Geochemical “fingerprints” for Olduvai Gorge Bed II tuffs and implications for the Oldowan- Acheulean transition

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Abstract

Bed II is a critical part of early Pleistocene Olduvai Gorge, Tanzania. Its deposits include transitions from humid to more arid conditions (with associated faunal changes), from *Homo habilis* to *Homo erectus*, and from Oldowan to Acheulean technology. Bed II (~1.8–1.2 Ma) is stratigraphically and environmentally complex, with facies changes, faulting, and unconformities, making site-to-site correlation over the ~20 km of exposure difficult. Bed II tuffs are thinner, less evenly preserved, and more reworked than those of Bed I. Five marker tuffs (Tuffs IIA-IID, Bird Print Tuff (BPT)), plus local tephra, were collected from multiple sites and characterized using stratigraphic position, mineral assemblage, and electron probe microanalysis of phenocryst (feldspar, hornblende, augite, titanomagnetite) and glass (where available) composition. Lowermost Bed II tuffs are dominantly nephelinitic, middle Bed II tuffs (BPT, Tuff IIC) have basaltic components, and upper Bed II Tuff IID is trachytic. The BPT and Tuff IID are identified widely using phenocryst compositions (high-Ca plagioclase and high-Ti hornblende, respectively), though IID was originally (Hay, 1976) misidentified as Tuff IIC at Loc 91 (SHK Annexe) in the Side Gorge. This work helps establish a high-resolution basin-wide paleolandscape context for the Oldowan-Acheulean transition and helps link hominin, faunal and archaeological records.

Introduction

Bed II (~1.8–1.2 Ma) is the most laterally extensive and paleoecologically varied of the Olduvai Gorge Beds, and is famous for its well-preserved record of Pleistocene hominin behavior and evolution (Leakey, 1971). Like underlying Bed I, Bed II preserves artifacts, fossils, and paleoecological indicators in a variety of depositional contexts, including saline-alkaline lake and lake margin, fluvial, freshwater wetlands, and alluvial and volcaniclastic fans. Bed II also documents environmental change over time, with a shrinking lake and an apparent change from more humid-adapted to more arid-adapted species (Leakey, 1951, 1965, 1971; Gentry and Gentry, 1978). These changes are coupled with changes in the hominin record, with the disappearance of *Homo habilis* and appearance of *Homo erectus* along with the end of the Oldowan lithic technology and the emergence of the Acheulean. The strata of Bed II also contain layers of both primary and reworked tephra derived from the nearby Ngorongoro Volcanic Highlands (NVH; Figure 1). However unlike in Bed I, these tephra are often contaminated, discontinuous, or even absent in addition to being highly altered, making correlation between sites more difficult. Post-depositional faulting, erosion, and alteration make it difficult to correlate across the basin.

The reconstruction and interpretation of Olduvai's diverse and dynamic paleoenvironments requires accurate chronological and stratigraphic control, provided in part by Hay's (1976) composite stratigraphic sections. Geochemical fingerprinting of individual tephra has led to a detailed tephrostratigraphic framework for Bed I (McHenry, 2004, 2005, 2012; McHenry et al., 2008), which helped correct the relative stratigraphic placement of western gorge fossiliferous deposits in relation to the better-known sites in the eastern gorge (Blumenschine et al., 2003). Since volcanic glass alters readily to clays and zeolites in many Olduvai depositional environments (McHenry, 2009, 2010), useful “fingerprints” rely on phenocryst compositions (feldspar, augite, hornblende, and titanomagnetite) as well as minimally altered glass.

This manuscript will extend this approach to the Olduvai Bed II tuffs. The objectives are to: (1) Geochemically and mineralogically characterize the major Olduvai Bed II marker tuffs, (2) document and recommend geochemical type and reference sections in different environments across Olduvai to help characterize the tephra record across the basin, and (3) identify geochemical “fingerprints” for key marker tuffs that can be used to support local stratigraphic correlation. This technique can provide tight stratigraphic control for paleoanthropological contexts for Bed II, which provides the resolution needed to conduct detailed investigations into the nature and timing of the Oldowan-Acheulean transition. This work also helps establish a basin-wide paleolandscape context for the Oldowan-Acheulean terminus and ties together hominin, faunal, and archaeological records, providing high-resolution evolutionary context.

Background

The sediments of the Olduvai basin are exposed by the ~20km long and deeply incised (up to 100 m deep) Olduvai Gorge, between the Serengeti Plains to the west and

Ngorongoro Volcanic Highlands (NVH) to the east (Figure 2). Exposed strata include non-volcanic sediments as well as tuffs, lavas, and ignimbrites. The two main branches of the gorge (the Main and Side Gorges) meet at the "Junction," about 9 km west of where the Olduvai river seasonally discharges into the Olbalbal drainage sump. Hay (1976) provides a detailed introduction to the Olduvai beds. His nomenclature for sites (Localities, or "Locs") and tuffs will be used throughout this manuscript. It should be noted that for Bed II, Hay (1976) uses the term "Tuff" to describe both primary volcanic ash units and reworked and contaminated sedimentary units of varying volcaniclastic content.

The NVH erupted diverse volcanic materials into the Olduvai basin. The focus of the current study is on Bed II, the second oldest and most extensive of the Olduvai Beds; a composite stratigraphic section is provided in Figure 1. Its tuffs are typically silica undersaturated, ranging from nephelinites to trachytes with some basaltic ash. Bed II can be subdivided into Lowermost Bed II, which is dominated by a saline-alkaline lake and lake margin similar to that of Upper Bed I; the Lemuta Member, an aeolian tuffaceous unit in the eastern gorge at the transition between Lowermost and Middle Bed II, and Middle to Upper Bed II, with its much smaller lake. A significant (but not well dated) disconformity separates the Lemuta Member from overlying deposits. Important marker tuffs include Tuff IF (uppermost unit of Bed I), Tuff IIA (within the Lemuta Member), Tuff IIB (a mappable unit in the Junction and Side Gorge with a limited volcaniclastic component), the Bird Print Tuff (BPT, locally preserved in the Junction, Side Gorge, and lake center), Tuff IIC (only a primary tuff locally on the south side of the eastern gorge), and Tuff IID (widespread trachytic tuff in upper Bed II).

Paleoanthropology

The nature and timing of the transition from *Homo habilis* to *Homo erectus* and Oldowan to Acheulean traditions is a longstanding debate in human origins research (e.g. Leakey et al., 1964; Leakey, 1966, 1971; Antón, 2003, 2012; Lordkipanidze et al, 2013; Wood, 2014). The *H. habilis* species, which, until recently (Harmand et al. 2015), was widely accepted to be the maker of the world's oldest tools (the Oldowan: Leakey et al. 1964), occurs only in the older deposits at Olduvai: from Bed I to the base of Middle Bed II (Leakey, 1951, 1971). While Oldowan cultural tradition is confined to the lower beds, the Acheulean industry, which is characterized by more advanced stone tools such as handaxes and cleavers, appears in Middle Bed II (Leakey, 1971).

Bed II contains a more varied – and contentious – archaeological record than Bed I, which is only associated with Oldowan technology (Leakey, 1971). Lowermost Bed II assemblages are similar to those of Bed I, and are widely attributed to the classic Oldowan (Leakey, 1971; Blumenschine et al., 2012). However, some differences in the stone tool kits of assemblages between Tuff IIA and Tuff IIB led Leakey (1971) to define a technological variant, the Developed Oldowan A (DOA). The first appearance of handaxes above Tuff IIB was originally interpreted as follows; assemblages with very few bifaces were attributed to the Developed Oldowan B (DOB), while those with larger numbers were considered as Acheulean (Leakey, 1971). Leakey (1971) linked the Lowermost Bed II Oldowan and the DOA and DOB stone tool assemblages to *Homo habilis*, whose fossil remains are found from Bed I to Middle Bed II. In her view, the appearance of the Acheulean at Olduvai was linked to the post-Tuff IIB advent of a new hominin (i.e. *Homo erectus*). However, this interpretation of the biological and cultural evidence in Bed II has proved contentious (e.g. Stiles, 1979; Semaw et al, 2009; Torre and Mora, 2005, 2014), and correlation between different types of lithic assemblages, hominin fossils and sedimentary units, requires detailed stratigraphic resolution at the level of detail performed in this study.

Paleoenvironments

Olduvai Bed II paleoenvironments varied in both time and space (Hay, 1976; Cerling and Hay, 1986). Lower Bed II was dominated by an extensive saline-alkaline lake and lake margin area similar to that of Upper Bed I, which expanded and contracted with changes in climate and rift-induced faults and tectonics. Alluvial and volcaniclastic fans fed the lake from both the west and the east, and interfinger with lacustrine sediments. Conditions became drier during the deposition of the Lemuta Member, which in the eastern gorge consists largely of eolian volcaniclastic deposits. The lake contracted and its depocenter moved eastward later in Bed II in response to faulting. The faunal turnover between Lower Bed II and Middle Bed II attests to the dramatic environmental shift from the lakeshore environments (of Upper Bed I and Lower Bed II) to fluvial dominated systems. By the end of the deposition of the Lemuta member various Bed I and Lower

Bed II mammals with affinity to lakeshore woody marshlands (e.g., *Deinotherium cf. bozasi* (Sanders et al. 2010), *Giraffa stillei* (Harris, 1976; Churcher, 1978), *Dinofelis sp.* (Lewis, 1997; Werdelin and Lewis, 2001) disappear from the record, while new faunas with affinity to inland riverine environments (e.g., *Pelorovis oldowayensis* (Gentry and Gentry, 1978), *Giraffa jumae* (Harris, 1976; Churcher, 1978), *Theropithecus* (Jolly, 1972) appeared for the first time during Middle Bed II along with *Homo erectus* and Acheulean lithic technology.

Geochronology

The base of Bed II is dated at 1.803 +/- 0.002 Ma, for Tuff IF at the top of Bed I (Deino, 2012). The dates for Bed II tuffs are less well established, with published dates for Tuff IIA ranging from 1.66 to 1.74 (Curtis and Hay, 1972; Manega, 1993). Tuff IID, in upper Bed II, has been dated using the $^{40}Ar/^{39}Ar$ Single Crystal Laser Fusion (SCLF) method by Manega (1993: 1.48 ± 0.05 Ma) and by Dominguez-Rodrigo et al. (2013: 1.338 ± 0.024 Ma), and inferred based on sedimentation rates at 1.35 -1.4 Ma (McHenry et al., 2007). Estimates for the age of the Bed II/ Bed III transition range from 1.1 Ma (Hay, 1976) to 1.34 (see discussion in McHenry et al., 2007). The lack of primary, juvenile magmatic K-feldspar in many Bed II tuffs makes them difficult to date using the $^{40}Ar/^{39}Ar$ method, and the high level of contamination observed in many Bed II tuffs contributes to this difficulty.

Methods

Field Methods and sampling sites

Initial sampling was guided by Hay (1976), based on descriptions of Localities ("Locs") with well-preserved tephra and composite stratigraphic sections with multiple tuffs. Sampling was coupled with stratigraphic measurements and lithological description of surrounding units, so that lithostratigraphic correlation could complement the tephrostratigraphy. A subset of these measured and sampled sections was selected to represent the Bed II tephrostratigraphic record in different areas of the Olduvai basin, and for specific parts of the Bed II record depending on preservation. Because of lateral variability and significant unconformities, no individual section contains a continuous record of all of Bed II.

Below is a list of the main sections used to characterize the Bed II tuff record, why they were chosen, and what they contain. Numbered localities follow Hay (1976) nomenclature, while named archaeological localities (in parentheses, e.g. FLK Maiko Gully) follow Leakey (1971). Samples are listed, with brief descriptions, in Table 1.

Locality 45c (FLK Maiko Gully) preserves multiple tephra units with fresh glass in the Tuff IF to Tuff IIA range, though Tuff IIB is locally absent. Above this level, the Bird Print Tuff (BPT) also contains fresh glass.

Locality 44 (HWK-W) preserves multiple tephra throughout Bed II, from Tuff IF to Tuff IID and above, though Tuff IIA is locally cut out by the incision related to Hay's (1976) Lower Augitic Sandstone (also known as Leakey's (1971) Sandy Conglomerate).

Locality 34a is one of few sites with Tuff IIC as a primary tuff, and includes fresh glass. Tuff IID is also present, though thin (~30 cm) and poorly developed.

Locality 88 (MNK) preserves Tuffs IIA and IIB along with the BPT, which was locally found in situ for the first time.

Locality 80 (RHC) is the only site found to date in the western Olduvai basin with in situ Tuff IID, though blocks of Tuff IID are recognized in a younger conglomerate over a broader area. The BPT is also well preserved at this site. Tuff IID from this site was dated by both Manega (1993: 1.48 ± 0.05 Ma) and Dominguez-Rodrigo et al. (2013: 1.321 ± 0.032 Ma). Tuff IID at this site does not preserve fresh glass or titanomagnetite and is not as well developed as at locations in the Junction and eastern gorge.

These sections are supplemented by samples from sites with exceptional preservation of individual tephra, including Localities 40 (MCK) and 14 (JK) for Tuff IID. For Loc 91 (SHK Annexe), a sample was collected from the tuff sitting directly above the archaeological material-bearing level excavated by Leakey (1971) and tentatively identified as Tuff IIC by Hay (1976).

Below is a description of the major Bed II tuffs:

The “twiglet” unit is a tuffaceous level between Tuff IF and Tuff IIA, so far identified exclusively in the “Junction” area of the gorge. In the sections selected for this analysis, it is represented at Localities 44 and 45c, both of which preserve fresh glass. The name “twiglet” derives from the abundance of white root traces found throughout this unit; it is not a primary airfall tuff and is in places mixed with silt to clay.

Tuff IIA is a marker unit within Hay’s Lemuta Member. While it contains fresh glass at some localities (e.g. Loc 45c), it is typically a tuffaceous sandstone. Hay (1976) correlates it with the middle of three Lemuta sandstone “tongues” to the east of the junction. It typically consists of an upper, dark, coarser unit and a lower lighter unit.

Tuff IIB, as identified by Hay (1976), is not actually a tuff, though it contains some tuffaceous material at some sites. It is characterized by its orange color, and often contains conglomerate, sandstone, and siltstone components. At Loc 44 (HWK-W) it is predominantly sandy and conglomeratic, while at Loc 88 (MNK) it also contains more clay and silt-rich intervals. Samples were collected from the finer horizons, and represent detrital material of likely tuffaceous origin (rather than primary tuff).

The Bird Print Tuff (BPT) is a thin (4-15 cm thick), yellow, fine-grained tuff found throughout the Junction and in parts of the western basin near Loc 80. Where absent, fragments can sometimes be identified in overlying conglomerate.

Tuff IIC, while identified in many Hay (1976) stratigraphic sections in the Junction and Side Gorge, is actually a sandstone without a notable tuffaceous component at most locations. Of the sites visited over the course of this study, it was only a primary tuff in the vicinity of Loc 34a, where it contains glass. A tuff identified in Hay (1976) as Tuff IIC(?) at SHK Annexe (Loc. 91) has a Tuff IID composition (contrary to Leakey, 1971); it is likely that other instances of Tuff IIC and IID in the Side Gorge are equally problematic, and that Tuff IIC is thus likely not as widespread as previously assumed.

Tuff IID is the most widespread of the Bed II tuffs, and is typically primary with multiple layers of differing grain size and bedding. It varies in thickness: it is over 2 meters thick at Loc 40, but only ~30 cm thick at Loc 34a and not readily identifiable at Loc 45c, except as highly weathered blocks. Blocks of Tuff IID have also been identified overlying an unconformity in the western basin, where the primary tuff was removed by erosion at all sites except for at Loc. 80, where a small outcrop retains in situ Tuff IID. At most locations it contains an unwelded pyroclastic surge component with low-angle cross beds, reminiscent of Tuff IF (Stollhofen et al., 2008), in addition to fallout and reworked components.

Laboratory Methods

Samples were disaggregated gently using a mortar and pestle, then sieved, with the 60-100 micron size fraction reserved for analysis (for particularly fine samples, the 100-230 micron size fraction was also used). The selected size fraction was washed in a solution of 4% hydrofluoric acid in a sonic bath for one minute, then rinsed at least three times in deionized water and dried under a heat lamp. Grains of each major type of phenocryst (augite, hornblende, titanomagnetite, feldspar) and glass were hand picked, mounted in epoxy, and polished. Rounded or discolored grains were avoided, and where possible minerals with glass attached were selected to avoid contaminant grains. Microprobe polished thin sections were also prepared for some samples (at least one per marker tuff), to establish the overall mineral assemblage and better constrain the context of the selected mineral grains; Table 2 reports which samples were prepared each way.

The grain mounts and thin sections were carbon coated and then analyzed by electron probe microanalysis (EPMA) using the Cameca SX 51 at UW Madison. Minerals were identified using electron backscatter and energy dispersive spectroscopy (EDS). Feldspar and nepheline phenocrysts were analyzed using a 15 kV, 10 nA focused beam, while augite, hornblende, titanomagnetite, and most other phenocrysts were analyzed at 15 kV, 20 nA, with a focused beam. Glass shards were analyzed at 15 kV, 6 nA, and a 5 micron spot size. Calibration standards included Kakanui hornblende (USNM 143965), magnetite (Minas Gerais, USNM 114887), synthetic chromite (USNM 117075), ilmenite (USNM 143965), synthetic Mn olivine, Monash andesine, microcline (asbestos), Amelia albite, and barite. More detailed methods are reported in McHenry (2012). One specific glass shard grain mount was analyzed during most runs as a check to ensure comparable results. Table 3 reports repeat analyses of glass and feldspar from this check sample, demonstrating the consistency of analyses between three separate runs (in 2013, 2014, and 2015).

Results

The relative abundances of primary igneous mineral phases observed in thin section (and confirmed by EDS) are reported in Table 2. Lithic fragments are not included. Note that this table reports only phases that are still present in altered samples; the absence of glass, nepheline, titanomagnetite, or other easily altered phases in a sample does not necessarily indicate that these phases were never present in the tuffs. Also note that for samples for which only a grain mount was analyzed, the abundances of minerals other than the target phases (glass, feldspar, augite, hornblende, and titanomagnetite) are likely underestimates, and should be regarded as present/absent. Secondary zeolites, clays, and iron oxy-hydroxides were abundant in many altered samples but are not reported here (see McHenry, 2009, 2010 for a characterization of Olduvai tuff alteration products).

EPMA results for example tuffs are reported in Table 4, while EPMA results for all samples reported (including standard deviations) are provided in Supplementary Appendix 1. Glass was preserved in few samples, but where present helps to distinguish between the different Bed II tuffs. Glass compositions include trachyte (Tuff IID), basalt (Tuff IIC, BPT), and intermediate undersaturated (e.g. phonotephrite: Tuff IIA and Twiglet) (Figure 4). Feldspar and augite are preserved and present in all samples, and show a broad range of compositions for most tuffs within individual samples. Feldspars for most samples (except the BPT) range from low-K sanidine to intermediate plagioclase, including anorthoclase; BPT feldspars are primarily high-Ca plagioclase (Figure 5). Augites also cover a broad range from high Mg to high Fe; some samples contain a population of Na-rich augite. Hornblende is abundant in Tuff IID and above and absent or scarce in all underlying Bed II tuffs. Titanomagnetite is not preserved in the most altered samples and where present covers a broad range of compositions, with considerable overlap between tuffs.

The most complete set of tuffs from a single section comes from Loc 44 (HWK-W), though Tuffs IIA and IIC are locally absent. The phenocryst compositions for all of the HWK-W Bed II tuff samples are presented in Figure 6 to illustrate the degree of overlap.

Discussion

Most Olduvai Bed II tuffs overlap in composition for feldspar, augite, and titanomagnetite, but there are some trends that can be used to identify individual tuffs or at least separate lower, middle, and upper Bed II.

Lower Bed II: Tuffs IIA, IIB, and Twiglet

Tuffs IIA, IIB, and Twiglet are indistinguishable using augite, feldspar, and titanomagnetite compositions, though each is distinctive in appearance and stratigraphic position. Feldspar and augite cover wide compositional ranges that overlap each other and partially overlap the compositions of the middle and upper Bed II tuffs as well. The Tuff IIA and Twiglet glasses cover the same broad range of silica undersaturated compositions (no Tuff IIB sample contained fresh glass for comparison) and while quite different from the other Bed II tuffs (and from underlying Bed I tuffs), are indistinguishable from each other. The lower Bed II tuffs are best distinguished from each other based on stratigraphic position (Twiglet is close above easily recognizable Tuff IF) and appearance (Tuff IIA tends to have a darker, coarser upper layer; Twiglet contains abundant white root traces, and Tuff IIB has distinctively orange fine-grained tuffaceous siltstone layers) rather than mineral and glass composition. The presence of biotite helps identify Tuff IIB, as it is abundant in the lower portion of IIB but rare or absent in all other Bed II tuffs.

Middle Bed II- the Bird Print Tuff (BPT) and Tuff IIC

The Bird Print Tuff and Tuff IIC of Middle Bed II are similar in composition, with basaltic glass and a population of high-Ca plagioclase feldspar. However, Tuff IIC feldspar is dominated by anorthoclase, which is rare to absent in primary BPT. Their augite and oxide compositions are similar in most elements. Volcanic glass for both tuffs is basaltic and similar in composition, though Tuff IIC glass has a slightly higher MgO concentration. These tuffs are best separated from the other Bed II tuffs (and from each other) by feldspar composition.

The uniqueness of the BPT composition within Bed II makes it a useful “check” for stratigraphic correlation across the gorge. The present work confirms that Hay (1976) correctly identified the BPT in both the Junction and western gorge (Loc. 80 (RHC)), two areas separated by kilometers with no exposure of Middle Bed II to allow for physical stratigraphic correlation. The BPT is recognized at sites further west from Loc 80 (RHC), but is not present in the eastern gorge, it disappears slightly to the east of Loc. 44/ HWK-W. It is widely identifiable in the Junction, and was identified in situ for the first time in the Loc 88 (MNK) area during the current project; Hay (1976) had only observed fragments of BPT material in younger conglomerate at this site. Its presence in the Loc 44 (HWK), Loc 45 (FLK), and Loc 88 (MNK) areas makes it an excellent marker for establishing the relative stratigraphic position of key Middle Bed II archaeological sites throughout the Junction area and into the Side Gorge.

Upper Bed II: Tuff IID and above

Tuff IID also contains a broad range of feldspar, augite, and titanomagnetite compositions (Figure 7), but can be distinguished from the underlying Bed II tuffs by the presence of abundant hornblende, which is absent to sparse in underlying tuffs. Trachytic glass, where preserved, also serves to distinguish Tuff IID from the more mafic and silica undersaturated tuffs below.

Tuff IID consists of multiple eruptive units, including volcaniclastic surges, airfalls, and reworked units. Some compositional trends can be identified within the tuff, though all contain the same basic mineral assemblage. Within Tuff IID there are two basic hornblende compositions; one with higher MgO and Al_2O_3 and lower FeO (Figure 7a); individual samples contain hornblende representing one or both compositions. Bed II tuffs above IID exclusively contain the higher MgO population. Sodic augites (with higher FeO concentrations) are infrequent in Tuff IID but more abundant than in other Bed II tuffs, including those above IID (Figure 7b).

Tuffs above Tuff IID within Bed II are compositionally similar to IID, though titanomagnetites from tuffs above IID have higher MgO (Figure 7d). The presence of abundant hornblende separates Tuff IID and higher tuffs from those of the rest of Bed II, while the presence of a lower-Mg hornblende population (in addition to a higher-Mg hornblende population) and the presence of few sodic augites helps distinguish Tuff IID from overlying tuffs.

Implications for paleoanthropology

Until now, a landscape approach to the paleoanthropology of the Olduvai basin has been applied mostly to the record of Beds I and Lower Bed II (e.g. Blumenschine et al. 2003, 2012), where time slices can be accurately defined by the presence of uniquely identifiable marker tuffs (e.g. McHenry, 2012). Correlations between known archaeological sites in Middle and Upper Bed II are difficult due to the tuff identification problems discussed above. The new geochemical fingerprints presented in this paper will help trace sedimentary units relevant for paleoanthropology across wider areas of the basin not only in the pre-Tuff IIA sequence, but now also in Middle and Upper Bed II. These findings are particularly important for the interpretation of key sites such as MNK, where paleoanthropological evidence is found below and above Tuff IIB (currently the stratigraphic base of handaxe-bearing assemblages).

The current stratigraphic framework places three distinct forms of human ancestors including *H. habilis*, *H. erectus*, and *Australopiths* within Bed II. Three hominin individuals including the *H. habilis* paratype (OH 13), OH 15 (cf. *H. erectus*) and an indeterminate hominin (OH 14) come from deposits associated with Tuff IIB at Loc 88 (MNK), while another hominin (OH 32) derives from higher sequences at the same site (Leakey et al. 1964; Leakey, 1971). The last appearance (LAD) of *H. habilis* can be discerned from one individual (OH 13) derived from Middle Bed II at Loc 88 (MNK Skull site (Leakey, 1971; Day, 1986). The most definitive evidence for the first appearance of H. erectus comes from sediments above Tuff IID at Loc 46 (LLK: OH 9 calvaria) and Loc 90a (SC: OH 36 ulna) (Leakey, 1971; Rightmire, 1980; Day, 1986). Accurately placing these and other hominin specimens within the stratigraphy at Olduvai is the first step toward understanding the ecology and landscape use of these taxa.

Overall, this higher resolution stratigraphic framework will help to better contextualize the biological and cultural change preserved in the Olduvai paleoanthropological record between Tuff IIA and Tuff IID, which includes the disappearance of *Homo habilis* and the appearance of *Homo erectus,* as well as the technological change from the Oldowan into the Acheulean. While additional work is required to determine the numerical ages of the tuffs described here, the framework presented will allow such ages to be applied directly to sites and intervals of great interest to paleoanthropology.

Conclusions

Bed II tuffs are, in general, discontinuous, contaminated, altered, and difficult to fingerprint individually based on mineralogy and geochemistry. However, general compositional trends between tuffs from Lower, Middle, and Upper Bed II help distinguish the intervals, and specific tuffs (e.g. the Bird Print Tuff, Tuff IID) are more compositionally distinct and can be distinguished. High-resolution stratigraphic mapping, coupled with tuff geochemistry where possible, will be required to improve the stratigraphic framework of Bed II to better constrain the position of the archaeological sites focusing on the transitions between Oldowan hominin species and lithic technologies.

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Tables

Table 1: Sample descriptions and sites

Table 2: Primary phases observed during EPMA analysis

Table 3: Repeat measurements on glass and feldspar, 3 different EPMA runs.

Table 4: Glass and phenocryst compositions as measured by EPMA.

Figure captions

Figure 1: Olduvai Bed II tephrostratigraphy, composite section. Note that Bed II tuffs are not preserved at most sites and differ significantly in thickness and tuffaceous content; this figure provides their relative stratigraphic positions and general compositions based on the results of this study and Hay, 1976. The division of Bed II into Lower, Middle, and Upper parts is based on Leakey, 1971. Dates from [1]Deino, 2012; [2]Curtis and Hay, 1972; discussion in Torre et al., 2012; [3]Manega, 1993; and [4]Dominguez-Rodrigo et al., 2013.

Figure 2: Map of the Olduvai basin, showing the outline of the modern gorge, and the extent of the paleo-lake at the time of deposition of the Bird Print Tuff (Middle Bed II) as

reconstructed by Hay, 1976. Locations of sampled and measured sections along with other sites mentioned in the text are indicated, using Hay (1976) locality names.

Figure 3: Sampled stratigraphic sections, documenting tuff positions, sample IDs, and surrounding lithologies. The sections for Loc 44 (HWK-W) and Loc 80 (RHC) represent the entire Bed II sections for those sites; the other sections are partial. The Bird Print Tuff (BPT) and Tuff IID are the most widespread and easily identifiable, while Tuff IIC was only recognized in the field as a true “tuff” in the vicinity of Loc 34a.

Figure 4: Bed II glass compositions. A. Silica/alkali diagram after LeBas et al., 1986. Tuff IID glass is dominantly trachytic, Tuffs IIC and the BPT are basaltic, and the lower Bed II tuffs (Twiglet and IIA) are undersaturated, covering a range of phonotephritic compositions. No Tuff IIB glass was identified at any site. B. Plot of MgO vs. Al_2O_3 for Bed II glasses. The BPT and Tuff IIC basaltic glasses are best separated using their MgO concentrations. C. Plot of TiO_2 vs. Al_2O_3 for Bed II glasses.

Figure 5: Plots of elemental compositions for individual mineral grains from example Bed II tuffs, as determined by EPMA. A and B: augite compositions (MgO vs. Al_2O_3 and Na_2O vs. FeO). Tuff IID contains a population of lower-MgO, lower Al_2O_3 augites, and more sodic augites. C. Titanomagnetite compositions (Al_2O_3 vs. MgO). D. Feldspar compositions (FeO vs. Na_2O). E. Feldspar ternary diagram. The Bird Print Tuff and a secondary population in Tuff IIC are characterized by high-Ca plagioclase (though most feldspar in Tuff IIC is anorthoclase).

Figure 6: Plots of elemental compositions of individual mineral grains from all tuffs sampled at Loc. 44 (HWK-W), as determined by EPMA. A. Augite, MgO vs. TiO_2. BPT augites trend towards higher MgO compositions, while Tuff IID has a low-MgO population. B. Feldspar compositions, K_2O vs. CaO. BPT feldspars are high-Ca plagioclase, unlike all other tephra sampled at the site. The other tuffs all include a wide range of feldspar compositions, from K-rich anorthoclase or sanidine to intermediate plagioclase. C. Hornblende composition, MgO vs. Al_2O_3. Hornblende is rare to absent in non-Tuff IID (and above) Bed II tuffs, and where present (e.g. Tuff IIB), differs in composition from Tuff IID hornblende.

Figure 7: Plots of elemental compositions of all Tuff IID (and above) samples, as determined by EPMA. A. Tuff IID hornblende, FeO vs. MgO. Tuff IID hornblende cover a broad range of compositions; higher-FeO hornblende is more abundant in the lower part of the tuff, while higher-MgO hornblende is more abundant in the upper portion and in overlying Bed II tuffs. B and C. Tuff IID augite, Na_2O vs. FeO and TiO_2 vs. Al_2O_3. Low TiO_2 and Al_2O_3 augite is more abundant in the lower portion, while higher TiO_2 and Al_2O_3 augite is more abundant in the upper portion and in overlying Bed II tuffs. D. Tuff IID titanomagnetite, MnO vs. MgO. Bed II tuffs overlying Tuff IID tend to have higher MnO titanomagnetites than Tuff IID. E. Tuff IID feldspar ternary diagram. Tuff IID feldspar cover a broad compositional range, from sanidine to intermediate plagioclase. Some especially low-K plagioclase grains (and high-K alkali feldspar grains) are likely detrital.