential for these further research studies as the natural extensions of the present study.

11.2.1 Relative Dating Technique for Archaeological Material Based on Weathering Research

If the weathering studies culminating in the Quaternary chronometric indicators of Colman and Pierce based on weathering rind thickness are reliable dating indicators, and if this approach to basalt and andesite weathering can be systematized worldwide (with rates of weathering most influenced by time) where factors like stoneworking are not present or quantifiable, the promise of a relative dating technique for basalt and andesite can include archaeological material rather than being applicable only to geological material over 20,000 yrs old. Additionally, as a more complete knowledge of stoneworking and its mechanisms of surface damage is applied from stoneworking-accelerated weathering contexts, the overall inter-relatedness of weathering factors will become more quantifiable. As suggested by prior and present research in the comparison of two samples.
greater time results in greater weathering for a relative dating application of basalt and andesite weathering in archaeological contexts.

Before this potential can be achieved, a rigorous global sampling programme (with a minimum subsequent combination of portable and fixed laboratory petrological analyses) must be undertaken to assess and explain the range of differences in mineralogy and effects of climate (to name a few factors) which could easily frustrate systematization.

While the studies of Colman et al. did not suggest a complete hierarchy of weathering factors, certainly the factor of time has been repeatedly raised as the most influential factor determining the extent of weathering (all others being equal between two contexts). If the present study has not completely supported this given the differences in sampling and parent materials as well as many stoneworking contexts, it has not cast any serious doubts on exponential weathering rate development with time (other than to show the need to integrate stoneworking as a factor), although the short term nature of archaeological weathering implies a less influential role of time than in long term geological weathering. In fact, it was hypothesized at the end of Chapter 10 that the dark weathering rind on most archaeological rinds may be a water-saturated stage (in the microfractures which have not yet become large pores) that might well precede the lighter leached rinds in a geological sequence (section 10.4.3).

On the other hand, stratigraphic differences have been raised
in the present study as another weathering variable (not directly assessed by Colman as his sampling was confined to a 30 cm surface horizon). Naturally, the variable of stratigraphy has been suggested as one which excavation archaeology will have to seriously consider in addition to other weathering variables.

All these variables (or weathering factors) must be analysed and prioritised as the present study has suggested in Chapter 10, albeit on a preliminary basis. There is at present no expectation that a dating technique derived from such study will be anything but relative, nonetheless, when calibrated with other techniques such as radiocarbon, dendrochronology, obsidian hydration, and other chronometric methods, the value of basalt and andesite weathering development in surface colour and in rind thickness can be appreciated as these become additional tools for understanding human history on a short term level (with staining due to oxidation) and on a longer term level (with weathering rind development), particularly as time-related functions.

11.2.2 Increased Effectiveness of Provenance Studies and Other Research Based on Portable Field Laboratory Use

As suggested in Chapter 3 of the present study, the potential application of a portable field laboratory for optical petrology of basalt and andesite is seen as greatly increasing field efficiency in sampling techniques for provenance studies. Being able to sample in situ archaeological material and having the capability of matching it with geological source material or being able to abandon unsuitable petrographic material could be a tremendous advantage for making better use of field time. The new materials investigated and prototype equipment assembled
Thus far for the present study have an excellent thin section mounting medium for stone and eminently portable equipment. The potential applications will far exceed the limited use such a prototype has seen in the present study.

This potential is especially dramatised in the case of the Levant olivine basalt, already noted by prior researchers as of a sufficiently uniform chemistry and noted in this study as possessing distinctive petrographic textures from one context to another. Here a field capability could ultimately provide the qualitative basis for further study by quantitative methods such as provided by fixed instrumental analyses (SEM + EDS, EPMA and XRF and perhaps XRD and trace element analysis). Without doubt the sampling versatility provided by microscopic analysis in a field laboratory could make determination of provenance a much faster and more accurate task, and could in the long run (probably even in the short run) be economical of field expense, particularly if a field lab could eliminate repeat field trips as inappropriate or unrepresentative sampling could be avoided if monument and artefact sampling can be effected in the light of continuing feedback from analysis of the samples.

Furthermore, as presented in the prior section of this chapter on anticipated weathering applications, it is quite probable that the field microscope of the portable laboratory can be further utilised to assess microfracture damage in stone which has been modified by battering, chiselling, grinding or other stoneworking method (Chapter 9) given suitable techniques of sample preparation. Certainly, as suggested before in Chapter 4, the field Swift FM-31 microscope was used at Palenque, Mexico, lto examine calcium bicarbonate polyps from limestone eaves of 430
Maya buildings. With simple removable polarisers on the first prototype, this Swift microscope can easily return to original functions of normal light transmission microscopy as could be required for slide examination. Adapting the microscope for use as a reflecting microscope would necessitate an additional light, but this could be effected without changing any existing elements (merely adding an oblique light source from the bottom of the stage at an appropriate angle). Thus, an additional feature of the portable laboratory could lead to other eventual uses (e.g. metallography, palynology) just by allowing flexible options for normal transmitting light or reflected light as well as polarized light with removable polarizing filters. In a broad sense, it has been anticipated from the start of the portable field laboratory that its use could forseeably extend well beyond optical petrology.

11.2.3 Assistance in Authentication of Basalt and Andesite Artefacts Based on Provenance and Weathering Research

Authentication of stone monuments can be vitally important to many sectors of archaeological research in helping to establish reference collections whose types are genuine. Such results will be appreciated not only by the museums, dealers, and collectors but also by the scholars in whose research domain the stone monuments lie and by society at large wherein the archaeologist has the responsibility of clarifying the past. Thus, the authentication of stone artefacts can fill a necessary and valid research need. A brief introductory discussion is provided, possibly for the first time in the literature, before direct application is made from the present study to potential results.
In the opinion of this researcher, authentication depends on the inter-relationship of at least four factors: 1) seriation or stylistic evidence, the focus of the art historian which has been dominant in authentication up to the last few decades of this century; 2) provenance evidence from petrological science to make the strongest possible identification of geologic source of stone used in the artefact (or monument); and 3) weathering evidence from geological science to determine if the material is consistent with other pieces of like age and environment. The last two factors could be termed archaeometric in that their domain is that of the scientist, and their role has been growing in the last few decades for the light they can shed on problems of authentication.

A fourth (but often unrelated) factor in authentication might be implicit in the use of "unassailable" for a reference collection or an individual piece. This unassailable authenticity could be a result of its known context, e.g. a stratigraphic position in an undisturbed deposit or a collection history of the piece which can clearly document its sources for at least a century (or whatever period satisfies international cultural property protection requirements). As can happen with a passage of time, some pieces may be out of context, that is, authentic but without documentation. While this could arouse suspicion, it cannot actually take away the authenticity of such a piece, it can only suggest that caution should guide attribution of authenticity just as it should collection, conservation, and exhibition of any piece in question. In normal circumstances, the first three factors mentioned in the previous paragraph
(seriation and stylistic evidence, provenance evidence, weathering evidence) should have precedence in authentication if an acquisition context is unknown. On the other hand, the sensible researcher involved in authentication of artefacts should peruse archaeological publications to be informed on archaeological theft, illegal activity, or pending international litigation claims regarding cultural property as well as be up to date on art and collector-oriented publications to be informed of any potential surfacing of or commercial transaction in such artefacts. Figure 11.1 below suggests the above inter-relating authentication factors as they are mutually important in establishing authenticity.

Figure 11.1 AUTHENTICATION FACTORS FOR STONE ARTEFACTS

![Diagram of authentication factors]

The processes for authenticating artefacts and even monuments (although they will be more likely to be in original contexts) can in some way follow at least two of the approaches which have largely concerned this thesis, i.e. provenance and weathering.

Needless to say, there are obvious external features (which can be resolved mostly by visual observation and documentation)
and internal features (which may be resolved by microscopic and/or technical processes and may be somewhat destructive).

A caveat which must be considered in probably each situation is that a positive interpretation of the evidence from all four factors would not necessarily provide guarantee of authenticity, particularly in light of the increasing sophistication of stone forgery. The experience to date of this researcher in the study of authentication suggests great caution in both the techniques used (e.g. UV light, petrography, SEM + EDS, EPMA, XRF, XRD, and such methods as thermoluminescence) and the responsibility to the larger community unconversant with the above techniques for clear communication of what can be and what cannot be achieved in any technique. It is also incumbent on all involved in authentication research to communicate that absolute certainty in authentication is to be expected or achievable given the as yet inchoate state of scientific authentication by archaeometric (i.e. applications of physical science to archaeological and art historical problems.

One interesting result of noticing the elevated sulphur level anomalous to the Huaccoto source material in the Cuzco placement in a Colonial context as discussed early in Chapter 10 is that it may have implications on authentication: if human modification of stone shows such elevated sulphur levels on SEM with EDS dot scan analyses, then a sulphur presence may raise questions of date or authenticity if attempts are made to accelerate weathering to resemble greater age (unless uric acid corrosion is noted as a normal phenomena in such contexts or such sulphur levels are normal to the stone in question). As such, EDS dot scan analyses
could show anomalous sulphur levels and accordingly raise alarms as to authenticity.

The present research may allow enhanced authentication of basalt and andesite artefacts or monuments in the following ways. A portable field laboratory can be easily transported anywhere in the world, even where technical services are unavailable. Sample material extracted from the piece in question (usually unobtrusive in that less than 2 mm deep and 1 cm square sampling is easily effected) may then be submitted to petrographic analysis for geological provenance and compared to known referent material (either by the experience of the researcher or by other available reference material or preferably both). Furthermore, sample material may be examined at the same time for weathering characterisation. Thus, both provenance and weathering analyses as examined in the present study on archaeological basalts and andesites can provide valuable resources and natural springboards to authentication.

Complex situations likely to be encountered may be beyond the scope of the present field laboratory, but the research experiences encountered thus far suggest a continuing and growing role in authentication of basalt and andesite archaeological material by the means and methods suggested and experimentally-tested in the present study.

11.2.4 Possible Climatic Inferences from Monitoring Basalt and Andesite and Other Potential Applications

This very brief subsection is basically in the form of two questions which a cursory discussion will not expect to answer. First, is it possible, as suggested through short term weathering
of basalt and andesite, that by a careful recording of such data as might be gathered and interpreting it accurately, a sensitive instrument for regional climatic monitoring (or changes in atmospheric and environmental pollution) could be developed? Photography of architectural and archaeological detail from early twentieth century archives is filling a viable role now by allowing comparisons of the state of deterioration on monuments in urban environments. In portraying the record of "before" and "after" via photography, climatic change (or at the very least microclimate atmospheric contexts of pollution) may be monitored. Thus the visual corollary already exists for such a climatic monitoring by basalt and andesite weathering in some regional contexts. No doubt, the mineral alteration evidence preserved in photomicrographs of this thesis could feasibly be used in a subsequent generation to assess further change, and where change might be noted in the stone, it could function as regional climate monitoring on a very specific basis if all other parameters (besides time) could also be assessed accordingly.

A final hypothetical application of the present research is the potential for conservation of archaeological basalt and andesite artefacts and monuments. Could the present study, in regional contexts as well as in global contexts where parent material and similarity of conditions might be comparable, make reasonable assessments of stone conservation needs? This would be based, for example, on consolidation research which accounted for environmental variables and such physical properties of a given stone as are examined in this thesis. Since the climatic factors of a tropical environment in Mexico and the same factors of a tropical environment in Java could presumably act on a stone
which had a very close lithology, if a stone conservation measure proved to be successful in Mexico, it might be reasonable to expect (or at least attempt) success with the same conservation measure or programme in Java. Many other possible conservation applications might be found, the feasibility of which is in some sense affected by the detailed observations this thesis has provided for some archaeological basalt and andesite contexts, which would be multiplied as other like studies are integrated into an accessible data base.

In conclusion, these potential applications from the present study are only a preliminary appraisal of directions for further research. Undoubtedly, improvements on the present methods and unexpected applications not identified in this research are the anticipated results for future research.

11.3 Summary of Research Results

The present study has contributed a significant proportion of original material to the body of research on archaeological basalt and andesite. The selected contexts, while limiting in many ways any comprehensive understanding of basalt and andesite weathering and global applications for problems of determination of provenance, are nonetheless valuable in themselves for the following reasons: 1) they allow comparative studies of basalt and andesite uses on regional levels as these fit into a global purview by integrating multiple regional studies; 2) they suggest the kind and range of problems and difficulties likely to be encountered in determination of provenance and in weathering studies; 3) they have provided both an impetus for assembling and
successful experimental procedures of a portable laboratory for optical petrology in the field, a necessary and desirable adjunct for provenance and weathering fieldwork; 4) they have resulted in a critical reassessment of short-term weathering in suggesting contrasts between geological and archaeological weathering; and 5) they have provided a framework for reconstructing possible human selection criteria for stone.

Another important index of the original contributions of this thesis is that it has in general collated and amplified preexisting knowledge of basalt and andesite in archaeological contexts which extend beyond regionalism. Many other unique contributions could be detailed for the specific Inca, Olmec, and Levant sites addressed herein with implications beyond basalt or andesite use. Furthermore, it has been suggested for future research how far-reaching such innovations (as well as the method of applying provenance and weathering together) can become in the dating and authentication of basalt and andesite artefacts and monuments, both of which developments (after appropriate further refinements beyond the scope of the present study) will be greatly appreciated by both the archaeological and art historical communities.
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