AQUIFER PROPERTIES OF THE PERMO TRIASSIC SANDSTONES OF THE UNITED KINGDOM

by

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To SALLY
for all her encouragement

I am being driven forward
Into an unknown land
The pass grows steeper,
The air colder and sharper.
A wind from my unknown goal
Stirs the strings
Of expectation.

Still the question:
Shall I ever get there?
There where life resounds,
A clear pure note
In the silence.

DAG HAMMARSKJÖLD
Vägmärken

ABSTRACT

The potential value of core analysis in hydrogeology is critically examined in the light of the results of a systematic study of the porosity, density and intergranular permeability of the Permo-Triassic sandstones in the United Kingdom, based on the examination of 3500 test specimens.

The Thesis begins with an account of the stratigraphy of the sandstones, illustrated by 51 vertical sections. This is followed by a description of the distribution and nature of the samples tested.

The principal experimental methods employed were the liquid resaturation technique for measurement of porosity and density, and a gas permeameter was used to determine intrinsic permeability. Equipment systems are described which enable large numbers of samples to be handled rapidly. An improved water permeability test system incorporating sterilising filtration is described and tentative proposals for automated instrumentation are presented. The centrifuge method of measuring specific yield is re-examined.

The test data are analysed in two ways: a) by making a detailed comparison of the lithology and physical properties of the test specimens, and b) by considering the porosity and permeability data as probability distributions. The second method permits the aquifer properties of the various sandstone subdivisions in different parts of the U.K. to be quantitatively compared for the first time.

The parameter "primary" transmissivity is introduced to describe the intergranular component of transmissivity. Values for this parameter are compared with values for "total" transmissivity derived from analysis of pumping test data from six localities in widely differing hydrogeological environments. It is suggested that this comparison allows some general conclusions to be drawn about the relative importance of intergranular flow in sandstone aquifers.

A further comparison is made of the permeability and transmissivity of British and German Triassic sandstone aquifers on the basis of data published by Hauthal (1967) and Durbaum, Matthess and Rambow (1969).

The study was deliberately intended to be of a general nature, so as to provide a firm basis for future more detailed work on the hydrodynamic behaviour of sandstone aquifers in the United Kingdom.

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CHAPTER ONE : Introduction

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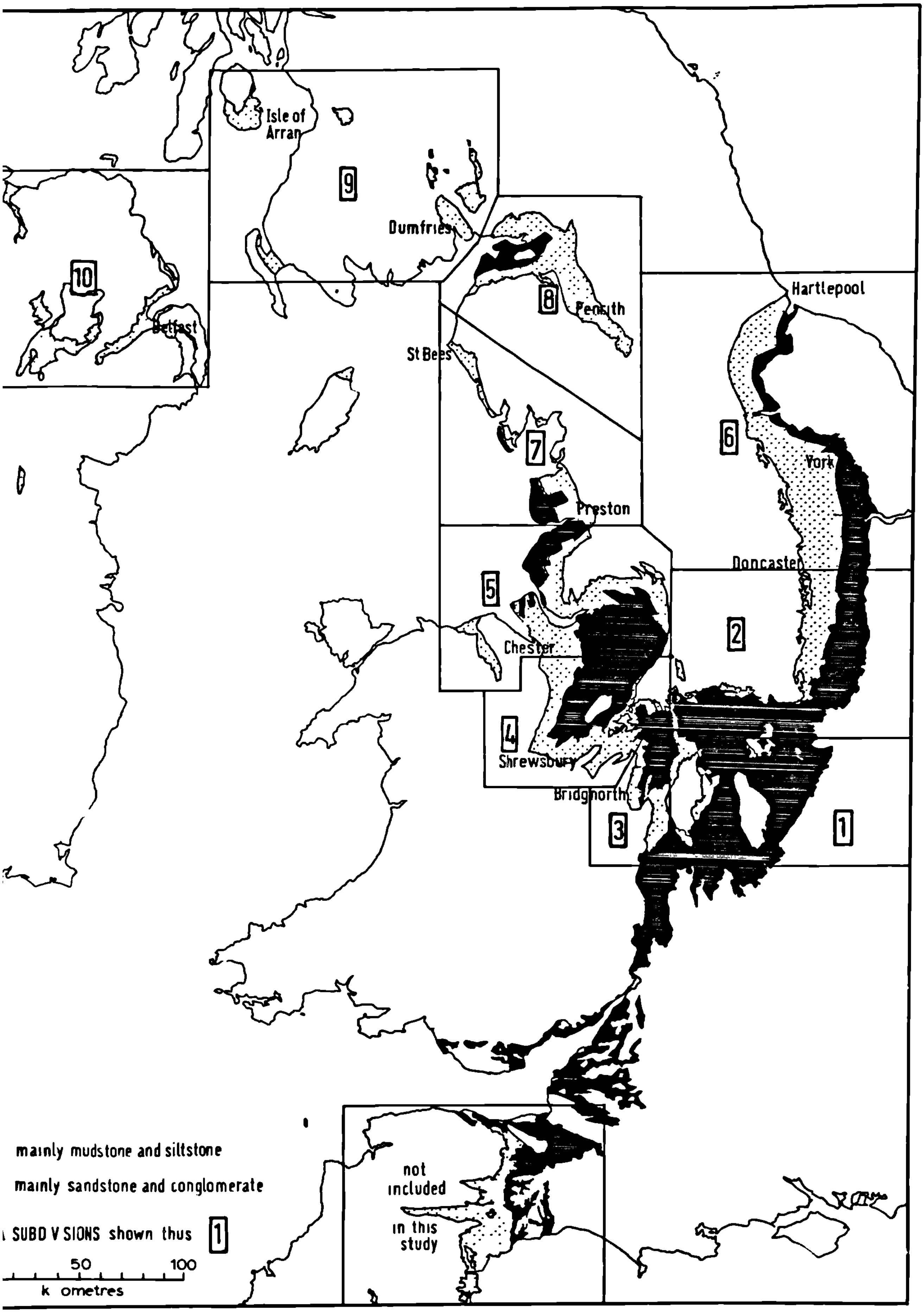
The term "core analysis" is used to describe the determination, by analytical methods, of the physical properties of reservoir rocks containing hydrocarbons, the chemistry of the various fluids they may contain and the physics of single or multi-phase fluid flow through them under both static and dynamic conditions. Ground water flow merely constitutes the special case in which the reservoir rock contains only two phases, air and water; below the water table or in a confined aquifer, this reduces to the simplest case of single phase flow of water alone.

The principal core analysis techniques which have potential value in hydrogeological studies are naturally those concerned with the evaluation of the permeability of reservoir rock to fluids, particularly water, the measurement of porosity or the volumetric storage of the reservoir and the determination of the rate of movement of the liquid phase (water) in the presence of a gas phase (air). The two-phase flow problem, long familiar to petroleum engineers who use the term "relative permeability" to describe it, appears in hydrogeology in the unsaturated zone where a normally static gas component controls a dynamic fluid.

The hydrogeologically important condition of specific yield can be considered to be the end point of the process, and this property has no direct counterpart in the petroleum reservoir system. In the present study, however, an attempt has been made to discover new ways of measuring specific yield rapidly and accurately in the laboratory.

In 1966, the writer began a 4-year research project in the Hydrogeological Department of the Institute of Geological Sciences to investigate to what extent core analysis studies could be used to quantify the aquifer properties of granular water-bearing formations, and this thesis summarises the results of this study. Aquifer properties are taken to include principally transmissivity and coefficient of storage, and specific yield. The most suitable British aquifers on which to undertake the work appeared to be the Permo-Triassic sandstone formation which is well developed in many parts of the U.K. (See Fig.1) These rocks comprise considerable thicknesses of friable, red sandstones of continental origin disposed in deep, often fault-controlled basins and commonly resting uncomformably on a very uneven Upper Palaeozoic floor. These sandstones are particularly promising for aquifer evaluation using core analysis on account of their high microscopic (or intergranular) permeability which appears to contribute significantly to their transmissivity.



MAP SHOWING DISTRIBUTION OF PERMO-TRIASSIC SANDSTONES IN THE U.K.

Yet the study of their physical properties has received very little attention, in spite of the fact that for well over 100 years the sandstones have been used as a very prolific and reliable source of ground water, principally in the Midlands and North west of England. In the more permeable parts of the formation, wells of 300 m depth commonly produce water at a rate of 5000 to 100,00 m^3 a day and currently the sandstones yield about 20% of the total ground water pumped in this country (Ineson, 1970).

There is surprisingly little published aquifer property data on these formations, despite the fact that simple measurement techniques have been devised for many years. Here mention should be made of the work of Howell and his associates of the University of Manchester, whose studies of permeability variation in the Triassic sandstones of South Lancashire have been presented in a number of recent papers (see Crook and Howell, 1970 and Bow, Howell and Thompson, 1970). In south west England, also, the ground water hydrology of the Trias has been studied by Sherrell, 1970. Apart from these publications there is very little published data available, in spite of the fact that the formations are well exposed in many localities and there has been no shortage of core material from new water wells, as even today many production holes are drilled using the old fashioned, but relatively inexpensive, rotary-shot system. One possible explanation for the lack of published data may lie in the fact that, for commercial reasons, reports of results determined for specific projects are likely to remain confidential to consultants and clients.

In the present study, samples have been examined from some 500 localities in all the principal areas over which the British Permo-Trias crops out, with the exception of Devonshire. These locations have included a significant number of fully-cored boreholes, sections in tunnels and mines, and naturally a great number of surface exposures, both natural and artificial. All the specimens have been subjected to core analysis in a standard manner. For statistical reasons described later, it was essential to develop a testing system which was rapid and could accommodate large numbers of standard specimens. Although these design criteria have always been very important in core analysis instrumentation, modifications to techniques were inevitably found to be required to overcome various experimental problems such as the poor cohesion of many of the sandstone samples.

The study developed into an attempt at a comprehensive analysis of vertical and lateral variation in the aquifer properties of the Permo-Triassic sandstone sequence, with the objective of producing a sound basis on which to predict the water yielding characteristics of these aquifers in areas where ground water development has not yet taken place. The principal results should be considered primarily in a hydrogeological context, although the data may also be of use in the allied fields of civil and petroleum engineering.

CHAPTER TWO : Stratigraphy of the Permo-Triassic Sandstones of the United Kingdom

CHAPTER TWO: THE STRATIGRAPHY OF THE PERMO-TRIASSIC SANDSTONES OF THE UNITED KINGDOM

2.1. INTRODUCTION

Certain characteristics become particularly important when rock formations are being considered as aquifers. By virtue of the fact that most rock formations are to some extent indurated and cemented, a considerable vertical thickness is necessary in order for transmissivity and storage to be high, especially in those formations which have been relatively unaffected by structural deformation. In this respect, vertical homogeneity is also desirable. Secondly, the rock aquifer should display minimal lateral facies change such that reasonable uniformity of conditions of flow exist within several square miles of outcrop.

In general, and this applies to both fissured and microscopically permeable formations, the concept of three-dimensional continuity is very important in the assessment of a formation as an aquifer. Provided the formation possesses continuity to a significant degree, then it can be developed as an aquifer in a rational and scientific manner in preference to development on a purely speculative basis.

It is suggested that the concept of continuity can be usefully applied in the study of Permo-Triassic sandstone formations in the United Kingdom, which in some areas have not yet been developed as aquifers for groundwater supply.

In the following stratigraphic account and the accompanying diagrams (Figs.2-11), particular consideration has been given to the nature and extent of vertical facies change and thickness variation in these rocks. This immediately brings forward the problem of stratigraphic correlation in the Permo-Trias of the U.K., which in the virtual absence of macro-fossils becomes an extremely difficult task. The correlation has to be tackled on the basis of lithology alone, and clearly this is fraught with dangers, if a satisfactory time-stratigraphic correlation is to be attempted. In hydro-geology, however, it is lithology which is important from the outset, and the fact that a continuous body of sandstone may be of a slightly different age in different areas is of little economic significance.

The problem of developing a completely satisfactory chronostratigraphy for the Permo-Trias in the U.K. has been the subject of a large number of scientific papers and books published since the middle of the nineteenth century, and the reader is referred particularly to the work of Hull (1869), Sherlock (1926, 1928 and 1947), Hollingworth (1942) and Wills (1956). The most recent publications on the subject are the papers contributed to the Geological Society of London's Symposium on the Triassic rocks of Great Britain held in 1967. Those principal conclusions which are of interest to this hydrogeological study have been summarised in Chapter 8 (p.241), where broad differences in the aquifer properties of Triassic sandstone aquifers in Britain and

Germany are discussed. The correlation diagrams (Figs.2-11) are primarily intended to illustrate the general succession and thickness variation of the Permo-Triassic sandstones. The basis is completely lithological and the sequences have been drawn up using the generally accepted classification at the time of writing. To produce them, the geological literature has been thoroughly examined and many opinions sought, both within the Institute of Geological Sciences and elsewhere. Two common datums have been used:

i) the base of the Keuper in most of the English areas

ii) the base of the Triassic in northern England, Scotland and Northern Ireland.

With regard to the first, the base of the Keuper appears to be a horizon widely recognisable in the field but its adoption here as a datum is not intended to suggest that it represents, in all areas, the same instant of geological time. It is being used as a lithological datum. Similarly with the second horizon, the base of the Trias in the northern regions of the U.K. is now thought most probably to lie within or near the top of the St.Bees Shales, which are widely accepted as passage beds. This conclusion is largely based on the apparently transitional nature of the St.Bees Shales, (Hollingworth, 1942) and on the behaviour of the Bunter Sandstone which passes, not into the Penrith Sandstone, but into the higher St.Bees Sandstone as it is traced northwards from Lancashire into Cumberland.

Similarly in Northern Ireland, it is suggested (Manning, personal communications) that the base of the Trias probably lies within the so-called Bunter Marls. These problems do not occur in the South of Scotland outcrops, where all the sandstones and breccias under consideration here appear to be quite definitely of Permian age, except on the Isle of Arran where a local lithological junction at the base of the Trias has been defined by Gregory (1915) and Tyrrell (1928).

Figs. 2-11 illustrate that the Permo-Triassic sandstones possess over wide areas, the three-dimensional continuity considered essential in a relatively undeformed aquifer. It is hoped that the experimental physical property data which appears in a later section of the Thesis will reinforce this conclusion.

For the description of the stratigraphy of the formation, the outcrops have been grouped for convenience into the following 10 Areas, shown in fig.1 , each of which are characterised by distinct facies:

AREA 1: South Staffordshire, Birmingham and Warwickshire

AREA 2: South Derbyshire and Nottinghamshire

AREA 3: Bridgnorth-Wolverhampton

AREA 4: Mid-Cheshire and Shropshire

AREA 5: North Cheshire, Merseyside and south Lancashire

AREA 6: Yorkshire and Durham

AREA 7: North Lancashire and west Cumberland

AREA 8: Vale of Eden and Carlisle Basin

AREA 9: South of Scotland

AREA 10: Northern Ireland.

Reference to both fig.1 and figs.2-11 enables a general view of the thickness and lithological variation over the whole country to be rapidly obtained. Certain of the stratigraphic columns fall just outside the Area in which they have been included; because of continuous lithological variation, it is difficult to ascribe hard and fast boundaries to the Areas, except for the practical purpose of considering samples as discrete groups.

2.2. AREA 1: SOUTH STAFFORDSHIRE, BIRMINGHAM AND WARWICKSHIRE (fig.2)

Comparison of fig.2 with figs. 4 and 5 demonstrates that although the Triassic rocks in the Birmingham district form a major element in the structure and topography of the area, the sequence is in reality quite thin. It does, however, have a sufficiently high transmissivity to render it very important in ground water supply.

The thick LOWER MOTTLED SANDSTONE of the Severn Valley is entirely lacking in this area. It cannot definitely be established whether its absence is total or whether it was removed by erosion before the deposition of Bunter Pebble Beds on the area east of the western boundary fault of the south Staffordshire coalfield.

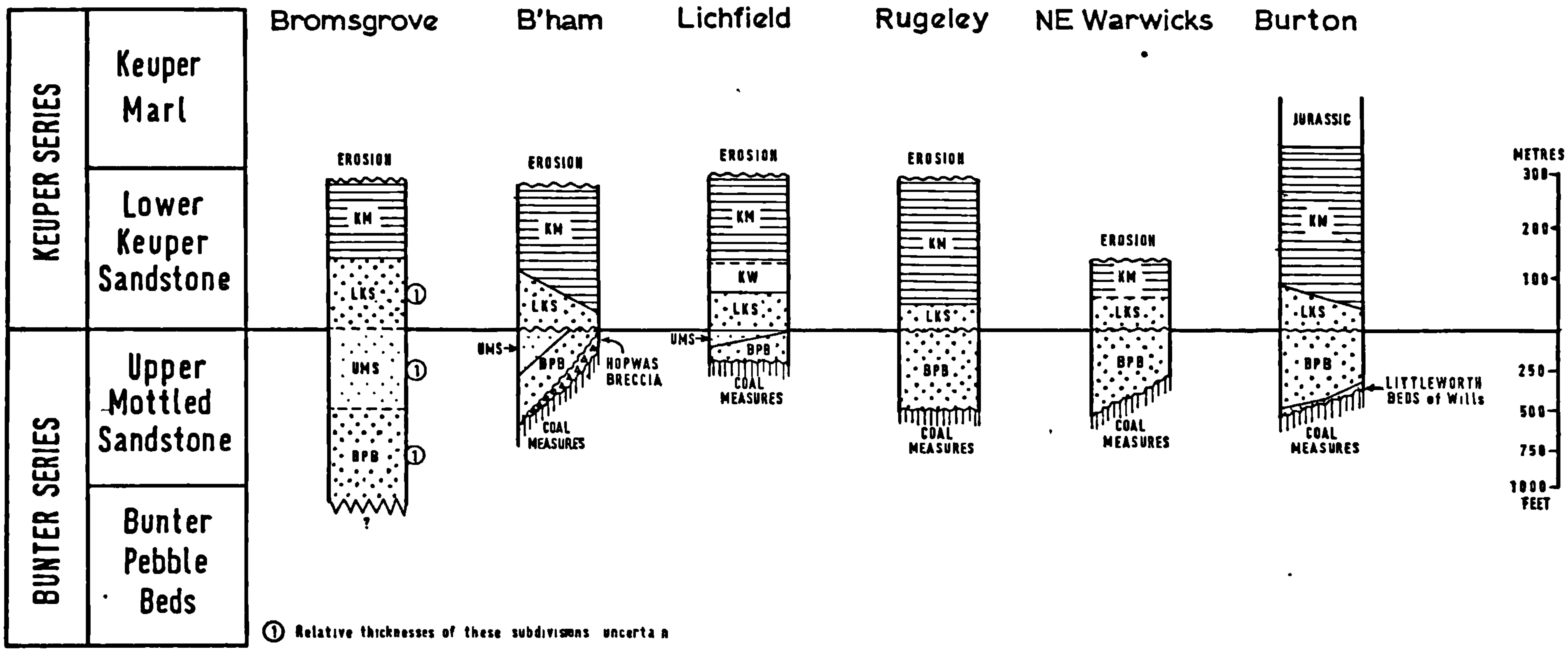
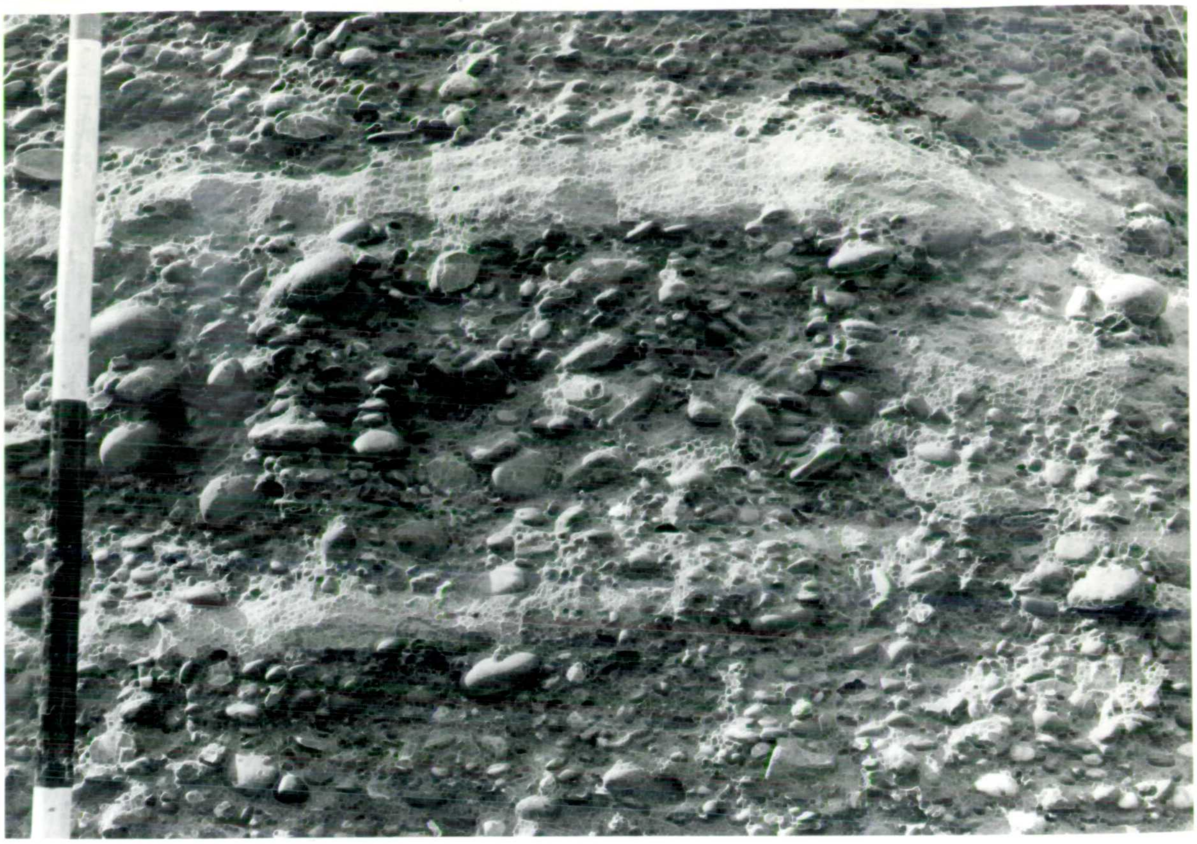


Fig.2. Representative sections through Permo-Triassic rocks : AREA 1 - South Staffordshire, Birmingham & Warwickshire

Further east, yellow pebble free sands proved underground at the base of the Pebble Beds in the Burton-on-Trent area were named Littleworth Beds, by Wills (1948) and they may be a local representative of the Lower Mottled Sandstone.

The BUNTER PEBBLE BEDS form the base of the sequence over much of the greater part of this area, and commonly rest unconformably on Upper Carboniferous red beds, or on Coal Measures where they often cause seepage problems in underground workings (Bailey 1909-10, Staley, 1944). They consist typically of pebbly red or brown sandstone, or partially unconsolidated quartzose gravel which reaches its maximum development on Cannock Chase (see PLATES 1A, 1B and 2A). The pebbles exceptionally reach 300 mm. in length. In the Burton-on-Trent area, the beds tend to be of finer grain and coarse bands of shingle are absent (Stevenson and Mitchell, 1955). The formation thins rapidly southwards and disappears south of Tamworth, the erosion apparently having taken place in pre-Keuper times.

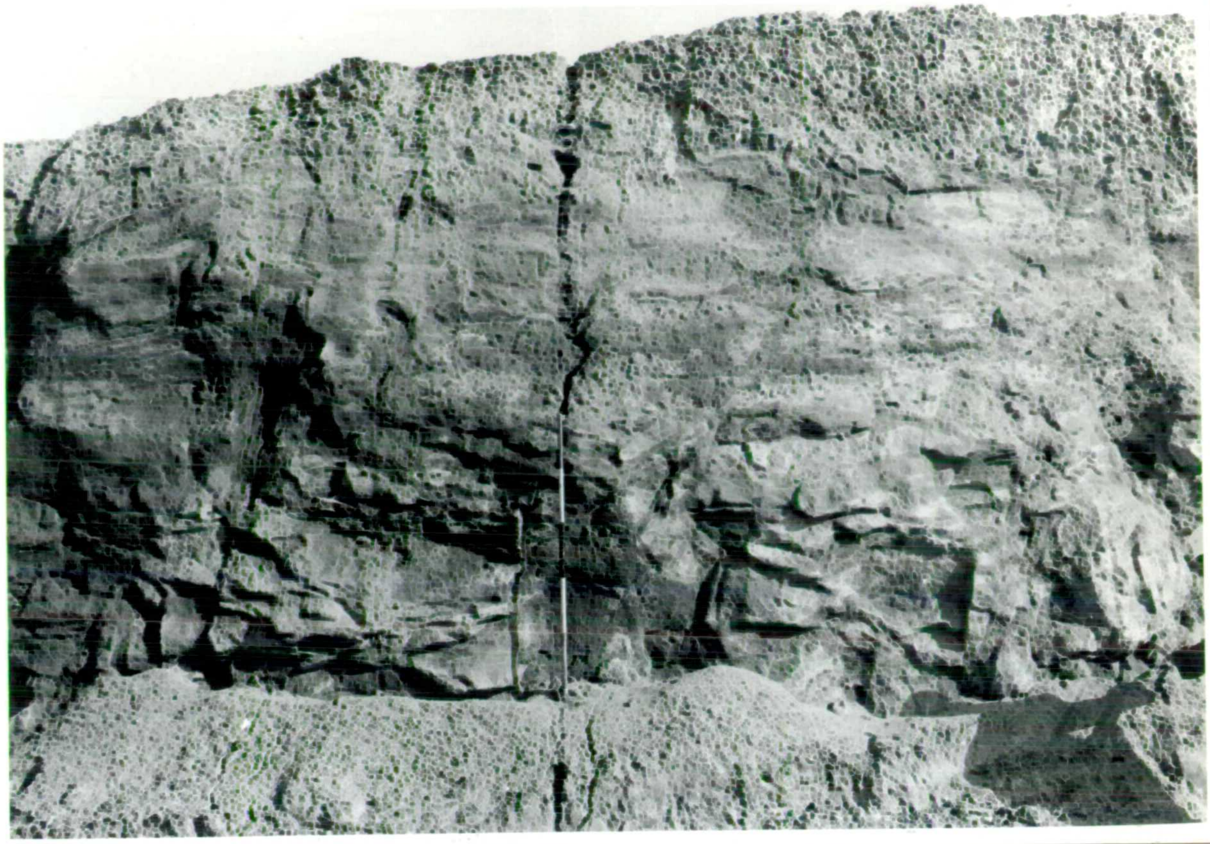
The UPPER MOTTLED SANDSTONE appears to have been deposited in a much smaller basin than the Pebble Beds, since it is absent east of Birmingham (see fig.2). It underlies, however, a large part of that city, and on account of its uniform grain size, it has been used extensively as a moulding sand in the Black Country. In lithology, it is no different from that exposed in the type area (Area 3).



A. AREA 1 : Shingle facies of BUNTER PEBBLE BEDS exposed at Dunning's Gravel Works, Huntington, near Cannock, Staffs

PLATE 1

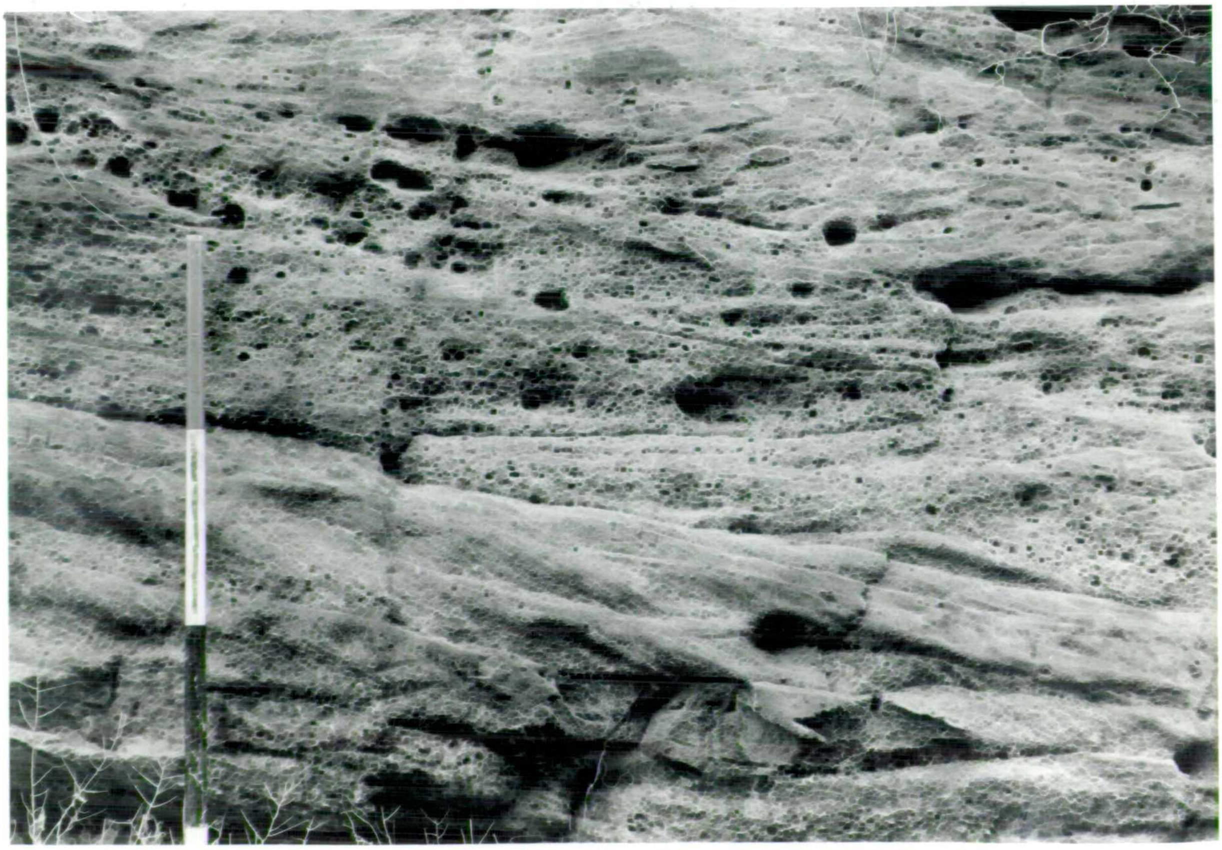
B. AREA 1 : Lenticle of sand-free shingle in BUNTER PEBBLE BEDS at Dunning's Gravel Works, Huntington, near Cannock



A. AREA 1 : Lenticular sandstone in BUNTER PEBBLE BEDS at Dunning's Gravel Works, Huntington, near Cannock, Staffs

PLATE 2

B. AREA 1 : Cross-stratified LOWER KEUPER SANDSTONE showing 'catbrain' structure (cavities) seen at Burcot, near Bromsgrove, Worcs



Keuper beds transgress the underlying Bunter sequence over most of the area, and in the east, overlap to rest directly on Coal Measures. The thickness of sediment deposited, however, is never very great, except in the west near Bromsgrove, where the Keuper beds may exceed 450 m (1500 ft.) thickness. The LOWER KEUPER SANDSTONE rests everywhere unconformably on the Bunter Pebble Beds or Upper Mottled Sandstone, and commences with a calcareous breccia and conglomerate group, which is substantially similar in lithology throughout the area. These beds pass upwards into coarse grained, open-textured white, red or brown sandstones, strongly current-bedded; in the Bromsgrove area, much 'catbrain' is present (see PLATE 2B). Around the north-eastern edge of Cannock Chase and near Burton-onTrent massive light coloured free-stones are developed, with interbedded red mudstones at approximately the same horizon as the Building Stone Group of Cheshire. Where the Keuper beds rest directly on Coal Measures as in east Warwickshire, the sequence is essentially similar.

At the top of the Keuper Sandstone, appear the passage beds into Keuper Marl which are conventionally termed KEUPER WATERSTONES. They are not well developed in this area, but consist of the usual intercalations of hard silty sandstone with an increasing proportion of red mudstone, exactly as in the other areas.

Finally, within the KEUPER MARL in Warwickshire appears a very late arenaceous development, the ARDEN SANDSTONE whose base lies about 110 m (350 ft.) above the base of the Keuper Marl. It is a thin fine grained pale coloured micaceous sandstone of limited hydrogeological significance.

2.3. AREA 2: SOUTH DERBYSHIRE AND NOTTINGHAMSHIRE (fig.3).

As fig.3 shows, there is a striking attenuation of the Permo-Trias sequence in the area bordering the southern edge of the Peak District. If fig.3 is compared with, for example, fig.5 for the Cheshire area, the true extent of this reduction in thickness can readily be seen. However, permeability in the relatively thin sequence in Nottinghamshire is sufficiently high to overcome the effect on transmissivity of the reduced thickness, and the Bunter Pebble Beds are a highly productive aquifer in south Nottinghamshire.

The sequence commences with the LOWER MOTTLED SANDSTONE which is thinly developed in the Nottingham district, reaches a maximum thickness of about 21 m (70 ft.) near Ollerton (Edwards, 1967) and thereafter to the north is replaced laterally by the Middle Permian Marl, until it disappears completely north of Worksop. In lithology, this unit consists of bright red, soft sand and sandrock of generally rather fine grain size.

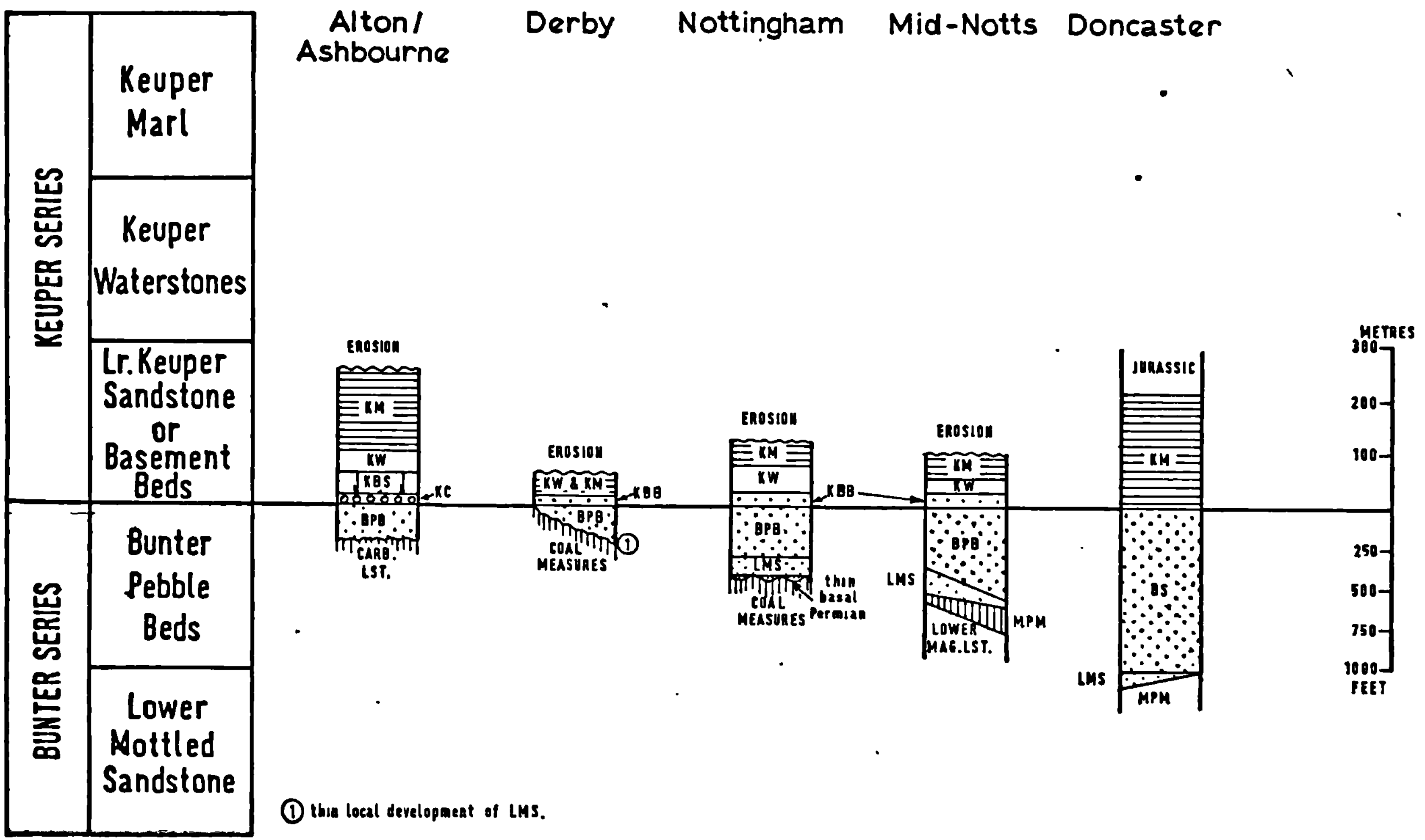


Fig.3 Representative sections through Permo-Triassic rocks : AREA 2 - South Derbyshire & Nottinghamshire

Narrow seams of angular rock particles and of red marl may occasionally be seen. Cross bedding is rather poorly developed. The unit is absent in the area between Alsager and Nottingham, where the Bunter Pebble Beds and Keuper rocks form the base of the Permo-Trias.

The BUNTER PEBBLE BEDS occur practically throughout the area and in the west they rest directly on Carboniferous rocks. They comprise a typical development of soft coarse conglomeratic sandstones which are soft yellow and light red in colour at Ashbourne, becoming white at Nottingham. North of Nottingham, they acquire the normal brownish-red colour of the other Midland outcrops. Numerous pebbles usually not exceeding 10 cm. in length occur at various levels in shallow lenticles. Red siltstone and mudstone bands up to 60 cm. thick also occur locally. The sands are clean and highly permeable. They possess a feeble coherence and display a cross bedding of variable intensity (see PLATE 5B). Lamplugh et al,(1911) gives values of 12-20^{o} dip in directions ranging from east to west-north-west. The pebble content decreases markedly towards the north, until in the Doncaster area the unit comprises 305 m (1000 ft.) of clean sands, virtually pebble free.

The Keuper rocks succeed the Pebble Beds without the usual development of UPPER MOTTLED SANDSTONE which is completely absent.

The Keuper sequence is much reduced, but may still be divided into the three units recognised farther west in the Cheshire-Shropshire Basin, viz., Keuper Building Stones (including the basal Keuper conglomerate) Keuper Waterstones and the Keuper Marl. Fig.3 indicates how thin and insignificant the beds are from a hydrogeological point of view. The KEUPER BUILDING STONES (and CONGLOMERATE) comprises white freestones with shale or mudstone partings overlying a white silica-cemented conglomerate, 12 m (40 ft.) thick at Alton (Hull, 1869). The freestones are typically soft, porous, white or brownish sandstones. The unit is scarcely recognisable in mid-Nottinghamshire except as a few feet of conglomeratic sandstone at the base of the KEUPER WATERSTONES. This unit comprises a group of passage beds - "irregular intercalations of mudstone and shale with soft red to brownish red or whitish, porous sandstones and compacted pale dolomitic sandstones" (Lamplugh et al, 1911). The frequency of the sandstone beds diminishes as the sequence is ascended until the rocks are entirely indistinguishable from KEUPER MARL.

2.4. AREA 3: BRIDGNORTH - WOLVERHAMPTON (fig.4)

This district has for a long time been taken as the type area for the Bunter of the West Midlands (Whitehead and Pocock, 1947). The triple division of the Bunter beds into Upper Mottled Sandstone, Pebble Beds and Lower Mottled Sandstone was first established in this area by Hull (1869).

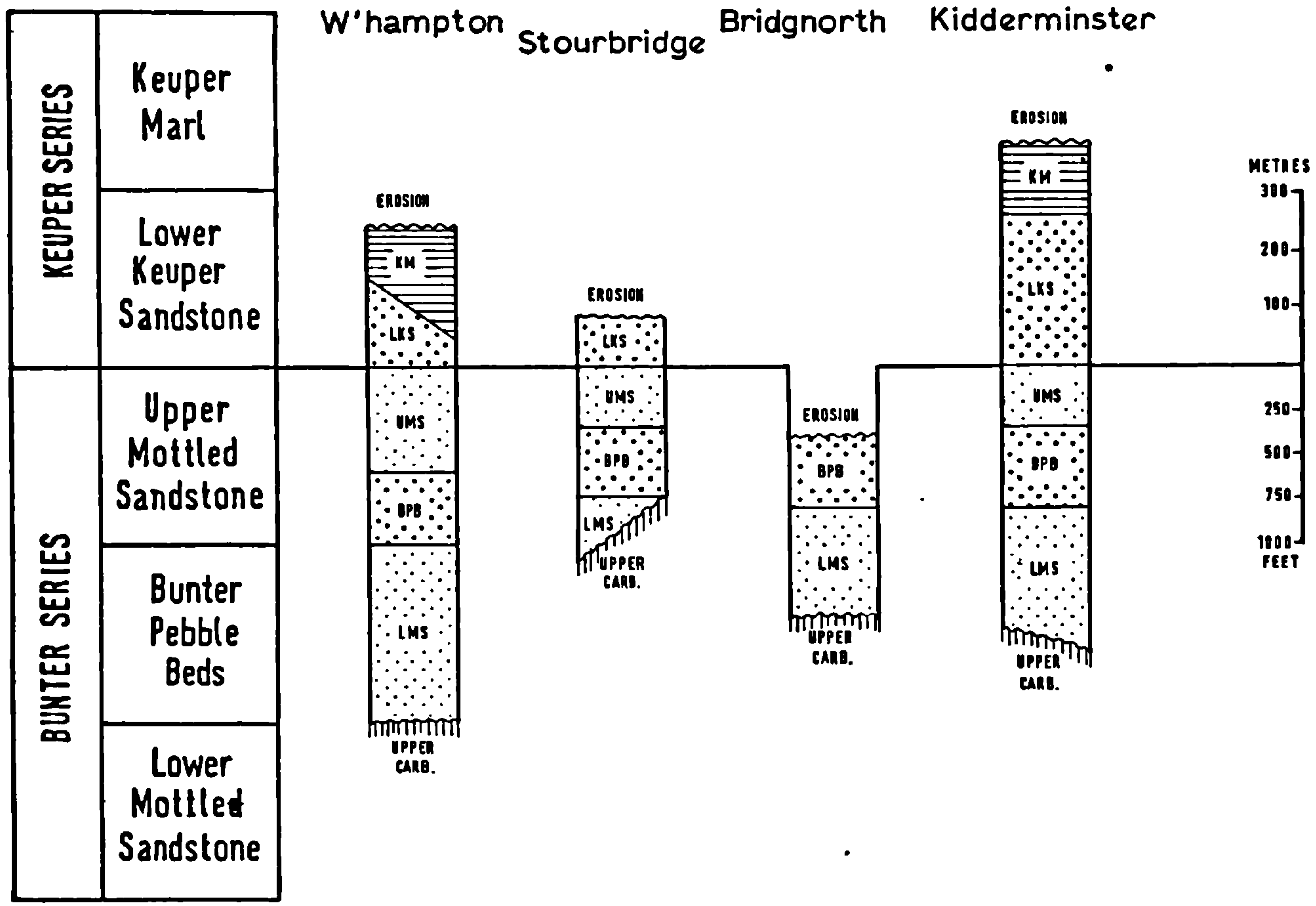


Fig.4 Representative sections through Permo-Triassic rocks : AREA 3 - Bridgnorth-Wolverhampton

Overlying the Bunter rocks and separated from them by a fairly sharp junction, is a moderately thick Keuper sequence, in which the lower sandstone member is the dominant unit.

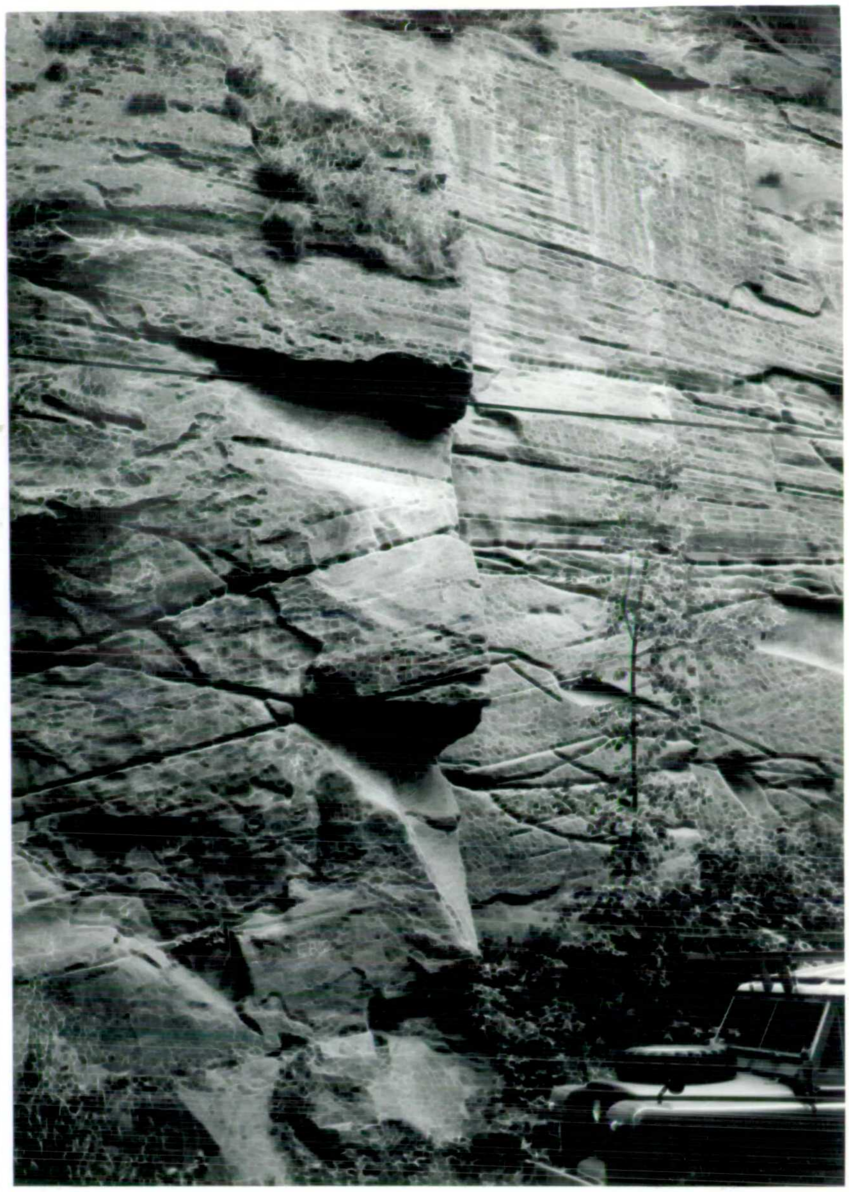
The LOWER MOTTLED SANDSTONE or DUNE SAND FORMATION of Shotton (1937) and Wills (1956) is especially well developed in the Bridgnorth area where numerous excellent exposures may be seen (PLATES 3A, 3B). It consists of bright red, mainly fine grained, soft but coherent sandstones in which the coarsest grains are well-rounded and referred to as millet seed grains. The formation is pebble-free and highly sorted (Shotton, 1937). Frequent blotches or bands of greenish colour may occur. It displays large scale cross-stratification with sets commonly 6-9 m (20-30 ft.) thick, and cross-dips of up to 30° in directions ranging from NW through W to SW. Shotton's view (1937) that the major part of the formation in this district represents partially compacted barchan dunes is now generally accepted. Whether this is true outside the middle Severn Valley is more open to question, as this unit of the Bunter seldom shows such well developed large scale cross-stratification elsewhere.

The succeeding BUNTER PEBBLE BEDS were laid down on a considerably eroded surface of Lower Mottled Sandstone (see PLATE 4B), which, in places, shows evidence of fluviatile action.

A. AREA 3 :
Large-scale cross-bedding in LOWER MOTTLED SANDSTONE at High Rock near Bridgnorth, Shropshire

PLATE 3

B. AREA 3 :
Smaller scale cross-bedding in LOWER MOTTLED SANDSTONE at Kinver Edge, Worcs



The Pebble Beds comprise pale grey, calcite cemented, basal breccias (PLATE 4A) overlain by brownish red, coarse grained, weakly cemented sandstones which are pebbly in places. The breccias are lenticular in form, and may show rapid lateral variation in grain size. Some thin bands of red marl occur locally. The Pebble Beds are thought at the present time to be wholly of fluviatile origin, transported and deposition by flood waters from desert rain storms in basins resembling present-day wadis. The Pebble Beds present special problems of groundwater flow which will be referred to in a later chapter.

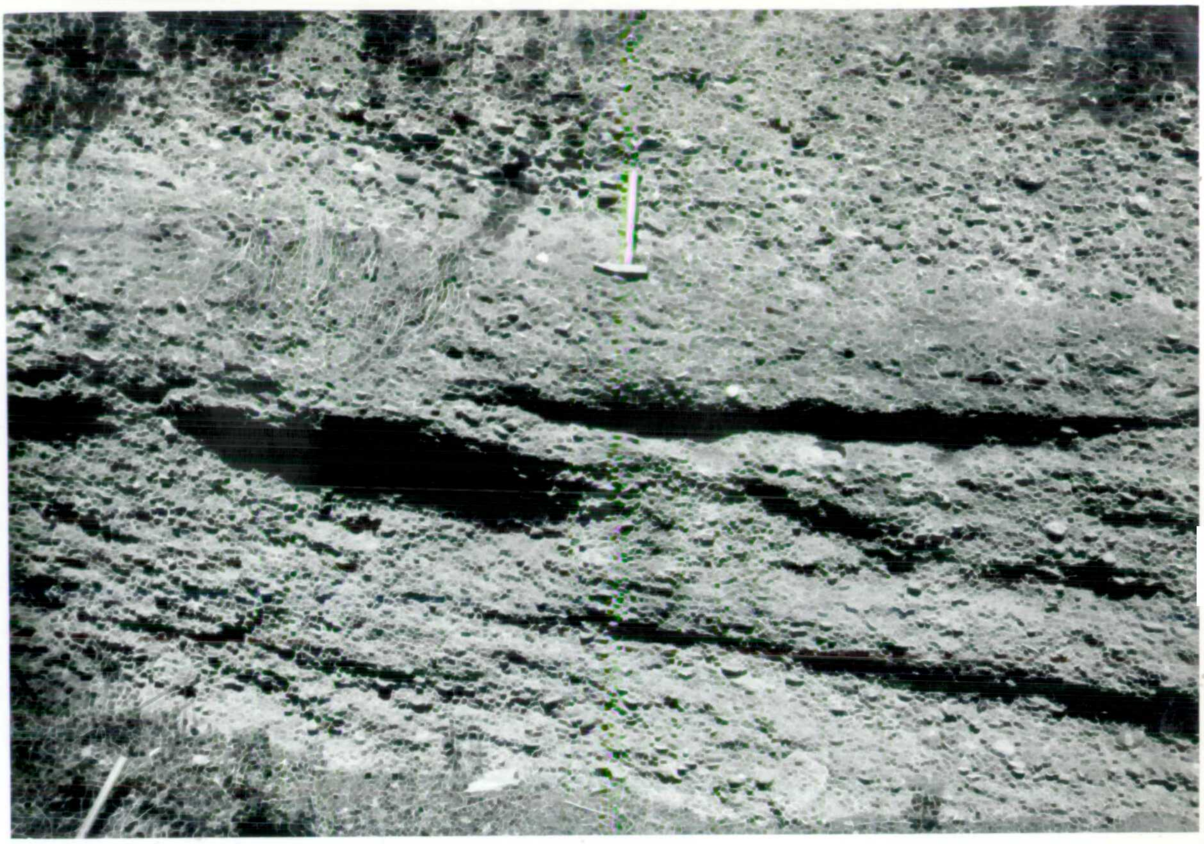
Above the Pebble Beds, a second thick sandstone occurs, the UPPER MOTTLED SANDSTONE, which is not preserved in the Bridgnorth area, but crops out further east, especially in the vicinity of Wolverhampton where the thickness may reach 305 m (1000 ft.) locally. This unit comprises bright red, fine grained laminated sandstones, weakly crossbedded with low-angled laminae. It is pebble free and shows frequent streaks or blotches of yellow or green, in the same manner as the Lower Mottled Sandstone. The patches have been shown to contain iron in the reduced or ferrous state (Fe^{++}) (Travis and Greenwood, 1911 and 1915), but they, rather surprisingly, bear no relation to the stratification, nor appear to be controlled by local permeability. The grains are well rounded and highly sorted, though not to the same degree as the Lower Mottled Sandstone.

In this district, the sandstone appears to be conformable to the Bunter Pebble Beds. Owing to the lower angle of cross-bed dips (seldom greater than 12-15°), the formation is thought to be of shallow water fluviatile origin.

Towards the top of the Upper Mottled Sandstone, occur some 12 m (30-40 ft.) of transition beds, bands of sandy marl with interbedded sandstones containing 'millet' seed grains and of a calcareous nature. The millet seed sandstones eventually disappear completely as the base of the LOWER KEUPER SANDSTONE is reached. In the Bridgnorth-Wolverhampton area this sandstone consists of buff to brownish, coarse grained, friable sandstones, quite commonly calcareous. They may be conglomeratic in this lower part and contain numerous marl flakes which break up and drop out of the rock on exposure, leaving a highly distinctive appearance described as 'catbrain' structure. White sandstones with intervening red marls are common towards the top. Cross-stratification is widespread, sometimes in units up to 3-6 m (10-20 ft.) thick.

A sharp junction occurs at the top of the sandstone with the overlying Keuper Marl; these red flaggy siltstones and mudstones, which become entirely dolomitic in the upper part, follow the sandstone conformably and complete the Permo-Triassic sequence in this district.

The thickness variation of the unit is shown in fig.3. An important feature is the easterly attenuation of the Lower Mottled Sandstone as the western boundary fault of the



A. AREA 3 : The cemented facies of the BUNTER PEBBLE BEDS seen near Bridgnorth, Shropshire.

PLATE 4

B. AREA 3 : BUNTER PEBBLE BEDS resting unconformably on LOWER MOTTLED SANDSTONE at Rindleford, near Bridgnorth, Shropshire.

South Staffordshire Coalfield is reached. This unit is not present to the east of the coalfield, but the Barr Beacon Beds and other similar breccias which occur at the base of the Bunter Pebble Beds may be lateral equivalents of the Lower Mottled Sandstone.

2.5. AREA 4: MID-CHESHIRE AND SHROPSHIRE (fig.5)

In many respects, the Permo-Triassic sandstone succession in this area can be considered to be transitional in facies between the classic tripartite Bunter formation of the Severn Valley (Area 3), and the much thicker but more consolidated succession of north Cheshire and south Lancashire (Area 5).

The major elements of the sandstone series are well represented, but each is subject to particular variations in facies and thickness. The basal LOWER MOTTLED SANDSTONE rests everywhere unconformably on late-Carboniferous rocks. As it is followed towards the north, the large scale dune-bedding tends to be less prevalent, the formation becoming a cross-stratified sandstone - mudstone sequence with millet seed grains segregated on the interbed surfaces. Commonly, the bedding is comparatively thin in units only a few centimetres thick.

The total thickness of the sandstone is subject to great variation.

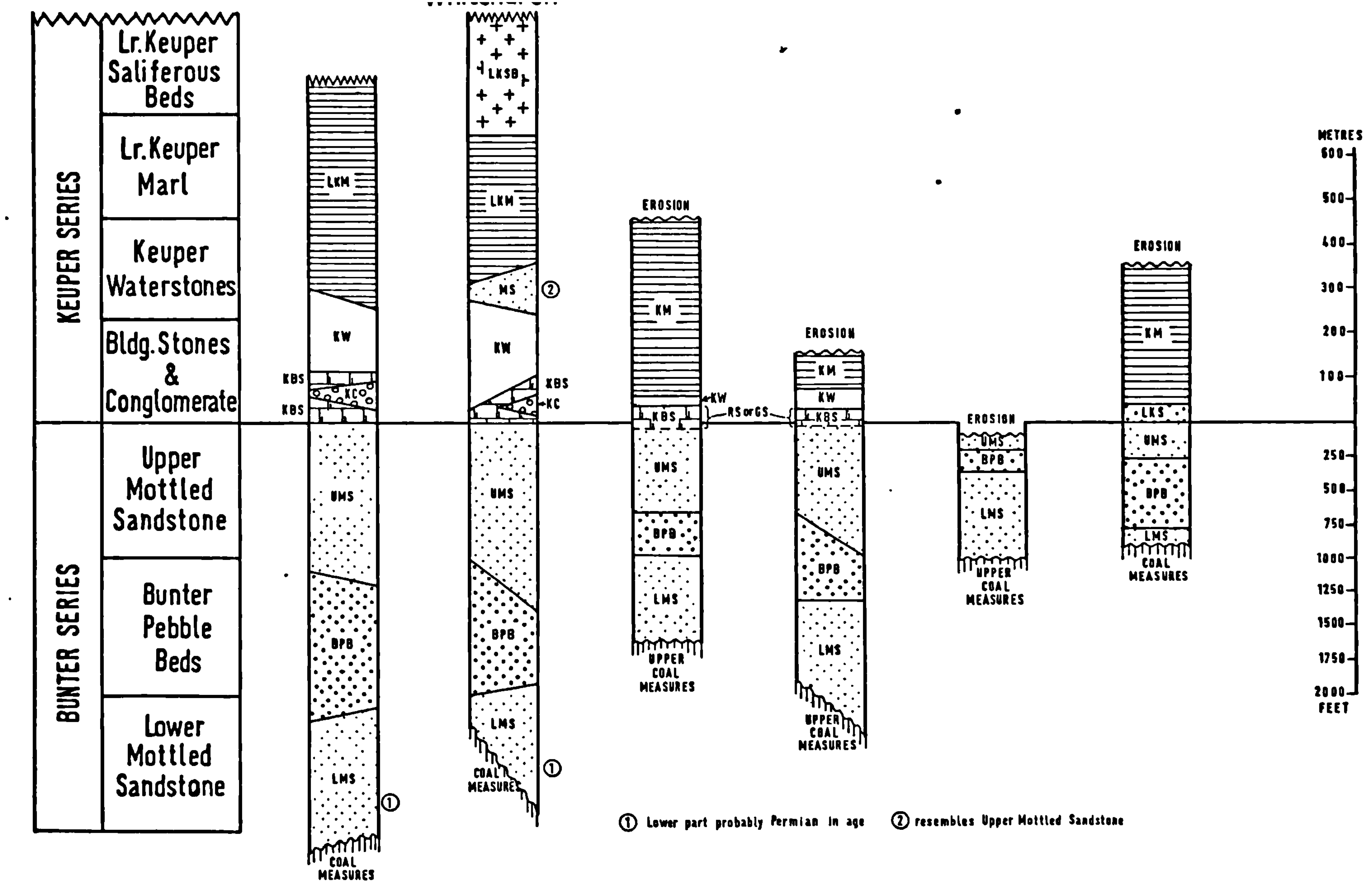


Fig.5 Representative sections through Permo-Triassic rocks : AREA 4 - Mid-Cheshire & Shropshire

According to Hull (1869) and Pocock and Wray (1925) it is completely absent between Market Drayton and Whitmore (Salop) where the overlying Bunter Pebble Beds overlap it to rest on the Keele Beds directly. It is also absent east of Stafford in the Stone area where it is difficult to prove whether it was ever present.

Fig.5 indicates that it shows a tendency to thicken towards the north from Newport to Chester and Nantwich. Current views consider that the lower part of the sandstone is quite probably of Permian age, since it can be traced laterally into sandstones, lithologically identical and continuous with the Collyhurst Sandstone of the Manchester area (Poole and Whiteman, 1966).

The succeeding BUNTER PEBBLE BEDS which in places rest with slight unconformity on the Lower Mottled Sandstone, exhibit great lithological variation, and reference to fig.5 again shows that the thickness tends to increase northwards. In general, the conglomerate and coarse sandstone sequence of the Severn Valley continues into this area. However, the formation consists of shingle beds only on the high ground to the east of Stafford, and in the Market Drayton area. In both districts, the calcareous cement so characteristic of the Bridgnorth district is absent and the conglomerate is usually poorly consolidated. Elsewhere, a more common lithology is displayed, coarse cross stratified reddish brown sand tones, with pebbles interspersed throughout in variable quantities.

Towards the north, the term "Pebble Beds" becomes more and more of a misnomer as beds of massed shingle and even thinly scattered pebbles may be apparently completely lacking. In the Nantwich area, Poole and Whitman (1966) have described rhythmic bedding in the middle Bunter. A typical cycle commences with a coarse pebble conglomerate which passes up into sandstones without pebbles; the grain size continues to decrease upwards until the uppermost bed of the cycle consists of a red mudstone, which is overlain by the basal conglomerate of the next cycle. The conglomerates are commonly lenticular and suggest strong current action during deposition. It is the gradual appearance of mudstone in the Pebble Beds which so clearly distinguishes this area from the other Midland outcrops.

The UPPER MOTTLED SANDSTONE reaches its greatest known thickness of about 430 m (1400 ft.) in the Tarporley area (Hains and Horton, 1969) in the middle of the Cheshire Basin. The formation thickens steadily towards this basin, and is consequently thinnest in the extreme south in the Shrewsbury-Newport district (see fig.5). It is conformable to the Pebble Beds and relatively uniform in lithology, resembling in many respects the Lower Mottled Sandstone, but some local facies changes occur in West Shropshire. Here, the upper beds of the Upper Mottled Sandstone and the lowest beds of the Keuper coalesce into a single unit, termed the Ruyton or Grinshill Sandstone (see PLATE 5A), which has long been used as a building material.

A. Massively bedded Grinshill Sandstone, seen at Grinshill, near Clive, Salop

PLATE 5

B. A typical exposure of the Bunter Pebble Beds in Nottinghamshire, at Ricketts Lane Blidworth.

According to Pocock and Wray (1925) the Keuper and Bunter boundary must be within the Ruyton or Grinshill Sandstone, although in the absence of any faunal evidence, it is difficult to see why the base of the Keuper should not be put at the base of this local unit. From a hydrogeological point of view, the Ruyton or Grinshill Sandstone would appear to have relatively uniform physical properties and should be considered as a separate entity.

The Upper Mottled Sandstone is absent to the east of Stafford where lowest Keuper rocks rest directly on the Pebble Beds. Near Malpas, some local barytes cementation is developed, and in places over the whole area silicified joints have been observed. The influence of these on ground water movement through the sandstone will be examined in a later section.

The detailed stratigraphy of the succeeding KEUPER beds is complex, since both vertical and horizontal changes in facies occur rapidly in the area. The relatively uniform Lower Keuper Sandstone unit of the West Midlands appears to split as it is traced northwards into three sub-divisions which can be broadly recognised over wide areas although they are not necessarily developed at the same level in different places.

The basic tripartite division is:

i) Keuper Waterstones

ii) Keuper Building Stones

iii) Keuper Basement Beds (with Keuper Conglomerate)

It is not considered appropriate here to go into the detailed stratigraphy of this sequence of beds which, at the most, comprise only about 30% of the total thickness of Permo-Triassic sandstones in the area, and of which the upper third, the Waterstones, comprise in the main, red mudstones, siltstones and thin bedded sandstones of very low intergranular permeability and low storage capacity. Fig.5 summarises the chief facies changes of these beds, together with the thickness variation.

The BASEMENT BEDS comprise reddish-brown conglomerates and local breccias passing up into fine to coarse grained sandstones with minor bands of red or green mudstone. The conglomerate horizon is almost certainly a horizon of minor unconformity as it overlaps other basal Keuper Beds in places. The Basement Beds appear to be absent in the west Shropshire area referred to above (Pocock and Wray, 1925) and east of Stafford where the lowest Keuper beds are cross stratified medium to coarse sandstones of a striking pale brown or yellow colour (Stone area).

The BUILDING STONES comprise the upper part of the Ruyton and Grinshill Sandstone, already referred to.

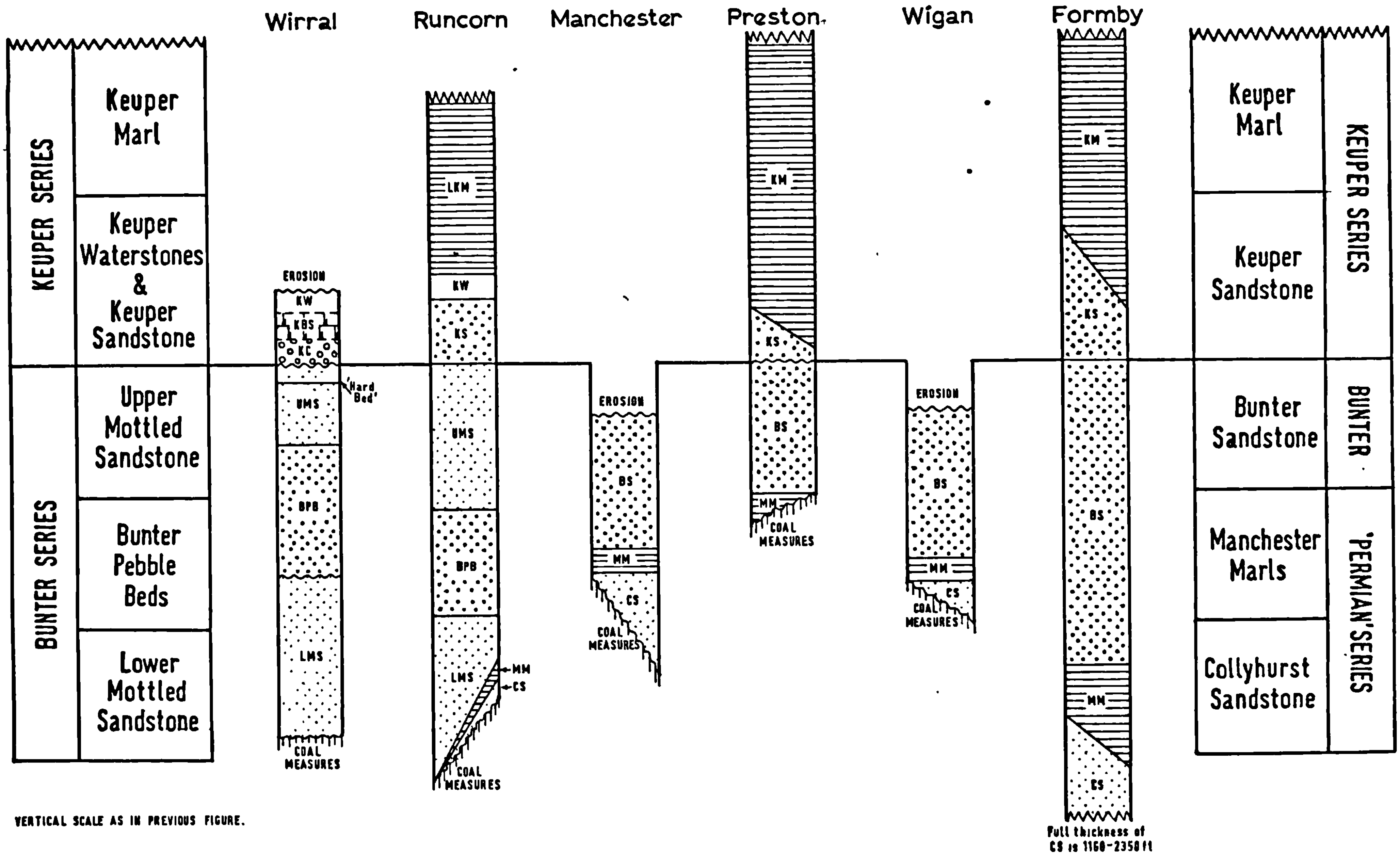
Elsewhere, they consist of the uniform yellow, white or brown freestones with shale partings, which intervene between the Basement Beds and the Waterstones.

This very thick sequence of water bearing rocks ends with the appearance of the WATERSTONES, which are in reality passage beds between Keuper Sandstone (sensu lato) and Keuper Marl. They are most extensively developed in Cheshire, where yet another sandstone intervenes between the top of the Waterstones and the overlying Keuper Marl (Malpas Sandstone). In general, however, the Waterstones mark the end of the long period of sand deposition in the Midland area, and everywhere else they pass gradually upwards into KEUPER MARL.

2.6. AREA 5: NORTH CHESHIRE, MERSEYSIDE AND SOUTH LANCASHIRE (fig.6).

In this area, the facies changes which have been already noted in Shropshire, continue to develop, and towards the north there is evidence of even further facies transition. Fig.6 shows the sequences at six localities in this area, and it indicates that only in the Wirral and Runcorn district can the tripartite division of the Bunter be observed. Elsewhere, the subdivisions merge into a single indivisible unit of Bunter Sandstone, underlain by the characteristic Permian sequence of the Manchester area.

This sequence begins with the COLLYHURST SANDSTONE; a deep red, soft sandstone with numerous millet seed sand grains, from which no pebbles or conglomerates have been recorded.



VERTICAL SCALE AS IN PREVIOUS FIGURE.

Fig 6 Representative sections through Permo-Triassic rocks : AREA 5 - N.Cheshire, Merseyside & S.Lancashire

It resembles very closely parts of the Lower Mottled Sandstone and the Penrith Sandstone. Like the former, it is subject to very rapid local thickness variation, formerly attributed in the Manchester area to fault control during sedimentation (Jones et al, 1938), but more probably due to natural geographic variation in the quantity of sediment available for deposition (Poole and Whiteman, 1955). The formation thins appreciably towards the south east flank of the Lancashire Coalfield, but it has been proved underground in deep boreholes in the Formby area, where its thickness is considerably greater than anywhere else. (Wray and Cope, 1948). In these wells drilled by British Petroleum (Kent, 1948), the formation comprises medium to coarse grained, grey, white to brown friable sandstone with conspicuous millet seed grains. The unit appears to thicken west and south-westwards towards the Irish Sea.

The MANCHESTER MARLS, which overlie the Collyhurst Sandstone, are demonstrably of Permian age, and consist of a few hundred feet of red, fossiliferous mudstones with thin interbedded limestones and siltstones. The marls overlap the Collyhurst sandstone in the Preston area (Price et al, 1963). Fig.6 shows their thickness variation, and indicates the considerable development in the Formby area where they have been proved underground.

They disappear altogether west of Runcorn where the Collyhurst Sandstone merges with the Lower Mottled Sandstone, and it is widely thought that probably the lower part of the Lower Mottled Sandstone over much of north Cheshire is of Permian age, and is laterally equivalent to the Collyhurst Sandstone of the Manchester area, which it very closely resembles.

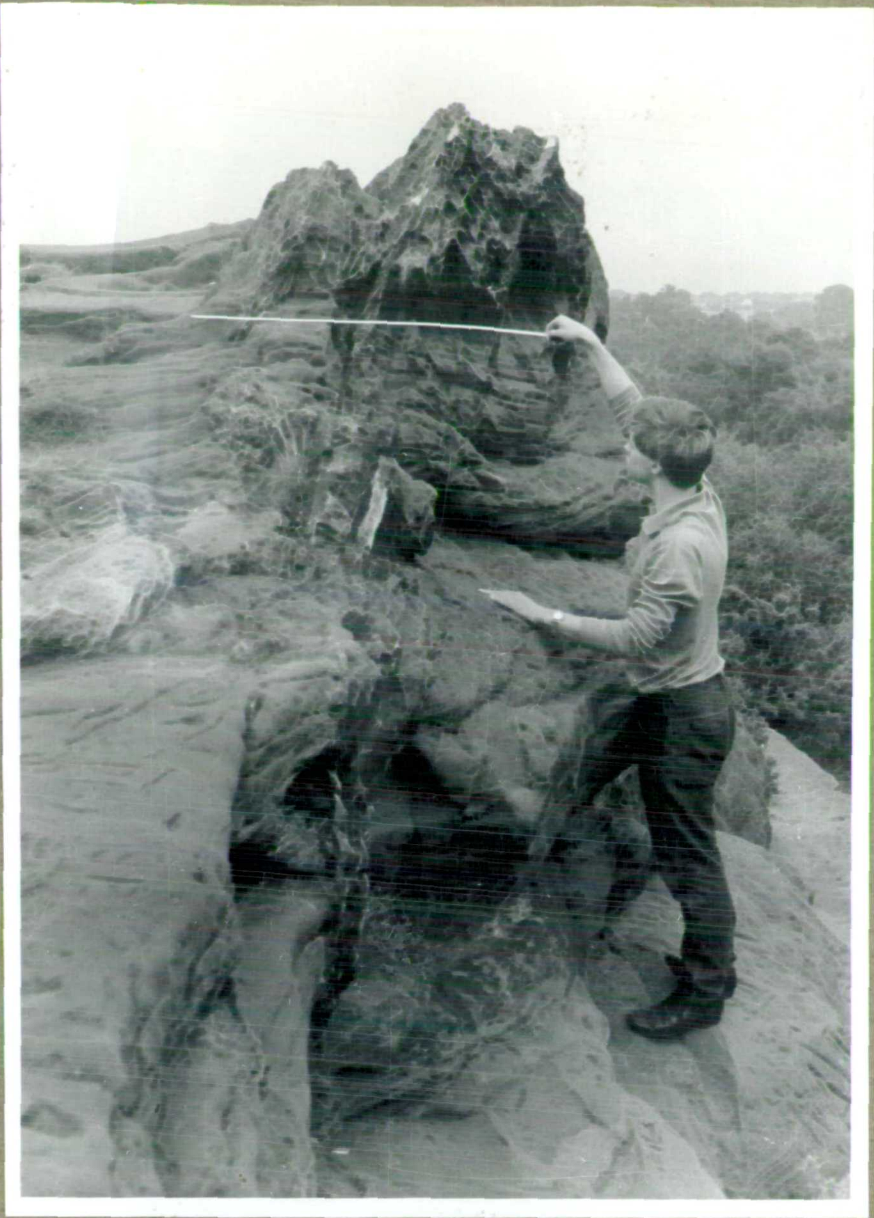
In the west of the area, the LOWER MOTTLED SANDSTONE forms the basal unit of the sequence, and rests unconformably on the Coal Measures. It comprises interstratified fine and coarse cross-stratified beds of red, yellow or white sandstone, free of pebbles, with many millet seed grains. In places, it appears to infill hollows in the pre-Triassic floor (Wedd et al, 1923).

The succeeding BUNTER PEBBLE BEDS in places appear to rest on the sandstone conformably (Hull, 1869); elsewhere they are either unconformable or overlap and rest directly on Coal Measures or older rocks. This is the case at Cheadle, Leek and parts of the Stoke-on-Trent district, where coarse, soft pebbly sandstones and conglomerates with a basal breccia are developed. Away from these marginal areas, however, the grain size of these beds steadily diminishes; near Chester they are coarse brownish red sandstones, streaked yellow in places with scattered pebbles, but in the Wirral, the pebbles are seldom abundant and are chiefly restricted to the harder beds.

At Liverpool, they comprise reddish-brown sandstones of very variable hardness and texture, sometimes totally lacking in pebbles. Hard greenish or reddish siltstone beds may also be present, and the whole unit displays large scale lenticular bedding with well developed joints. This facies is in striking contrast to the scarcely coherent shingle beds of Stoke, Cheadle and Leek.

Above the Pebble Beds, the UPPER MOTTLED SANDSTONE is strongly developed in the Wirral and west Lancashire where it reaches a considerable thickness. Characteristically fine grained, it possesses a variable cementation, and often shows a thinly bedded flaggy structure, superimposed on cross-stratification (PLATE 6A). It is generally red or yellow in colour, but hard white or greyish siliceous veins are locally present in the Wirral (PLATE 6B), trending east-west, and these may be of considerably hydrogeological significance (see p.163).

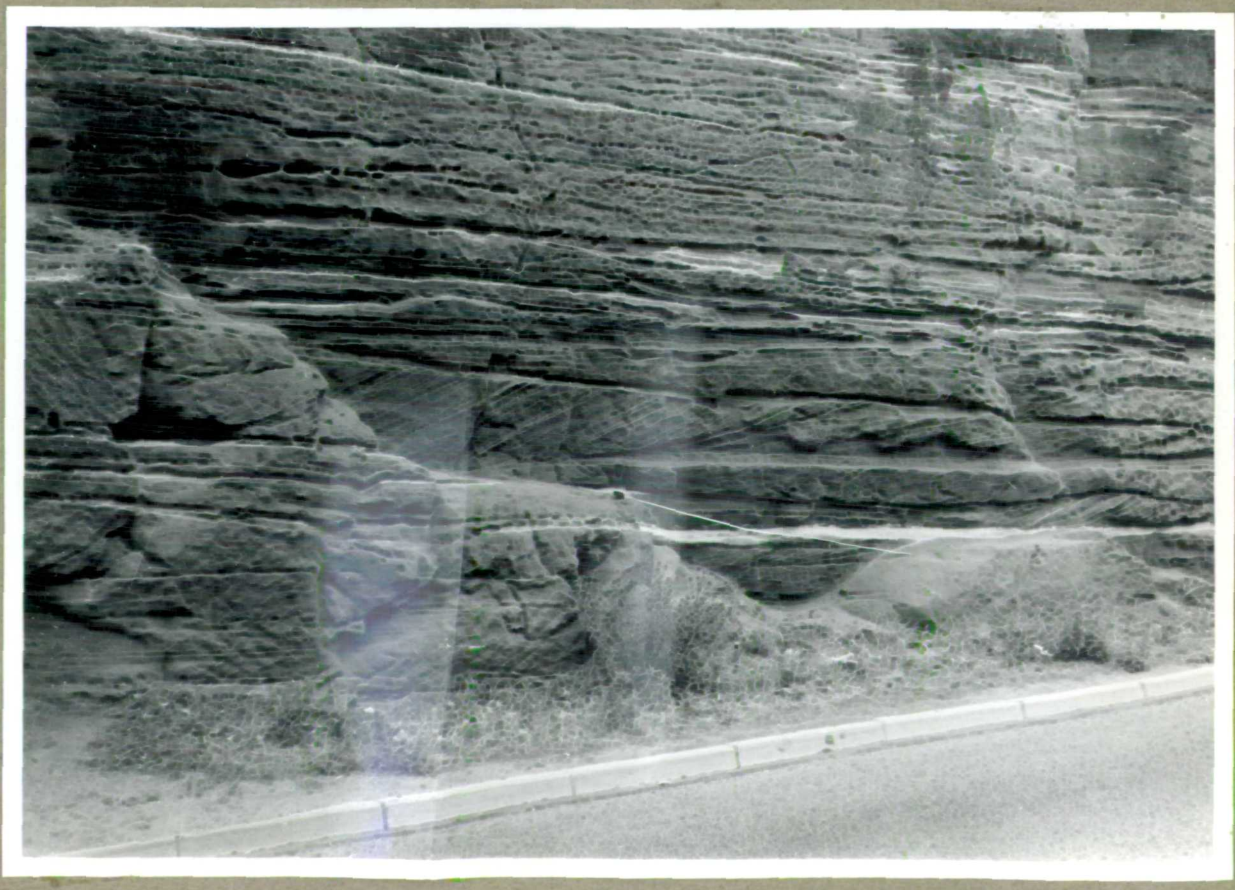
To the east and north of Liverpool, the Bunter beds merge into a single unit, the undifferentiated Bunter Sandstone of south Lancashire. In places, for example, Formby, the top and bottom of this unit may be characteristically fine grained, but clear junctions with the coarser middle interval are virtually impossible to define and subdivision cannot be attempted.



A. AREA 5 : UPPER MOTTLED SANDSTONE seen at Thurstaston Hill, Wirral, Cheshire

PLATE 6

B. AREA 5 : High-angle silicified fracture zone in the UPPER MOTTLED SANDSTONE at Thurstaston Hill, Wirral, Cheshire



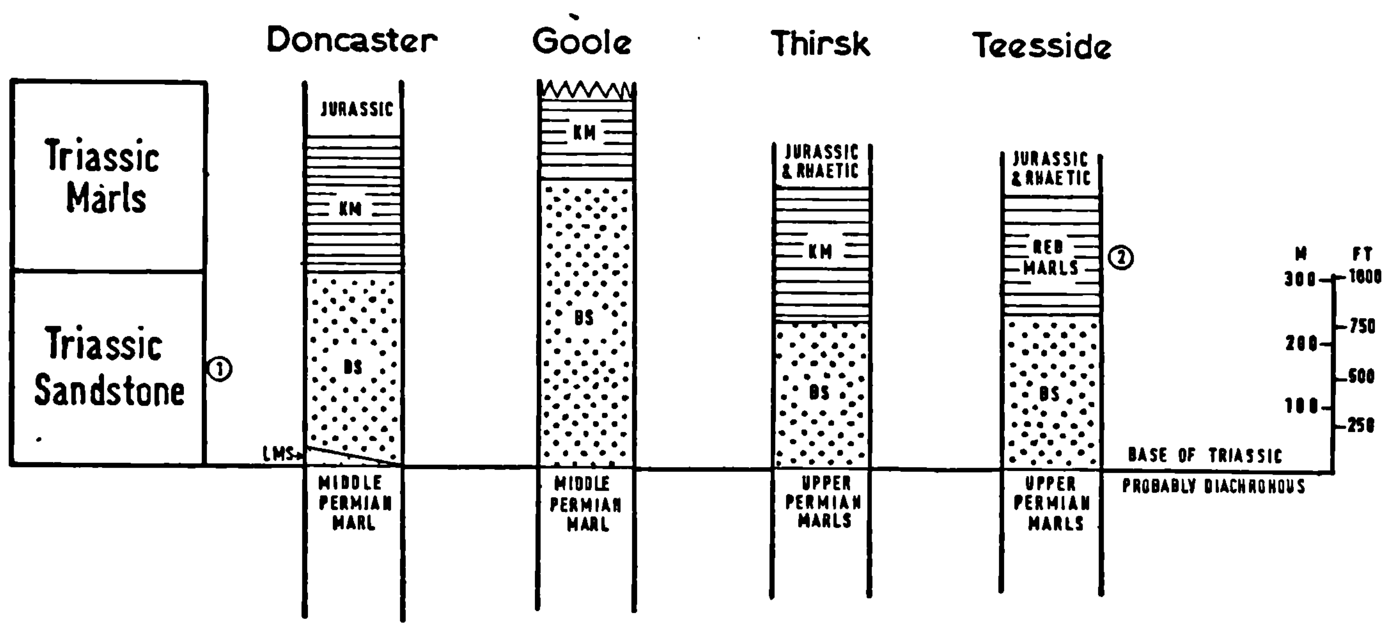
On the flanks of the Lancashire Coalfield, the Bunter typically comprises well bedded red or yellow, fine to coarse- grained soft sandstone with, for the first time, thick beds of red mudstone occurring at intervals in the sequence. Pebbles are generally very rare and in the Preston area, the sandstone tends to be medium to fine grained.

The KEUPER BEDS are strongly represented in the Merseyside area where the three-fold division of the Cheshire sequence into Basement Beds (with conglomerate) Building Stones and Waterstones, can be generally applied. The BASEMENT BEDS are clearly transgressive at Liverpool and Ormskirk where a basal conglomerate is seen to rest on an eroded Bunter surface. The conglomerate passes upwards into coarse, hard yellow or pink sandstones with marl pellets and quartz pebbles (similar to the 'catbrain' lithology of the West Midlands). Above, the BUILDING STONES are distinct in the Wirral, consisting of white, yellow and red freestone with occasional bands of red and grey marl. Further east on both banks of the Mersey estuary, these beds are softer and generally resemble the Upper Mottled Sandstone; here they are given the local name "Frodsham Beds". At the top of this unit there is the usual abrupt change of grain size as the WATERSTONES appear, which comprise thin bedded compact brownish sandstones, siltstones and shales which are often ripple-marked.

To the east of Warrington, all the Keuper beds have been removed by erosion, and the Bunter sandstone is the highest Triassic unit present. To the north of Liverpool, around the north-western fringe of the Lancashire Coalfield, a thick Keuper sequence of sandstone and marl is preserved. There is, however, a tendency for the sandstone to thin northwards and be replaced by Keuper Marl (compare the Formby and Preston sequences in fig.6). At Formby, the Keuper Sandstone contains hydrocarbons but is otherwise very similar to the Liverpool sequence. Finally, north of Preston, the Keuper sandstone is completely replaced by the red mudstones of the Keuper Marl and does not appear again in the sequence to the north, except in Northern Ireland.

2.7. AREA 6: YORKSHIRE AND DURHAM (fig.7)

The sequence of beds already described in Area 2 (South Derbyshire and Nottinghamshire) continues with minor but progressive changes in lithology as it is traced up the east side of the Pennines through Yorkshire. Eventually, the broad outcrop of the Permo-Trias turns to the north-east and reaches the coast between Tees-side and West Hartlepool. To the east, it has been proved to be present at a number of locations in deep boreholes, and in recent years has also been encountered in offshore exploration wells for hydrocarbons (Kent, 1967).



① Partly equivalent to Bunter and probably also partly equivalent to Keuper Sandstone
② Includes rock-salt

Fig.7 Representative sections through Permo-Triassic rocks : AREA 6 - Yorkshire & Durham

Fig.7 indicates four sections through the sandstone part of the sequence at locations widely spaced along the outcrop. The principal unit of importance in this study is the BUNTER SANDSTONE, which is commonly referred to as simply 'Triassic' Sandstone in this area, because it is thought to be partly of Keuper and partly of Bunter age (Gray et al, 1969). Its base is commonly transitional with the underlying Middle or Upper Permian Marls, and no distinct break in the sequence can be recognised. Fine to medium grained red sandstones with red and grey mudstone partings form the main mass of the unit in the Yorkshire-Durham area. There is a progressive reduction in the grain size of the formation in a northward direction, and there appears to be some evidence that this takes place at the expense of the upper parts of the sequence. In the Tees-side area, fine grained sandstone is common, and the upper part of the Triassic sandstone is in reality, siltstone. Evidence from offshore wells (Kent, 1967), suggests that grain size also reduces down dip eastwards.

Extensive glacial drift deposits mantle the formation over most of the outcrop, much of which has low relief. By reason of this, surface exposures are uncommon, and cored boreholes are urgently needed to improve our knowledge of the overall nature of the sandstones, especially in the Vale of Mowbray.

Towards the top of the sequence the arenaceous beds may be pale or white in colour. The proportion of mudstone also increases rapidly and the beds become indistinguishable from Keuper Marl. The Marl is everywhere developed on the eastern side of the Triassic outcrop where it is in a position to confine groundwater in the underlying sandstones.

2.8. AREA 7: NORTH LANCASHIRE AND WEST CUMBERLAND (fig.8)

The facies changes which prevail in the south Lancashire area continue into the north of that county along the western margin of the Pennines. Fig.8 shows how the section changes as we pass into Cumberland. The complete disappearance of the Keuper Sandstone, the lateral passage of Bunter Sandstone into the rather different St.Bees Sandstone and the absence of a Permian dune-bedded formation, are the three most striking featuresof the stratigraphy of this area.

In the Fylde area, north of Preston, the sequence commences with red gypsiferous mudstones, usually referred to in borehole logs as PERMIAN MARLS. These occupy a stratigraphic position equivalent to the Manchester Marls of South Lancashire and to the St.Bees Shales of West Cumberland. In the Furness district, the lowest beds of the sequence, which rest unconformably on Carboniferous rocks, comprise brockrams, magnesian limestone and gypsum.

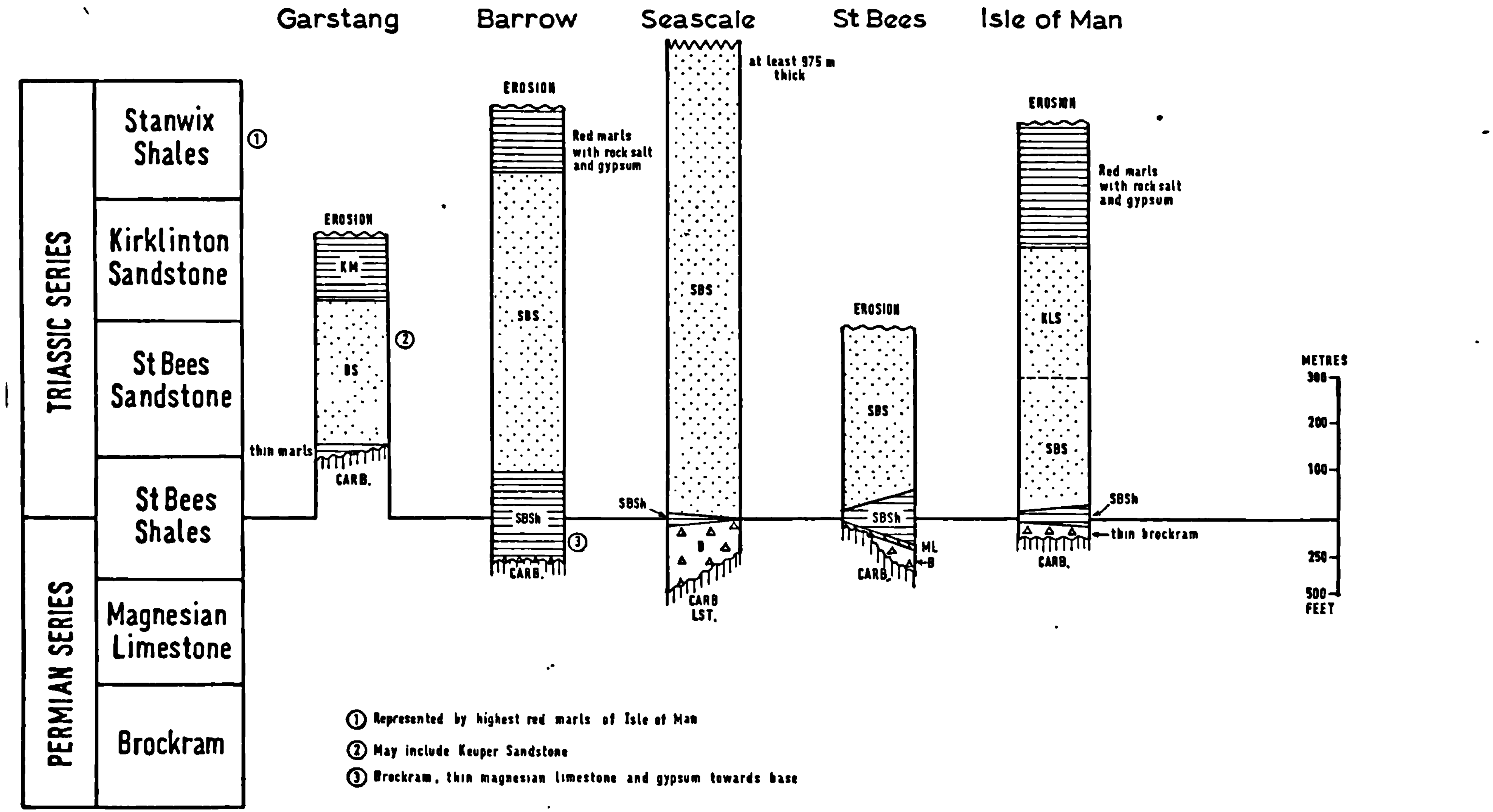


Fig.8 Representative sections through Permo-Triassic rocks : AREA 7 - N.Lancashire & W.Cumberland

The term "brockram" is used to describe even-bedded well jointed breccias generally composed, to a large extent, of angular lumps of limestone cemented in a calcareous matrix. They are common in the basal part of the Permian, in practically all districts north of Furness, including Northern Ireland (q.v.). Over most of the district, a thin MAGNESIAN LIMESTONE appears to form the base of the series (Dunham and Rose, 1941). This is overlain by a considerable thickness of St.Bees Shales which interdigitates with brockrams near the junction with the underlying Carboniferous. In south-west Cumberland, the St.Bees Shales are closely associated with two brockram horizons, and with thin inter-calated plant beds and beds of gypsum and anhydrite. In the Gosforth area, the shales are sandy in the east along the edge of the Lake District massif, and they appear to thicken seawards (Trotter et al, 1937). Near St.Bees, the shales are again associated with thin brockrams, and they appear to thicken away from the Palaeozoic massif on the east. For completeness, the Isle of Man sequence has also been inserted on fig.8., and it is a closely comparable succession of shale and brockram developed at the margin of a Lower Palaeozoic massif.

From a hydrogeological point of view, the Permian sequences in the area as a whole, are of very little significance, principally on account of the virtual absence from them of sizeable thicknesses of dune-bedded sandstones of the Penrith type.

The main Permo-Triassic aquifer of the area is undoubtedly the sandstone lying above the St.Bees Shales or Permian Marls, which is thought to be of Triassic age. This sandstone is referred to as BUNTER SANDSTONE in the Fylde area where it has been proved in a large number of trial and production boreholes for groundwater (Law, 1965). Here it comprises a relatively uniform sequence of red sandstones of coarse, medium and fine grain which have a well defined lower junction with the underlying marls . The beds may contain small pebbles over short intervals, and mudstone bands are common, generally being 15-30 cms (6 in. - 1 ft.) thick. Exceptionally, the mudstone interbeds may reach 4 m (13 ft.) in thickness. The sandstones show a variable degree of induration, which may have been induced by periglacial action.

Between the Fylde and Barrow-in-Furness, the Bunter beds pass into the ST.BEES SANDSTONE, which closely resembles the Bunter of north Lancashire, but contains a greater proportion of mudstone in the form of frequent partings. The sandstone is typically dull red in colour, of medium grain and the thinner bedded material is inclined to be micaceous. Calcareous cementation is common at depth. The red mudstone or shale partings commonly separate cross-stratified arenaceous units. Sandstones of Kirklinton aspect (see p.37), soft and yellowish in colour, may occur in the sequence towards the top.

The St.Bees Sandstone reaches a very great thickness along the western edge of the Lake District massif and appears to have been laid down in rapidly sinking, fault-controlled peripheral basins. It is over 1000 m (3200 ft.) thick at Seascale (Gregory, 1915), only a few miles from the junction with the older rocks of the Eskdale complex.

As in most other areas, with the exception of Scotland, the uppermost unit of the Permo-Trias in north Lancashire and west Cumberland, is the Keuper Marl, which differs little from that encountered elsewhere. It comprises the familiar dull red dolomitic siltstones and mudstones with associated evaporite deposits principally rock salt and anhydrite, which are worked at Preesall, and are known to be present at depth below Barrow-in-Furness. North-west of Furness, the Keuper Marl has not been preserved, and the sandstones of Kirklinton aspect form the top of the succession.

2.9. AREA 8: VALE OF EDEN, AND CARLISLE BASIN (fig.9)

In many respects, the Permo-Triassic sequence of Edenside, and in the Carlisle or Solway Basin, resembles a greatly expanded version of the west Cumberland succession already described.

An unconformity is always present at the base of the formation which rests on an irregular eroded surface of Carboniferous rocks. Basal breccias are widespread and these are usually referred to as 'brockrams' both in this district and in Northern Ireland.

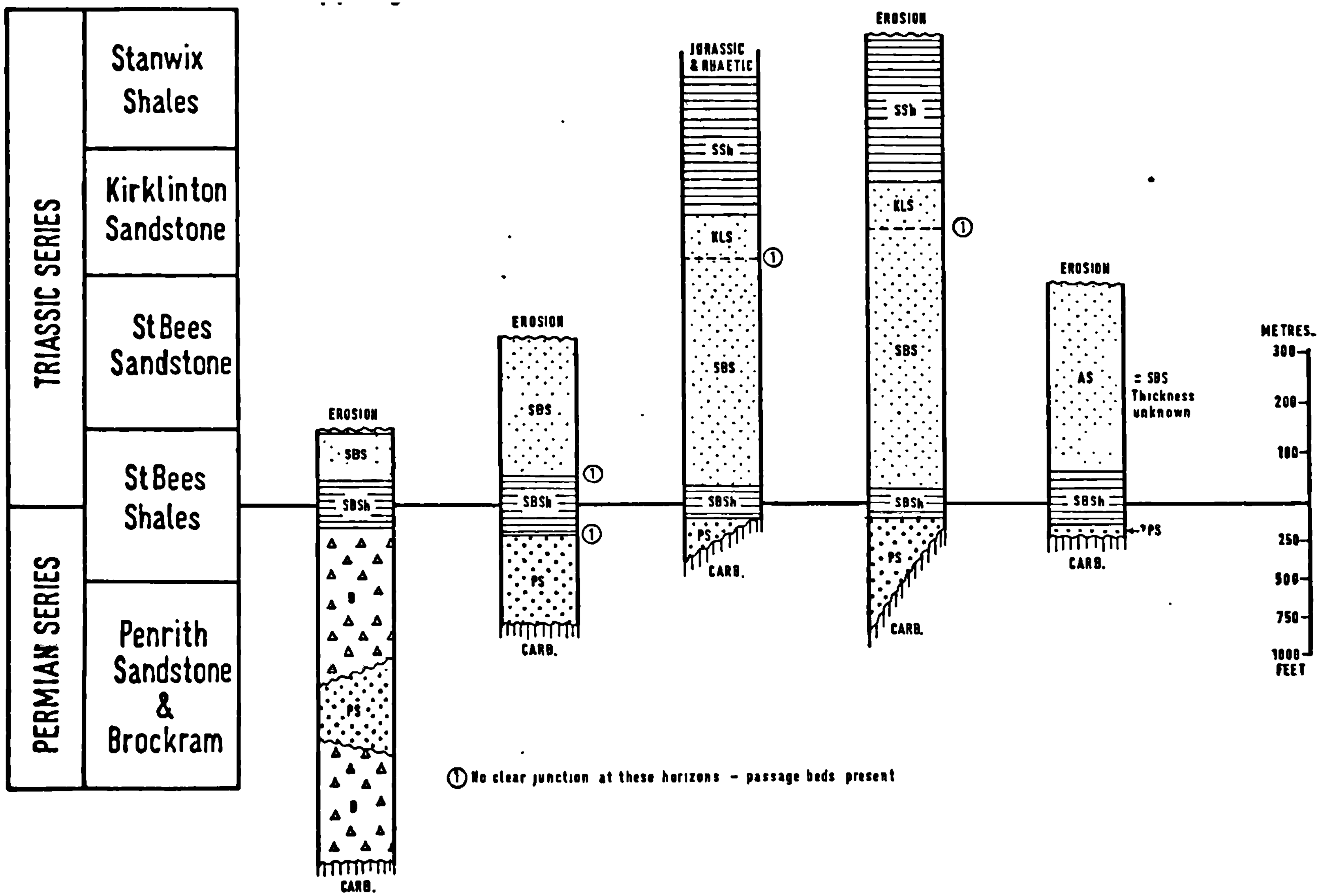


Fig.9 Representative sections through Permo-Triassic rocks : AREA 8 - Vale of Eden and Carlisle Basin

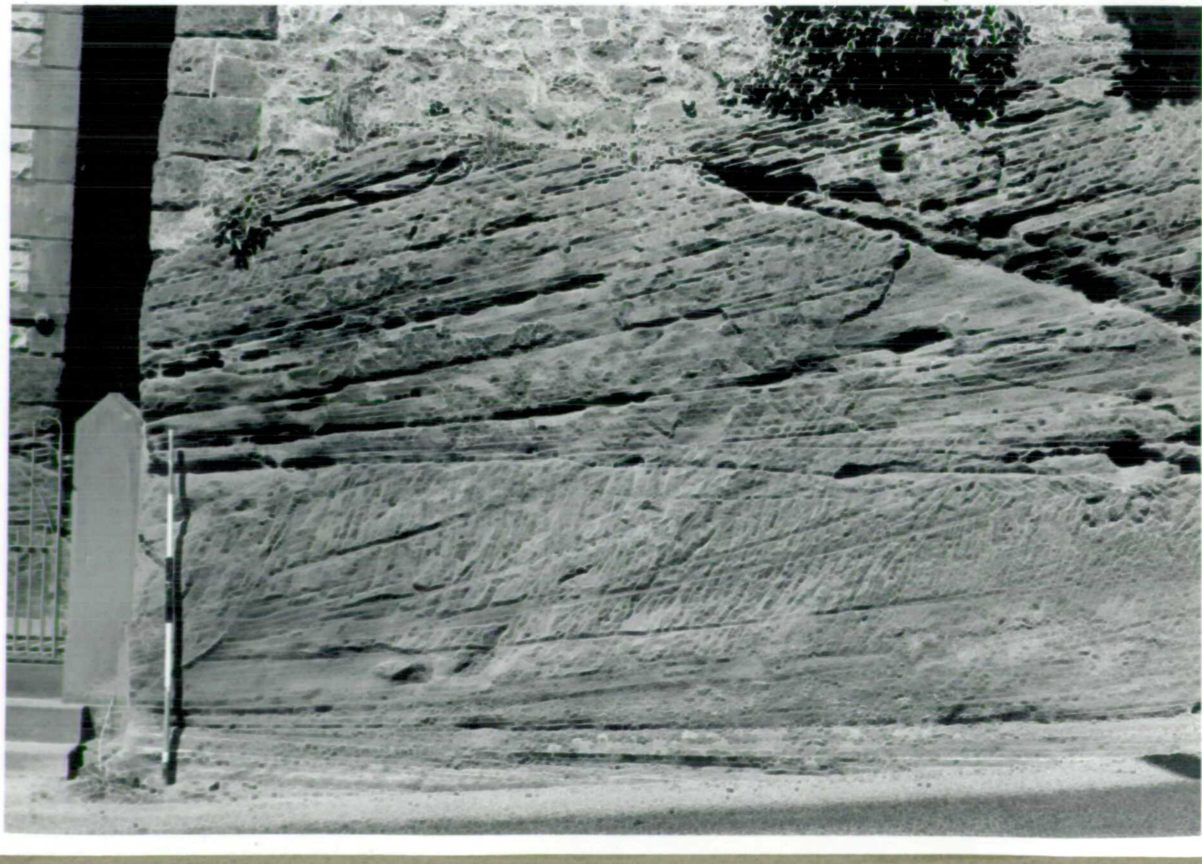
The LOWER BROCKRAM forms the lower part of the PENRITH SANDSTONE (sensu lato) and reaches its maximum development in the Appleby-Kirkby Stephen area. It typically comprises even bedded to massive, grey breccia in which 90% of the fragments are limestone (see PLATE 7A). The pieces tend to be angular in shape, usually up to 5 cms in length, embedded in calcareous cement. The beds may show massive jointing, and this appears to be the only path for groundwater movement through the formation. In the Appleby-Kirkby Stephen area, the Lower Brockram is overlain by a wedge of copper-coloured shallow water/eolian sandstone (the PENRITH SANDSTONE,sensu stricto seen in PLATE 7B), which in turn is overlain by the UPPER BROCKRAM. Both brockrams appear to die out rapidly north-westw rds; this is undoubtedly caused by lateral passage into r d sandstone of Penrith-type.

The PENRITH SANDSTONE (s.s.) first makes its appearance between the two breccias near Warcop, Westmorland. There it consists of moderately hard, thickly bedded red sandstone (PLATE 8A). No true bedding planes are generally visible owing to the presence of large scale current bedding (PLATES 8B and 9B), in the form of lenticular masses and in curved wedges which have been interpreted as dunes (Dakyns et al, 1897; Versey, 1940). Probably this sandstone was deposited in a mixed depositional environment of shallow water and eolian conditions. There are often signs of scooping and penecontemporaneous erosion.

A. AREA 8 : The lowest member of the Permo-Trias sequence on Edenside, the BROCKRAM, seen here at Burrells, near Appleby, Westmorland

PLATE 7

B. AREA 8 : PENRITH SANDSTONE in Bongate, Appleby showing large scale cross-bedding. Cf. Plate 3A



The dip of the cross beds is generally westwards in agreement with those in the Lower Mottled Sandstone of the Severn Valley, which the formation strongly resembles. Shale is noticeably absent.

Traced progressively north-westwards, the Penrith Sandstone greatly expands at the expense of the brockrams and shows much lateral variation. Between Appleby and Penrith, soft half-consolidated cross-bedded red sandstone is common, much of which consists of thinly bedded alternations of sandstone and mudstone with millet seed grains packed on the interbed surfaces, exactly as in parts of the Lower Mottled Sandstone. In the Penrith district, there is much secondary silicification (PLATE 9A), and in places the formation becomes as consolidated and well-jointed as parts of the Millstone Grit of Derbyshire. Further north-west, the silicification diminishes and in the Carlisle and Brampton area, the dominant rock type is soft, medium to coarse grained red sandstone with millet seed grains. Breccias appear near the base, but do not form a significant proportion of the total thickness in these areas. In the vicinity of the Scottish border, the Penrith Sandstone appears to be very attenuated, only 10 m (30 ft.) being present in the section on the River Esk at Canonbie, thought to be Triassic by Barrett (1942). To the west of Canonbie, it apparently dies out, owing to overlap by the St. Bees Shales which rest directly on Carboniferous.

A. AREA 8 : Section in PENRITH SANDSTONE parallel to strike of cross-stratification, Hilton Beck, near Appleby, Westmorland

PLATE 8

B. AREA 8 : Section in PENRITH SANDSTONE parallel to dip of cross-stratification, near Cliburn, Westmorland

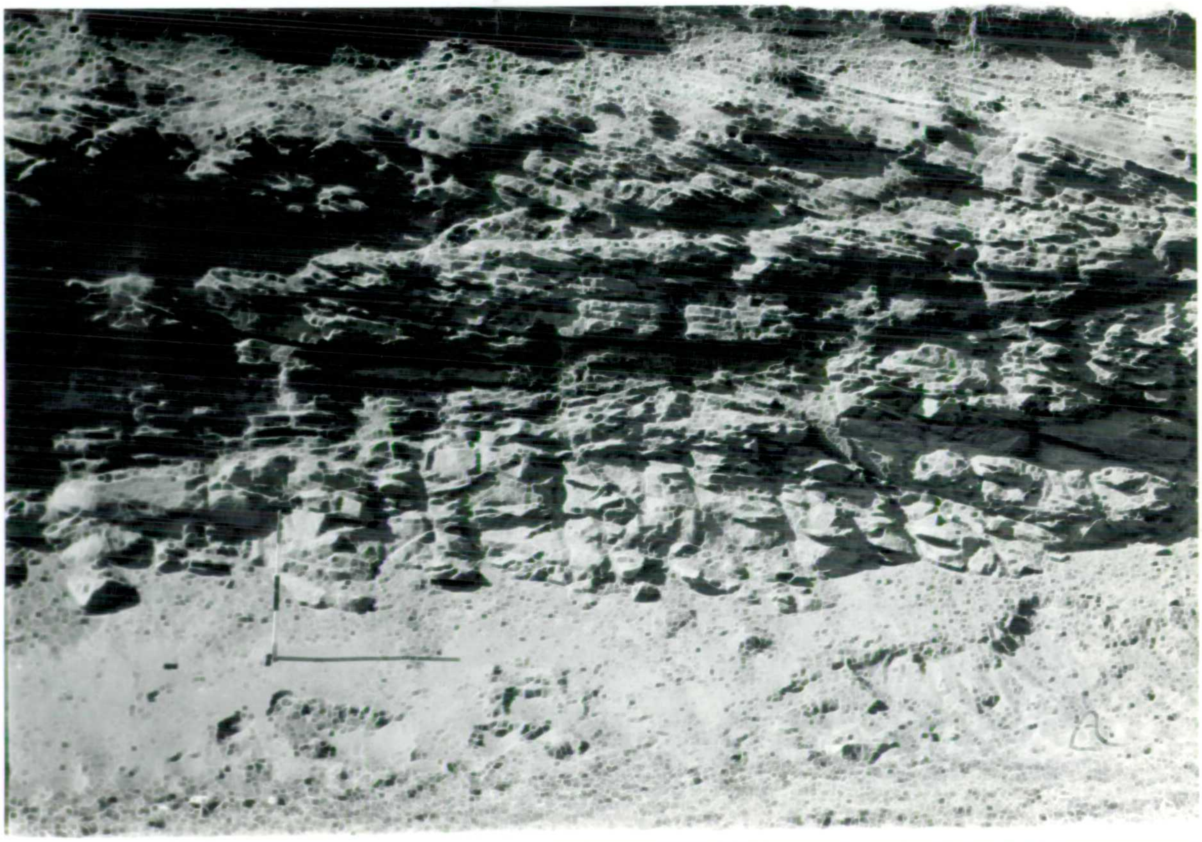
The ST.BEES SHALES, with the associated beds of rock salt, anhydrite, magnesian limestone and plant beds, form an important low permeability barrier between the underlying Penrith Sandstone and the overlying St.Bees-Kirklinton units. They are generally interpreted as passage beds between the Permian and the Trias. It would appear that boreholes drilled through the shales into the sandstone beneath are likely to encounter confined groundwater conditions on Edenside and in the Carlisle area. Fig.9 shows that the thickness of the shales with their associated beds, is fairly constant, but it should be remembered that both upper and lower boundaries are transitional. The main mass of the shales comprises dull red to chocolate coloured mudstones with gypsum and anhydrite in bands or nodules.

These mudstones become progressively more sandy and flaggy towards the top of the sequence, as the ST.BEES SANDSTONE is approached. This thick sandstone contrasts strongly with the much older Penrith Sandstone, in that it is regularly bedded, of finer and more uniform grain size, and of a slightly darker colour (PLATES 10A and 10B). The sandstone is commonly micaceous and moderately hard, but lacking secondary silicification. Cross-stratification is not uncommon, and a shallow water origin is indicated by such structures as ripple marks and rain pits.

A. AREA 8 : Silicified zone in PENRITH SANDSTONE near Edenbr-idge, Temple Sowerby, Westmorland

PLATE 9

B. AREA 8 : Marked cross bedding in a face of un-cemented PENRITH SANDSTONE at Commonholm Scar, near Cliburn, Westmorland

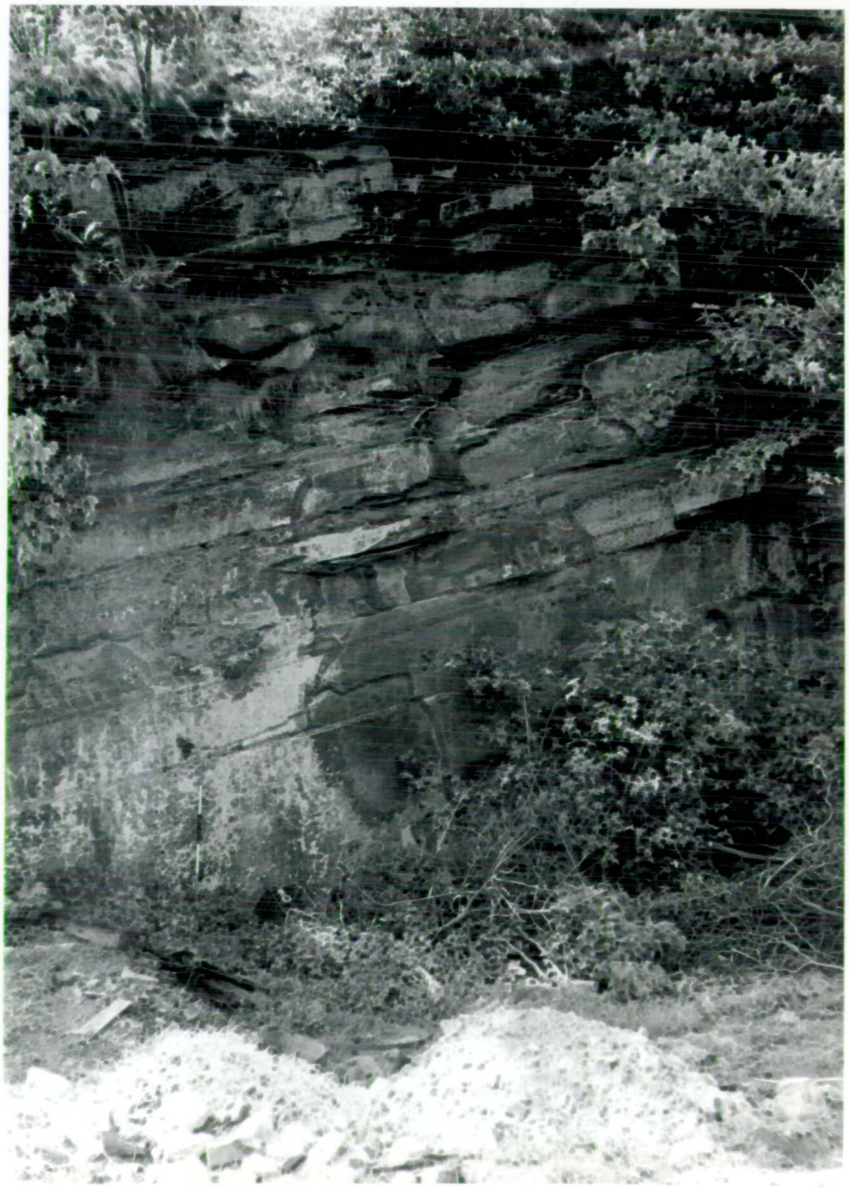


Reddish-brown shale bands occur throughout, and they maybe form 50% of the sequence near the base, decreasing to about 2% near the top (Trotter and Hollingworth, 1932). The St.Bees Sandstone is widespread throughout the area, and is represented in the South of Scotland as the Annan Sandstones of doubtful thickness (shown in PLATE 11B).

No clear junction has been recognised between the St.Bees and the closely associated KIRKLINTON SANDSTONE which overlies it. Indeed, the most realistic reading of the sequence (Trotter and Hollingworth, 1932) suggests that the transition from one unit into the next, takes place over probably 75 m (250 ft.) of strata, which can only be described as 'passage beds'. The Kirklinton Sandstone proper displays a lithology which immediately brings to mind the Upper Mottled Sandstone of the Bridgnorth area - soft, fine grained, bright red sandstone, showing low angle cross-bedding and with scattered millet seed grains (see PLATE 11A). Yellow, grey or white patches are also common, and near the top, black iron-stained layers have been noted (Dixon et al, 1926); shale is absent. The subdivision is not preserved in the Annan district. A fairly abrupt change occurs at the top of the Kirklinton beds, with the appearance of the red and green mudstones and siltstones of the STANWIX SHALES, long thought to be laterally equivalent to the Keuper Marl. These beds are not extensive, except in the central region of the Solway Basin to the west of Carlisle, where they are in a position to confine groundwater in the underlying Kirklinton and St.Bees

A. AREA 8 :
St.BEES SANDSTONE seen near Hilton village, Appleby, Westmorland

PLATE 10



B. AREA 8 :
St.BEES SANDSTONE seen at Croglin, Cumberland

2.10. AREA 9: SOUTH OF SCOTLAND (fig.10)

In this area, Permo-Triassic deposits are preserved in a number of small basins. The Triassic part of the sequence is only preserved on the Isle of Arran, and it seems doubtful whether the Trias was ever present in the other basins.

The most southerly basin, centred on Dumfries, contains a thick sequence of breccias, breccio-conglomerates and sandstones (PLATES 12A and 12B), mainly of a deep red colour resting on Upper and Lower Palaeozoic rocks. On the evidence of a gravity survey, Bott and Masson-Smith (1960) estimated the total thickness of Permian deposits to be not less than 460 m (1500 ft.). Coarse locally-derived breccias form the base of the sequence near the edges of the basin. Towards the centre, these breccias are split up by numerous massive cross-stratified sandstone beds, which show a tendency to be both coarse and indurated (shown in PLATE 13A). Certain beds resemble the silicified zone of the Penrith Sandstone, but on the whole, the resemblance between the two formations is not very close (c.f. Horne and Gregory, 1915).

Similar coarse, indurated sandstones and breccias occupy the basin centred on Lochmaben, but in this case no estimates of thickness from geophysical data are available, and the structure has not been drilled. It is probable that several hundreds of feet of Permian deposits are present, resting on Lower Palaeozoic rocks unconformably.

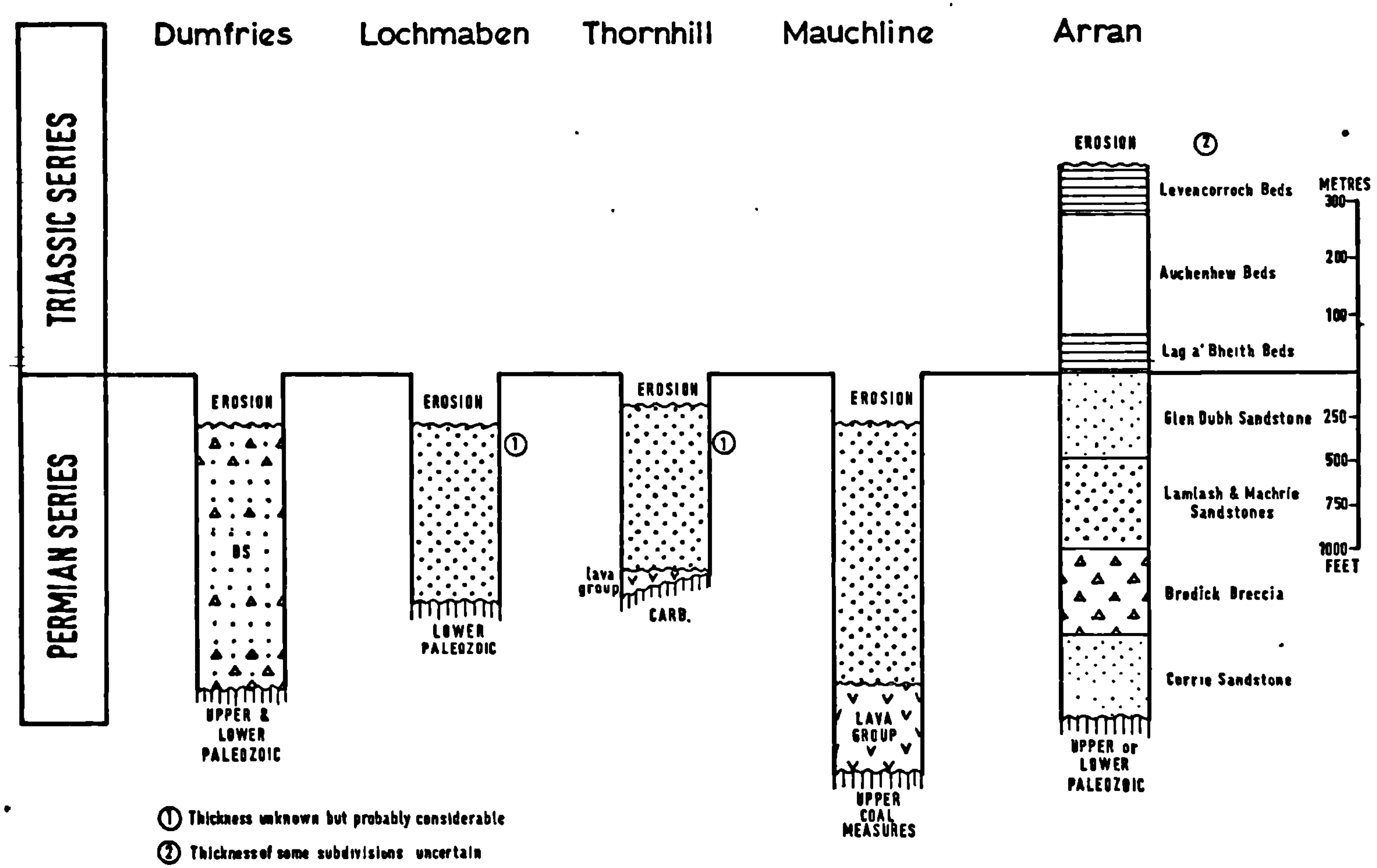
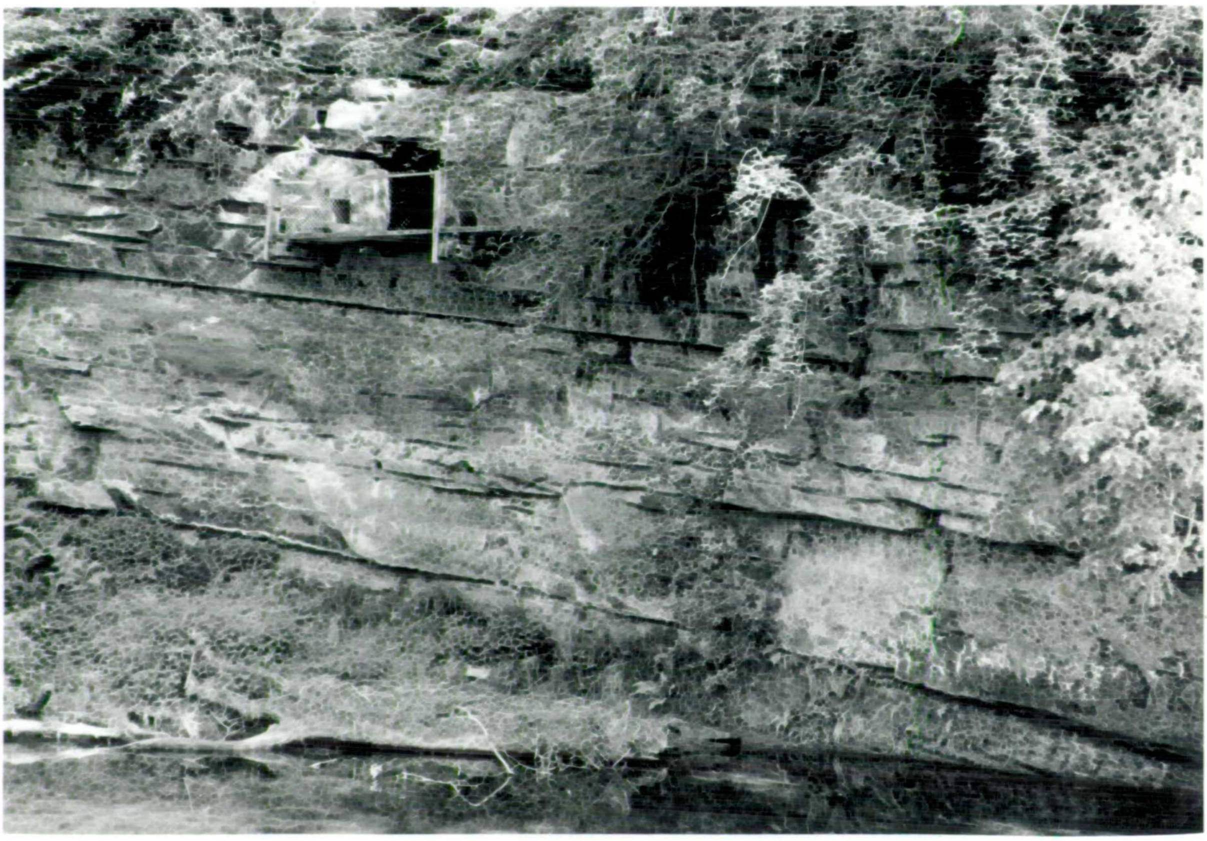


Fig.10 Representative sections through Permo-Triassic rocks : AREA 9 - South of Scotland

A. AREA 8 : KIRKLINTON SANDSTONE seen in the banks of the River Irthing, at Ruleholme Bridge, near Brampton, Cumberland.

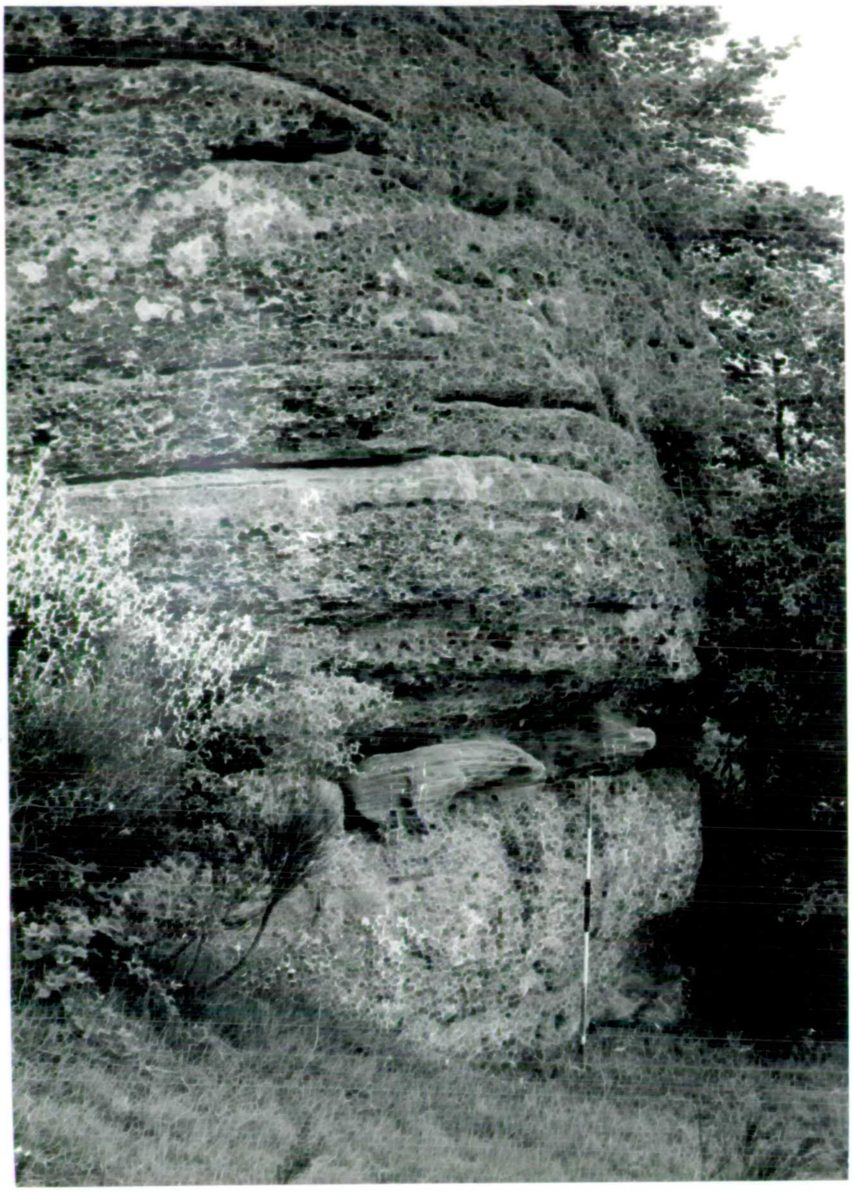
PLATE 11

B. AREA 8 : Exposure of ANNAN SANDSTONE in the banks of the Annan Water at Robert the Bruce's Cave, Kirkpatrick Fleming, Dumfriesshire



Further north, in the upper part of the Nith Valley, Permian rocks are again encountered in the Thornhill Basin, where a thin group of basalt lavas resting unconformably on Carboniferous beds, is overlain by a considerable thickness of brick-red cross-stratified sandstones. The base of the sandstone group is irregular as they appear to have been laid down on a very uneven old lava surface (Simpson and Richey, 1936). A thin breccia is frequently developed at the junction. The sandstones show evidence of having been deposited under arid conditions, e.g. perfect rounding of larger grains and the often high angles of the planes of cross-stratification. The finer grained parts of the sequence, however, tend to be horizontally bedded and mudstone bands are uncommon.

Some 50 km (30 miles) northwest of the Thornhill Basin, a large outlier of Permian rocks is preserved in a shallow syncline near Mauchline, Ayrshire. There the lava group is greatly expanded, and consists of about 150 m (500 ft.) of basalt flows with thin intercalations of tuff and red desert sandstone. Resting on this group unconformably, lies a great thickness of bright red sandstones which show cross-stratification apparently of aeolian origin, on an unusually large scale; the cosets formerly visible in the Ballochmyle quarries reach a thickness of the order of 15 m (50 ft.).



A. AREA 9 :
The breccia facies of the PERMIAN SANDSTONE of Dumfries seen at the Creags, near Dumfries

PLATE 12

B. AREA 9 :
Cores of PERMIAN SANDSTONE AND BRECCIA from the No.2 Borehole at Dumfries Factory

Still further to the west on the Isle of Arran in the Firth of Clyde, a thick Permo-Triassic sequence greatly intruded by Tertiary igneous rocks has been preserved, which is remarkable in two respects, viz., the absence of lavas of the Mauchline facies from the Permian part of the sequence, and the occurrence of a thick upper series of beds which are referred on lithological grounds to the Triassic (Gregory, 1915, Tyrrell, 1928). The Permian beds are divided into four units (Richey, 1961):

Glen Dubh Sandstone - white, yellow and pink, massive calcareous sandstone.

Lamlash and Machrie Sandstones - coarse red sandstones, slightly cross-stratified, in places thinly bedded.

Brodick Breccia - coarse quartzose breccia with thick lenticles of dune-bedded sandstone.

Corrie Sandstone - cross-stratified brick red sandstone with millet seed grains.

By contrast, the overlying Triassic beds are generally finer grained, and of more variable lithology. They commence with the Lag a'Bheith marls, cornstones and calcareous sandstones. Above comes a middle group of sandstones and shales (Auchenhew beds) and the sequence ends with the Levencorroch unit, which resembles the Lag a'Bheith beds.

Other small outliers of deposits thought to be of Permian age on lithological grounds occur in the South of Scotland, but these were considered to be insignificant in the present study. Amongst these should be mentioned the outliers in Moffatdale, near Moffat, and at Loch Ryan in Wigtonshire.

2.11. AREA 10: NORTHERN IRELAND (fig.11)

In this the final area under consideration, the Permo-Triassic sequence resembles more closely the west Cumberland succession rather than the Scottish deposits. Volcanics are absent, apart from later unrelated minor intrusions of Tertiary age, and the Keuper Sandstone reappears in the sequence, but does not reach any great thickness. As in Cumberland, the deposits appear to have accumulated in deep fault-controlled basins, bordering older Palaeozoic massifs.

The succession commences in most places with coarse Permian breccias, or BROCKRAM, resting unconformably on Carboniferous or older Palaeozoic rocks. These brockrams are very similar in lithology to their counterparts on the other side of the Irish Sea in west Cumberland, and consist of angular fragments of pre-existing Palaeozoic rocks cemented in a calcareous or gypsiferous matrix. The occurrence of the breccia beds is closely associated with culminations in the rugged pre-Permian erosion surface.

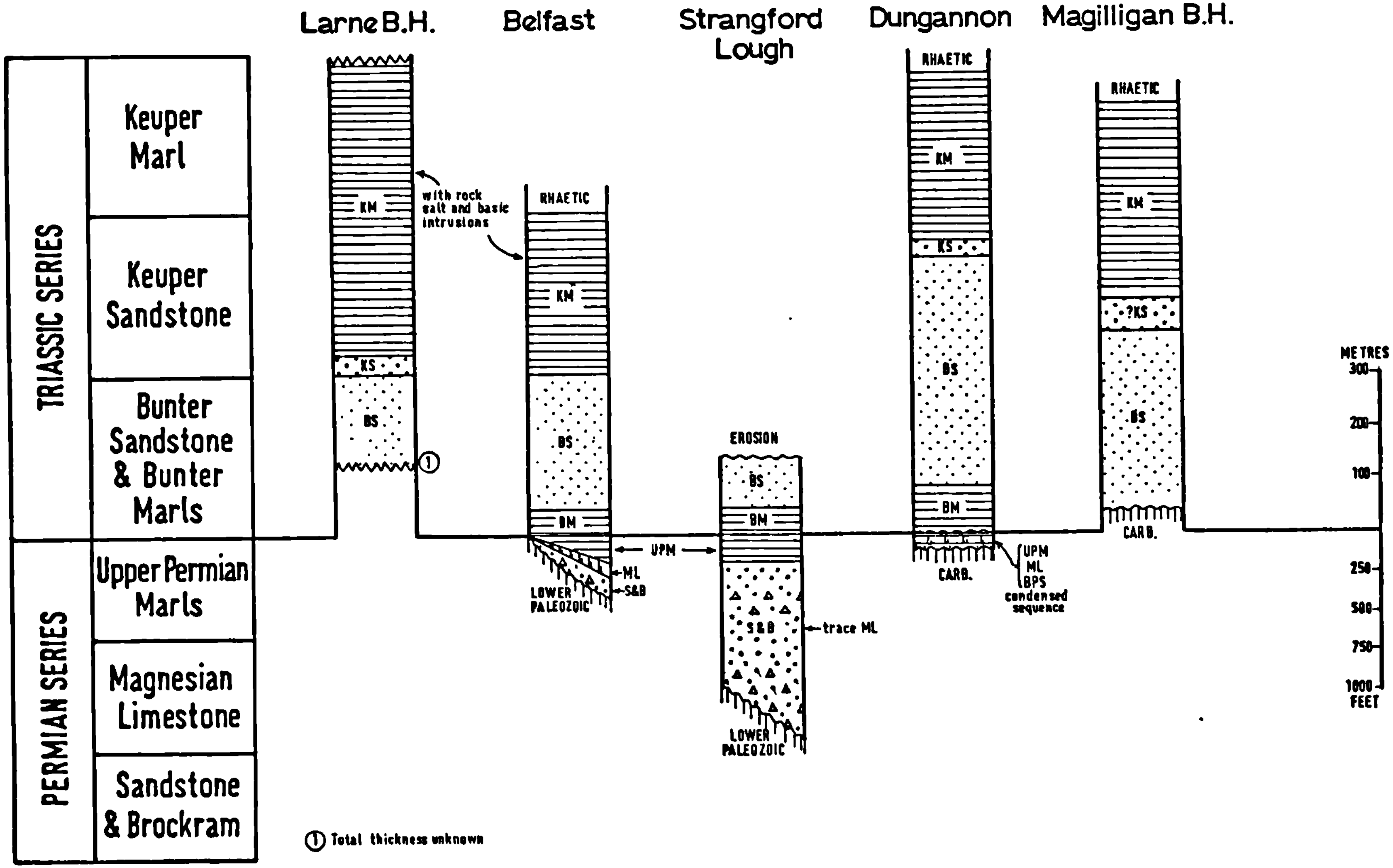


Fig.11 Representative sections through Permo-Triassic rocks : AREA 10 - Northern Ireland

A. AREA 9 : PERMIAN SANDSTONE at Knowehead Quarry, Locharbriggs, near Dumfries

PLATE 13

B. AREA 10 : BUNTER SANDSTONE seen near Ardtrea, Dungannon, Co. Tyrone, Northern Ireland

Away from these buried hills, the brockrams may be found to interdigitate with coarse friable red sandstones of Penrith type, apparently strongly cross-stratified and containing millet seed grains. These were proved to be present in the Kennel Bridge B.H. near Comber, Co.Down (J 455 700). Owing to the almost complete lack of exposures of the Permian sequence, because of thick drift cover and burial beneath later Mesozoic rocks, it is very difficult to deduce the distribution of these highly permeable sandstones.

In the Dungannon area, thin BASAL SANDS, overlain by a highly porous purple or grey MAGNESIAN LIMESTONE, form the local base of the series (Fowler and Robbie, 1961). The limestone is less than 20 m thick, and mainly consists of calcareous dolomite. This marginal facies of the Magnesian Limestone is also developed in the Belfast area.

Both the Magnesian Limestone and the brockrams with their associated sandstones are overlain by red mudstones, in places non-sequentially, which are referred to in the lower part as UPPER PERMIAN MARLS, and in the upper part as BUNTER MARLS. These beds, which also contain a fair proportion of siltstone and fine grained sandstone with some evaporites, are the lateral equivalent of the St.Bees Shales and appear to be of similar thickness. Like the St.Bees Shales, their upper boundary is transitional, and the gradual passage into the red, fine to medium grained BUNTER SANDSTONE takes place over several metres of strata.

The BUNTER SANDSTONE is the most widespread of the Permo-Trias units beneath the drift cover in Northern Ireland, but its distribution is very scattered and discontinuous (fig.11). In general, it resembles the ST.BEES SANDSTONE, particularly on account of the prevailing grain size and the frequency of mudstone partings (shown in PLATE 13B). It differs, however, in containing occasional coarse laminae with millet seed grains. It may be massive or current-bedded. In deep boreholes drilled at the margins of the Antrim Basalt Plateau, where geophysical data indicated the probable presence of deep sedimentary basins, the Bunter Sandstone is found to be far more consolidated than in the shallower outcrops indicated on fig.11. It also shows a tendency to be grey in colour, rather than red, and conglomerate beds are occasionally present.

Near the top of the sandstone, the beds become variegated, friable and coarse grained, and this part of the sequence is classified as KEUPER SANDSTONE. The sandstone is characteristically fawn, yellow or grey in colour, and is generally lacking in detrital mica (Fowler and Robbie, 1961). It has been recognised in most parts of the Six Counties, but appears to be absent in the Belfast area where the red dolomitic siltstones of the KEUPER MARL follow on from the Bunter directly.

A typical development of Keuper Marl is present associated characteristically with thick beds of rock salt, currently worked in the Antrim Saltfield. The marl is overlain by Rhaetic beds, which complete the Permo-Triassic sequence.

The reader will have noted in reading this account, that no mention has been made of the Devonshire Permo-Trias sequence, which includes some classic sections in the Bunter Pebble Beds. It was decided that in view of the recently published work of Sherrell (1970), and the fact that the aquifer is approaching full development in this area, that there would be greater merit in concentrating the study on the more northerly outcrop areas. In addition, there were sampling difficulties brought about by deep weathering of surface outcrops and the lack of cored boreholes in the Devonshire area. Preliminary sampling was, in fact, carried out, but very few valid test results were obtained, owing mainly to the extremely friable nature of the Lower and Upper Sandstones, thought to be Permian and Triassic in age respectively. The omission is therefore deliberate, but it is to be hoped that the regrettable gap in the data will be filled in the near future, preferably on the basis of a few well-placed cored boreholes.

CHAPTER THREE : Sampling programme

CHAPTER THREE: SAMPLING PROGRAMME

3.1. INTRODUCTION AND PRINCIPLES

The evaluation of the aquifer properties of a formation using laboratory methods necessitates the execution of a very careful, thorough and comprehensive programme of sampling. Under ideal conditions, the programme should ensure that:

i) All vertical and lateral lithological changes in the formation, whether they be induced by sedimentological, structural or diagenetic processes, should be covered,

ii) the full thickness of the formation should be sampled,

iii) material in both the weathered and the unweathered states should be examined, by selection of samples from surface exposures and drill-cores.

The broad principles on which sampling for aquifer property evaluation should be based, have already been described (Lovelock, 1970. See Appendix 1).

In reality, especially in glaciated countries, formations are often inadequately exposed, and the drilling of expensive cored boreholes may not always take place at scientifically selected locations. A compromise must, therefore, be reached between the ideal scheme outlined above, and the actual field conditions, and the evaluation has to be based on results from the most comprehensive set of samples which it has been possible to select, within the practical and economic limitations of the project.

Taking the Permo-Triassic formations in particular, two factors assisted in the availability of sample material. On the one hand, despite glaciation and the resultant thick cover of glacial drift over many of the outcrop areas, the sandstone aquifers are quite well exposed, and numerous accessible sections occur in road and railway cuttings in the Midlands, and in stream beds in the North and in Scotland. On the other hand, numerous boreholes, often cored, have been put down into the Permo-Trias in the U.K. during exploratory or production operations for ground water, hydrocarbons, rock salt, gypsum and anhydrite. For a variety of reasons, the Institute of Geological Sciences is well placed to obtain samples from these boreholes, and a large number (763) were forthcoming during the study under discussion.

3.2. SAMPLING PROCEDURES

3.2.1. Surface exposures

A total of 302 samples were taken from surface exposures, and their distribution is shown by means of solid dots with reference numbers, on the accompanying figs.12-18. The locations were chosen with the principles outlined above clearly in mind. The photographs which illustrate Chapter Two of this thesis show the type of rock faces commonly encountered.

With some exceptions, it was found that most faces exposed in road cuts and stream sections showed relatively uniform lithology, and as a general rule, only one sample was selected from each locality in order that the geographic and geological distribution could be kept as wide as possible. The minimum size of the samples was controlled by the experimental procedures described in Chapter Four; wherever possible, cuboid blocks of approximately 15 x 15 x 15 cms size, were taken out of the rock face, using sledge hammer, pick and chisel. Fresh material was selected in preference to rock which showed obvious signs of deep weathering. Two people were normally present during the sampling operation, and this assisted the selection of a representative block or blocks. The size of the blocks also enabled test specimens to be taken from below the weathered surface skin which, in these formations, may be several centimetres thick.

A portable petrol-driven diamond coring rig using direct drive and water flush, was tried out in the field with the object of producing short 75 mm. diameter cores. It was not found to be satisfactory, owing to anchorage and vibration problems.

As might be expected, in a few areas the sandstones at outcrop proved to be completely cohesionless, and no undisturbed samples could be obtained.

In these localities a bag sample of the material was taken for sieve analysis, and permeability estimation by the Hazen (1893) method. Such conditions were only encountered in the Bunter Pebble Beds in parts of Nottinghamshire (and Devonshire). Elsewhere, the sandstones were frequently extremely friable and loosely consolidated, but it was found that if great care was taken during sampling and transportation, large pieces of these rocks could be handled in the undisturbed state.

3.2.2. Underground Exposures

Similar methods were used for the extraction of samples from rock sections exposed in the New Mersey Tunnel (pilot drivage) and in an adit at Stamp Hill Mine, Kirby Thore, Westmorland. In both cases, the smoothness of the sandstone faces presented a considerable problem, which was also encountered in some surface outcrops.

3.2.3. Borehole Cores

Sites from which borehole cores were obtained are indicated by means of open circles on figs.12-18.
A total of 763 samples were selected from drill cores, with the following two factors borne in mind:

i) The general range of lithology shown by the cores.

ii) the extent of any core loss within a cored interval and the likely nature of the missing material.

TABLE 1

LIST OF THE MORE IMPORTANT BOREHOLES FROM WHICH CORES WERE ANALYSED*

AREA	BOREHOLE NAME	N.G.R.	SAMPLE No.	FORMATIONS
1	Newton Regis(Fig.19)	SK 2822 0728	330	LKS, BPB
	Appleby Parva	SK 3067 0858	466	LKS, BPB
	Webheath	SP 0098 6693	695	LKS, UMS, BP
	Austrey House	SK 3027 0485	325	LKS
2	Edwinstowe No.5	SK 6343 6814	505	BPB
	Edwinstowe No.8	SK 6345 6808	508	BPB
	Edwinstowe No.9(Fig.20)	SK 6347 6818	509	BPB
3	Bellington No.4(Fig.21)	SO 8776 7689	465	UMS, BPB, LM
4	Shiffords Bridge	SJ 690 350	461	BPB, LMS
	Rodway	SJ 6623 1825	746	BPB, LMS
	Sheepbridge	SJ 6714 2067	747	BPB, LMS
	Bolas Bridge (Fig.22)	SJ 6457 2027	763	BPB, LMS
5	A1, Vale of Clwyd	SJ 1132 6191	748	BS
	B1, Vale of Clwyd	SJ 0641 6536	749	BS
6	Hatfield Woodhouse	SE 685 097	485	BS
	Highfield Lane	SK 6598 9536	486	BS
	Boston Park Farm(Fig.24)	SE 677 045	501	BS
7	Low Prior Scales	NY 0579 0725	750	SBS
	Robertgate Bridge	NY 0461 0746	751	SBS
8	Blackmosspool (Fig.26)	NY 4824 4816	588	PS
9	Drungans No.2 (Fig.27)	NX 9471 7486	329	P
10	Kingsmill	H 864 759	669	BS
	Twyfords Mill	H 842 630	670	BS
	Ballyloughan Bridge	H 847 804	671	BS
	Haw Hill (Fig.28)	J 4830 6952	673	BS

LKS	Lower Keuper Sandstone	BS	Bunter Sandstone (undivided)
UMS	Upper Mottled Sandstone	SBS	St.Bees Sandstone
BPB	Bunter Pebble Beds	PS	Penrith Sandstone
LMS	Lower Mottled Sandstone	P	Permian Sandstone

In the earlier stages of the Project, it was considered sufficient to select only as many specimens as would adequately represent the range of lithology present. Later it became apparent that interpolation of physical property values over non-sampled intervals by reference to a geological or drillers log was difficult to achieve with any accuracy, especially with regard to permeability. A different technique was therefore adopted, in which samples were selected at fixed intervals throughout a cored interval. In this way, the sampling procedure is put on a firm statistical basis, and human bias is thereby avoided. There is, however, a risk that using this method the number of samples to be prepared and tested may become excessive, and discretion must be used in the selection of an acceptable interval.

As a general rule, and in common with current practice in the oil industry, it is wiser to select samples from as many different horizons as possible, rather than to concentrate on rigorous testing of numerous samples from relatively few horizons. Figs.19-28 illustrate both the range of lithology and the frequency of sampled horizons in selected boreholes from the 10 sampling Areas. Whereas Stubbins Lane, Garstang was sampled on a "representative lithology" basis; that at Bellington was on the more scientific "regular interval" basis which naturally can only be properly used where core recovery approaches 100%.

TABLE 2

NUMBERS OF SAMPLES EXAMINED FROM EACH SANDSTONE SUBDIVISION

AREA	FORMATION	TOTAL NUMBER
1	Bunter Pebble Beds	31
	Upper Mottled Sandstone	34
	Lower Keuper Sandstone	88
2	Lower Mottled Sandstone	2
	Bunter Pebble Beds	119
	Keuper Waterstones	4
3	Lower Mottled Sandstone	18
	Bunter Pebble Beds	25
	Upper Mottled Sandstone	22
	Lower Keuper Sandstone	12
4	Lower Mottled Sandstone	42
	Bunter Pebble Beds	24
	Upper Mottled Sandstone	8
	Lower Keuper Sandstone	7
	Keuper Waterstones	1
5	Lower Mottled Sandstone	2
	Bunter Pebble Beds	62
	Upper Mottled Sandstone	56
	Keuper Sandstone	24
	Keuper Waterstones	3
	Bunter Sandstone (Vale of Clwyd)	20
6	Bunter Sandstone	96
7	Bunter Sandstone	54
	St.Bees Sandstone	77
8	Penrith Sandstone	63
	St.Bees Sandstone	16
	Annan Sandstone	5
	Kirklinton Sandstone	3
9	Permian Sandstone	42
10	Permian Sandstone	9
	Bunter Sandstone	91
	Keuper Sandstone	5

In more recent studies not described in this thesis, sampling intervals of as little as 30 cm have been employed in order to obtain as full a picture of physical property variation as is practicable, and to enable geophysical well logs to be accurately calibrated for use in uncored bore-holes drilled in the same formation.

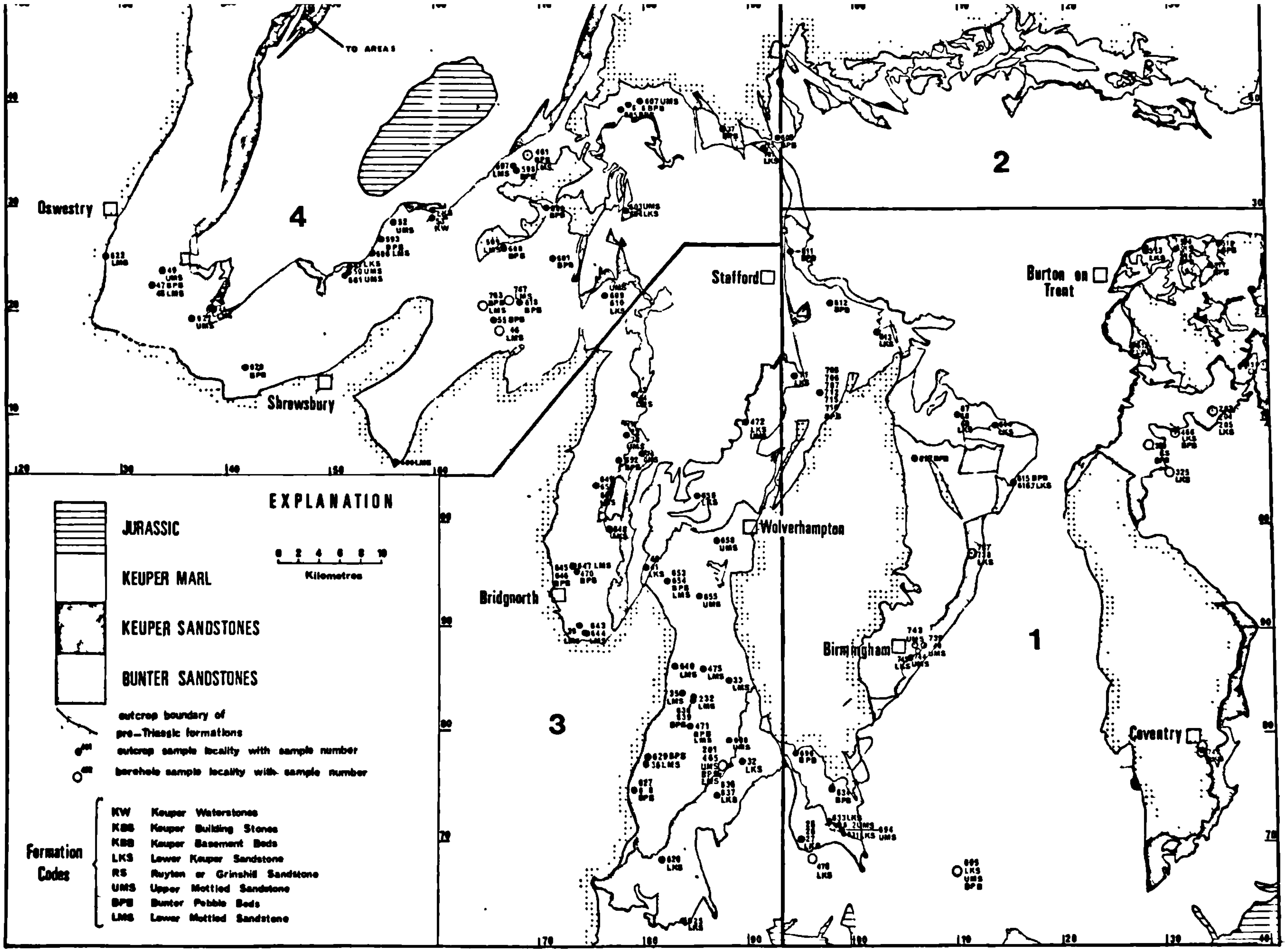
3.3. DISTRIBUTION OF SAMPLES

Figs.12-18 indicate clearly the extent of the sampling operation. Further information relating to each area is given below.

AREAS 1, 3 and 4 (fig.12): most of the well documented exposures were sampled, but work was hampered by poor exposure in the Birmingham area, and parts of west Shropshire (drift covered). No samples were obtained in the Ashbourne area (Bunter) or Kenilworth area (Keuper).

AREAS 2 and 6 (South) (fig.13): difficulty was experienced in the central and southern parts of Nottinghamshire, owing to the extremely soft nature of the formation. Extensive data was obtained, however, from cores at the Edwinstowe site of Water Resources Board.

AREAS 5 and 7 (fig.14): most of the accessible exposures were sampled, and some preferential selecting of these had to be carried out in the well exposed Bunter outcrop in Cheshire.


EXPLANATION
JURASSIC
KEUPER MARL
KEUPER SANDSTONES
BUNTER SANDSTONES
outcrop boundary of pre-Triassic formations
outcrop sample locality with sample number
borehole sample locality with sample number
0 2 4 6 8 10
Kilometres
Formation Codes
KW Keuper Waterstones
KBS Keuper Building Stones
KBB Keuper Basement Beds
LKS Lower Keuper Sandstone
RS Ruyton or Grinshill Sandstone
UMS Upper Mottled Sandstone
BPB Bunter Pebble Beds
LMS Lower Mottled Sandstone
Oswestry
Shrewsbury
Stafford
Wolverhampton
Bridgnorth
Birmingham
Burton on Trent
Coventry
TO AREA 1
1
2
3
4

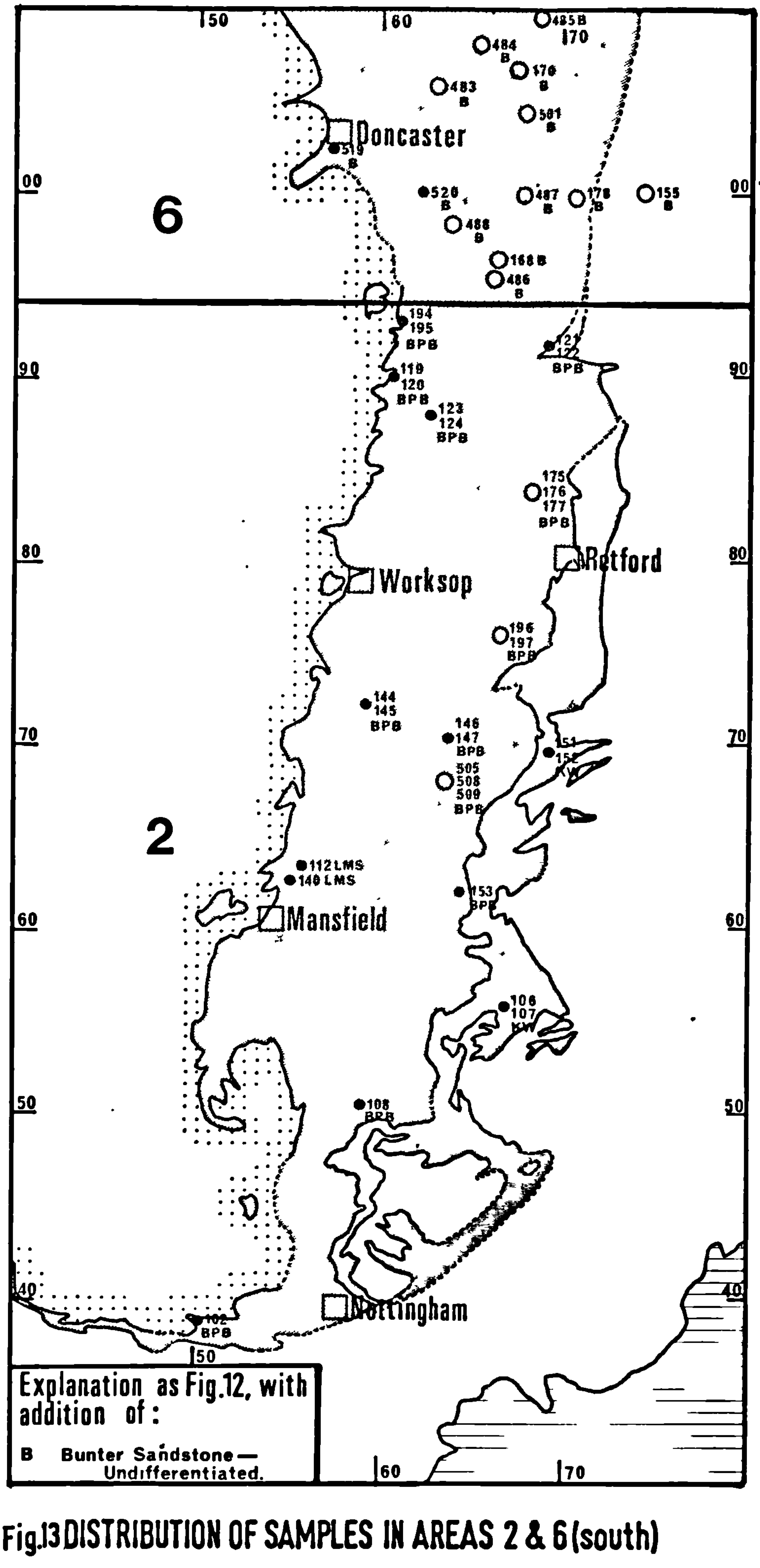
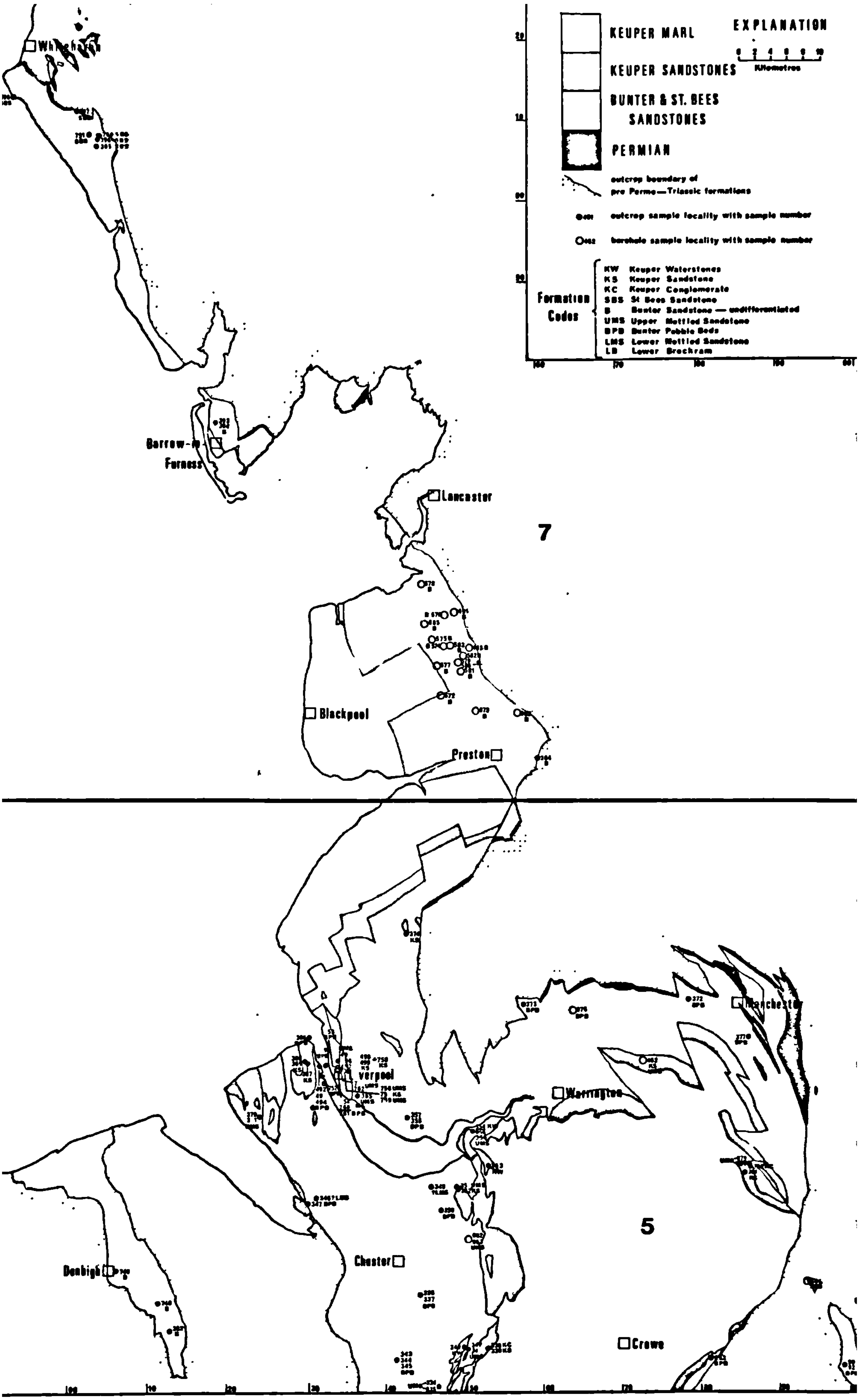


Fig.13 DISTRIBUTION OF SAMPLES IN AREAS 2 & 6 (south)



ig 14 DISTRIBUTION OF SAMPLES IN AREAS 5 & 7

The surface samples were backed up by core samples (mainly from odd horizons, as available) from 20 boreholes, of which 15 were drilled by Fylde Water Board in the Garstang area of Lancashire over which the Bunter beds are virtually unexposed.

AREA 6 (North) (fig.15): the Trias is poorly exposed over this tract of country. All the known surface exposures were visited and samples taken; a few cores were obtained from 5 boreholes, but the overall distribution remains inadequate at the time of writing.*

AREA 8 (Southern part) (fig.16): this area was selected for intensive surface sampling because it includes an extensive outcrop of Penrith Sandstone well exposed in many places, and virtually undeveloped as a source of ground water. Surface samples were taken from most accessible exposures known to Institute field staff. In addition, a few core samples were obtained from three cored boreholes which penetrated Penrith Sandstone. Representative surface samples of St.Bees Sandstone were also taken from the more readily accessible outcrops. Drilling is now in progress at Cliburn, where three I.G.S. cored-boreholes are being constructed.

* Since this section was written, six cored boreholes have been recently drilled into the Trias of the Vale of York, and work is in hand to subject this material to rigorous core

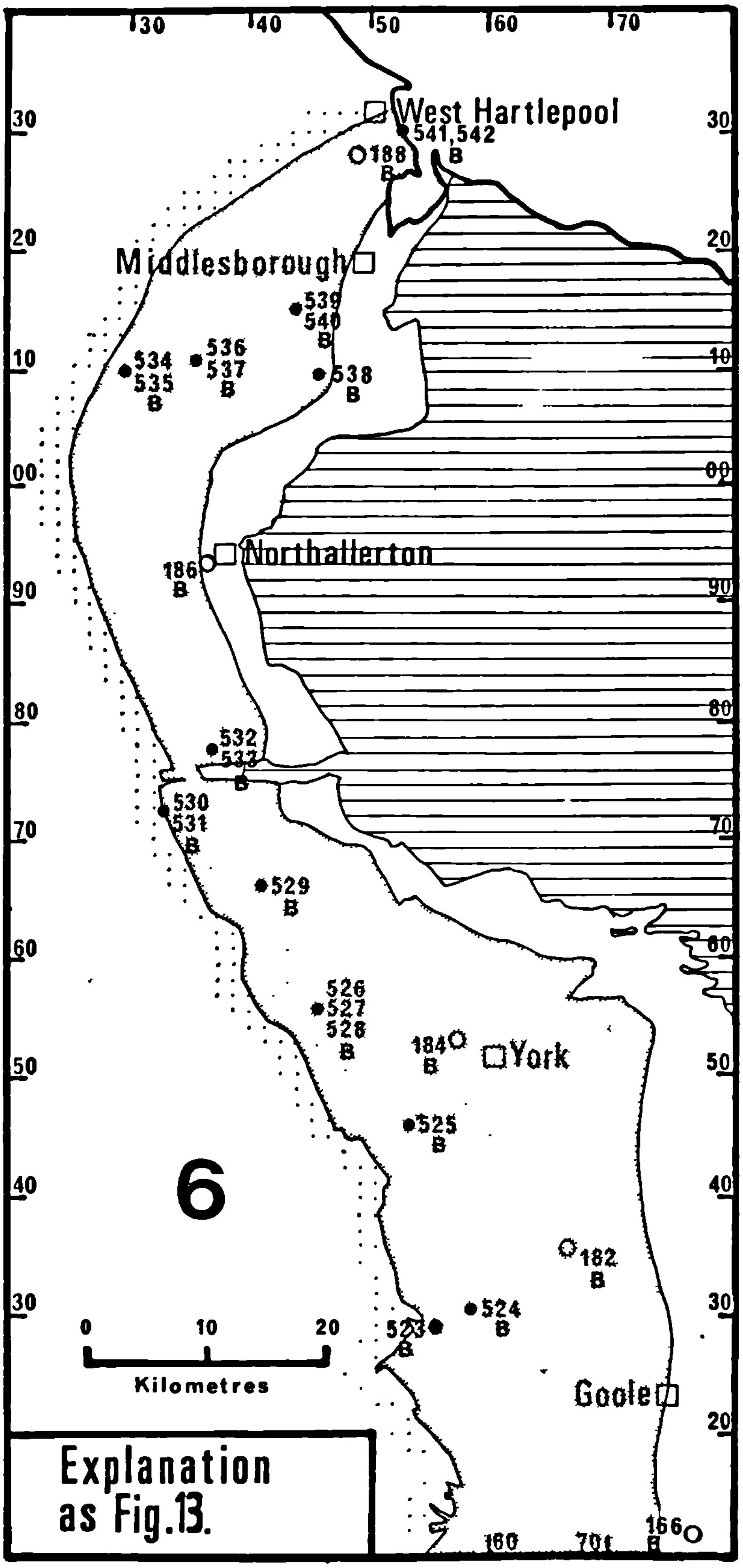


Fig.15 DISTRIBUTION OF SAMPLES IN AREA 6 [north]

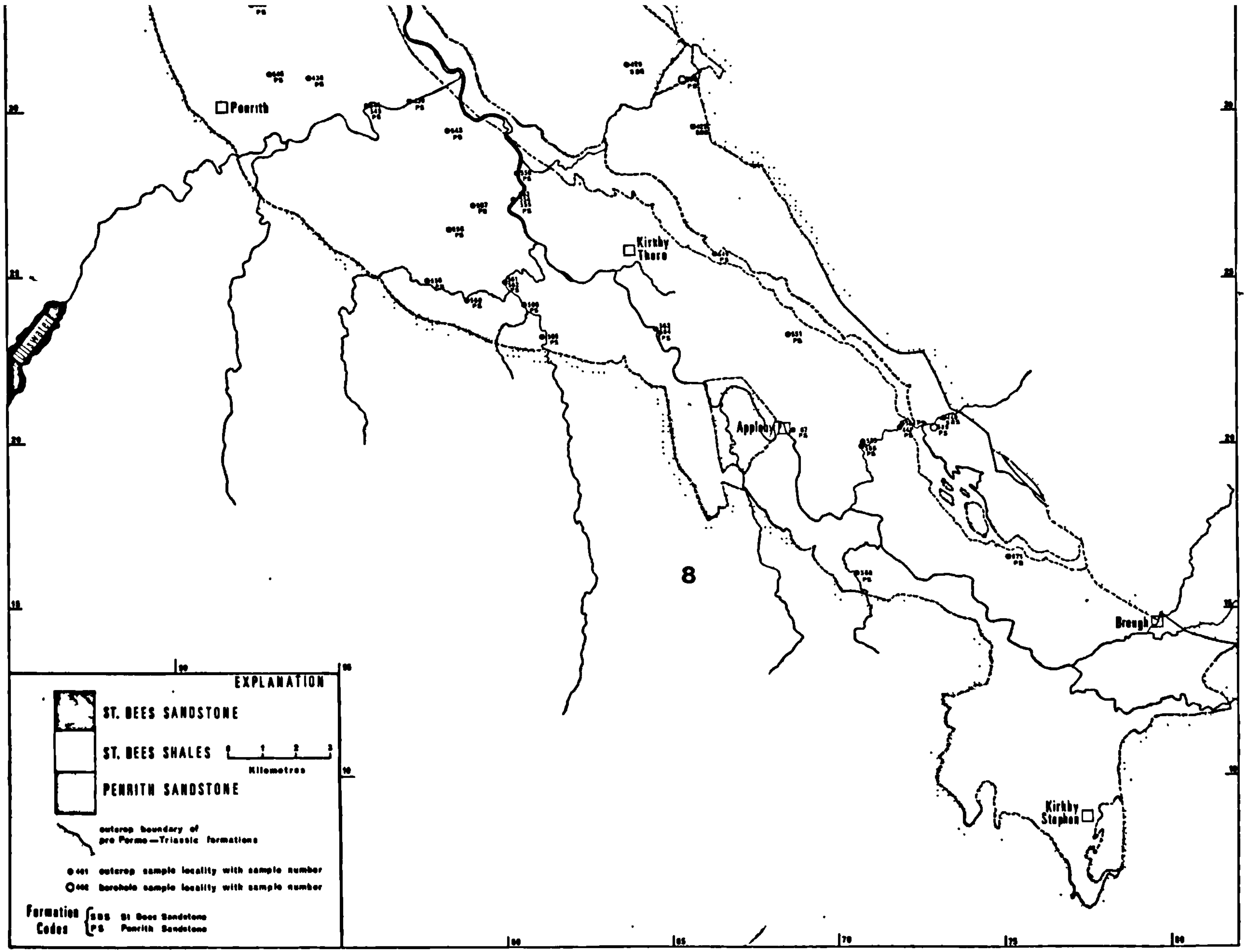
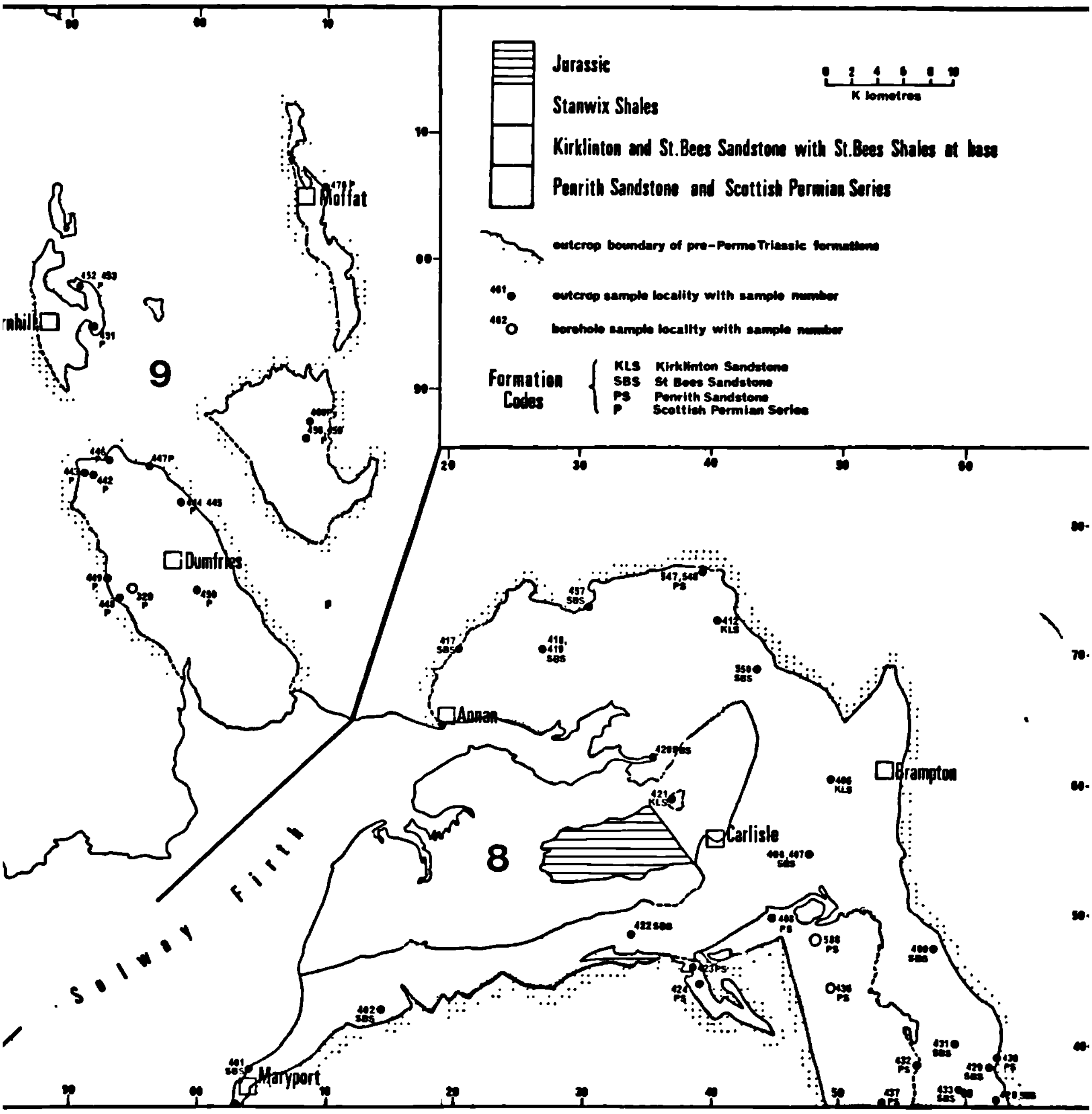


Fig. 16 DISTRIBUTION OF SAMPLES IN AREA 8 (cont.)

AREA 8 (Northern part) and AREA 9 (fig.17): over this area reliance was mainly and unavoidably placed on surface samples, but borehole cores were obtained from two locations, one in the Penrith Sandstone, the other in the Permian Sandstone at Dumfries. Note that the Annan Sandstone has been grouped for convenience with the St.Bees Sandstone.

AREA 10 (fig.18): in Ulster, surface exposures of the Permo-Trias are exceedingly rare, but a considerable number of cored boreholes have been drilled into it. As a result, the majority of the samples examined from Northern Ireland were taken from borehole cores on a statistical bases (at 5 locations), and odd horizons were sampled from a further 6 boreholes. The overall coverage, therefore, is satisfactory.



STRIBUTION OF SAMPLES IN AREAS 8(north) & 9

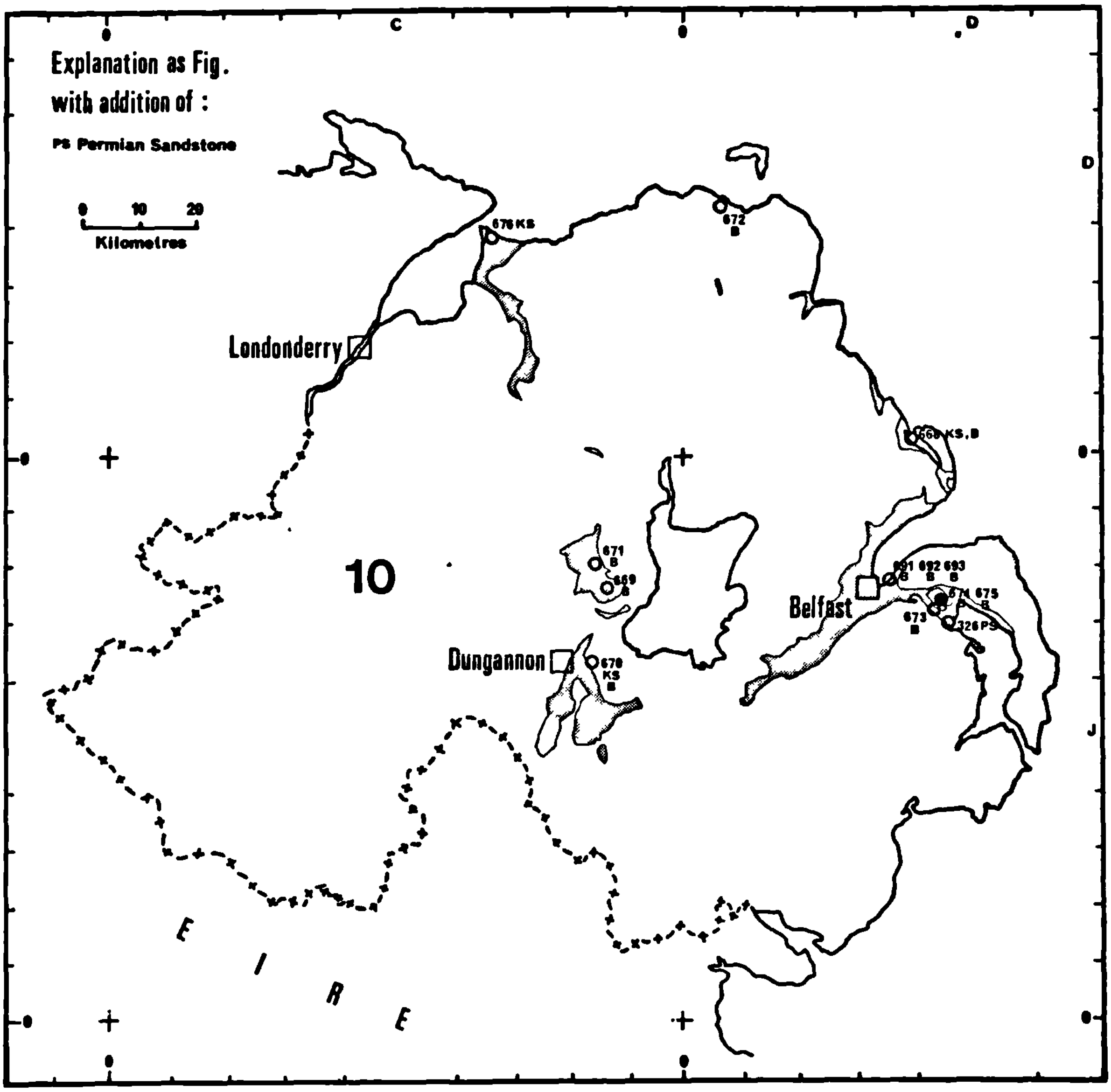


Fig.18 DISTRIBUTION OF SAMPLES IN AREA 10

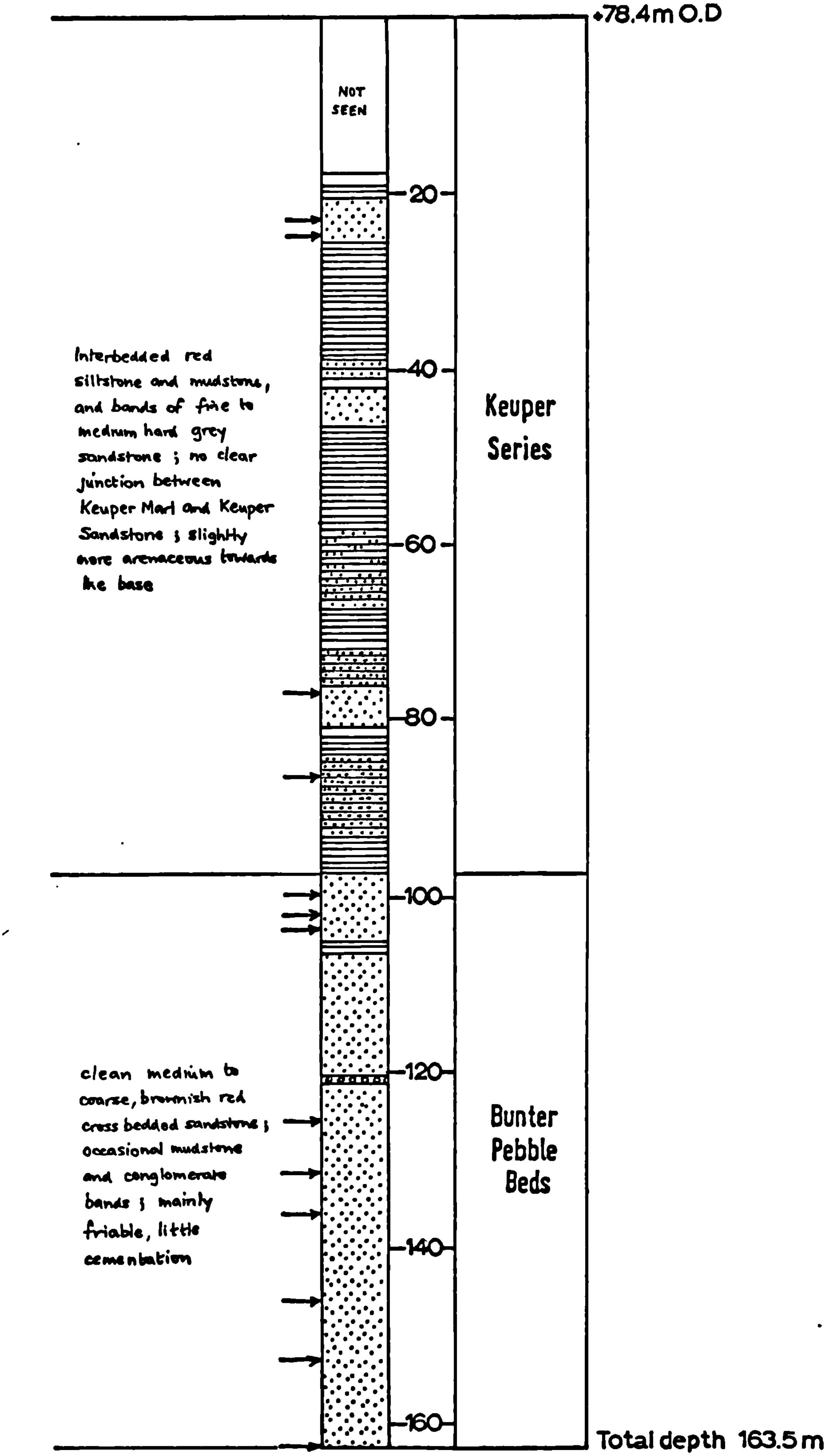


Fig 10 Representative Well Logs : AREA 1 – NEWTON REGIS B.H [1968]

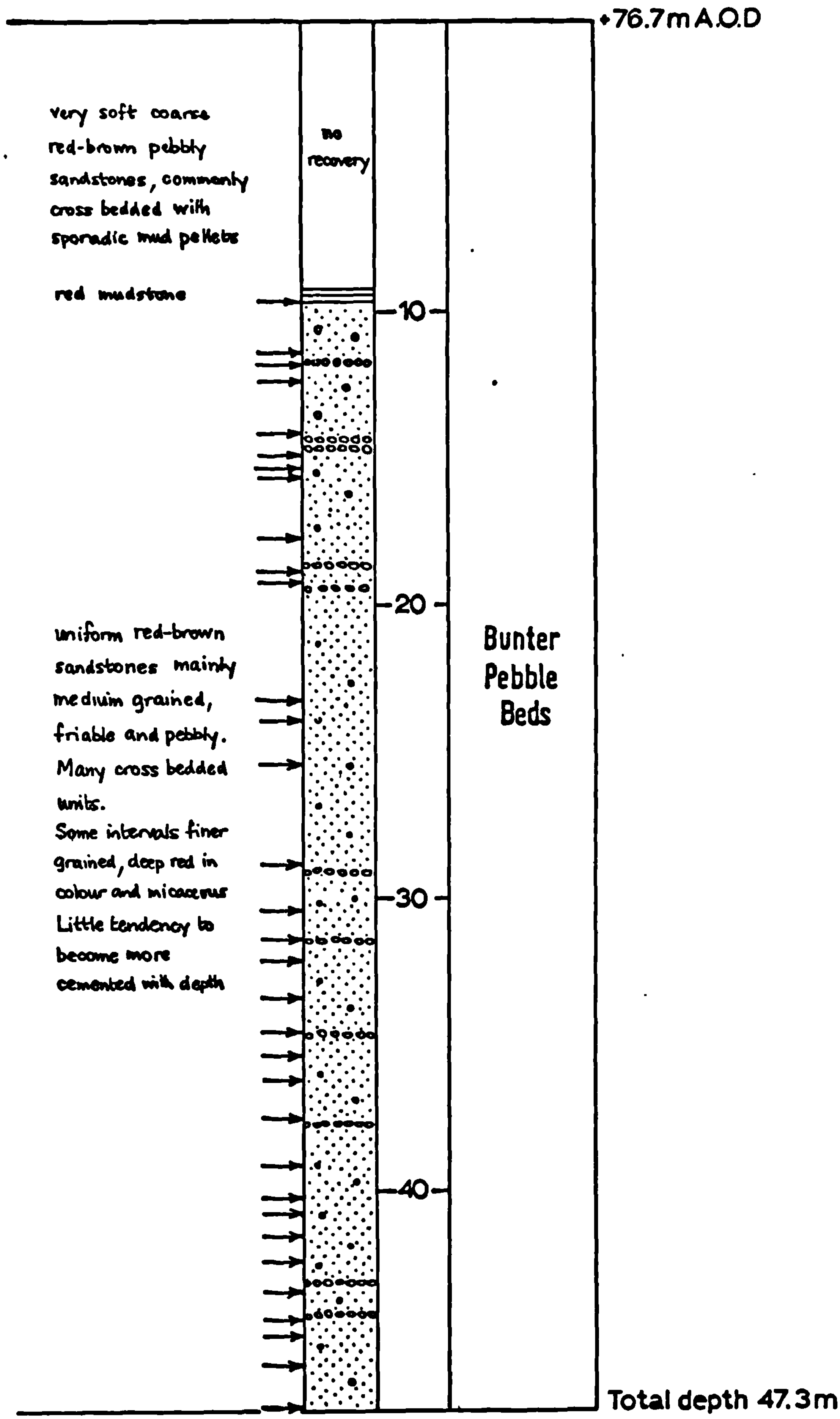


Fig.20 Representative Well Logs : AREA 2 - EDWINSTOWE No 9 B.H. [1969]

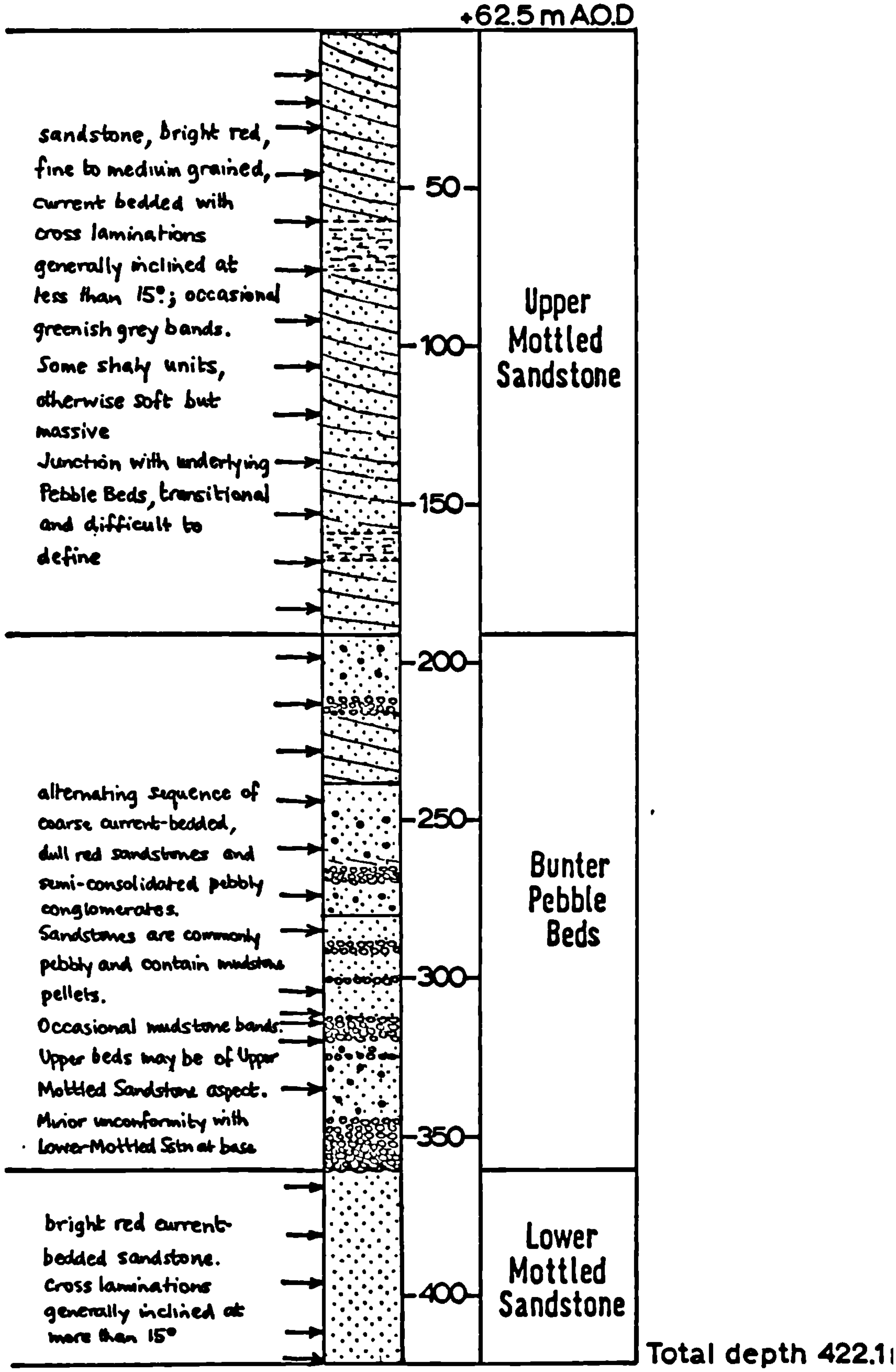


Fig.21 Representative Well Logs : AREA 3 - BELLINGTON No 4 BH [1968] · KIDDERMINSTER, WORCS

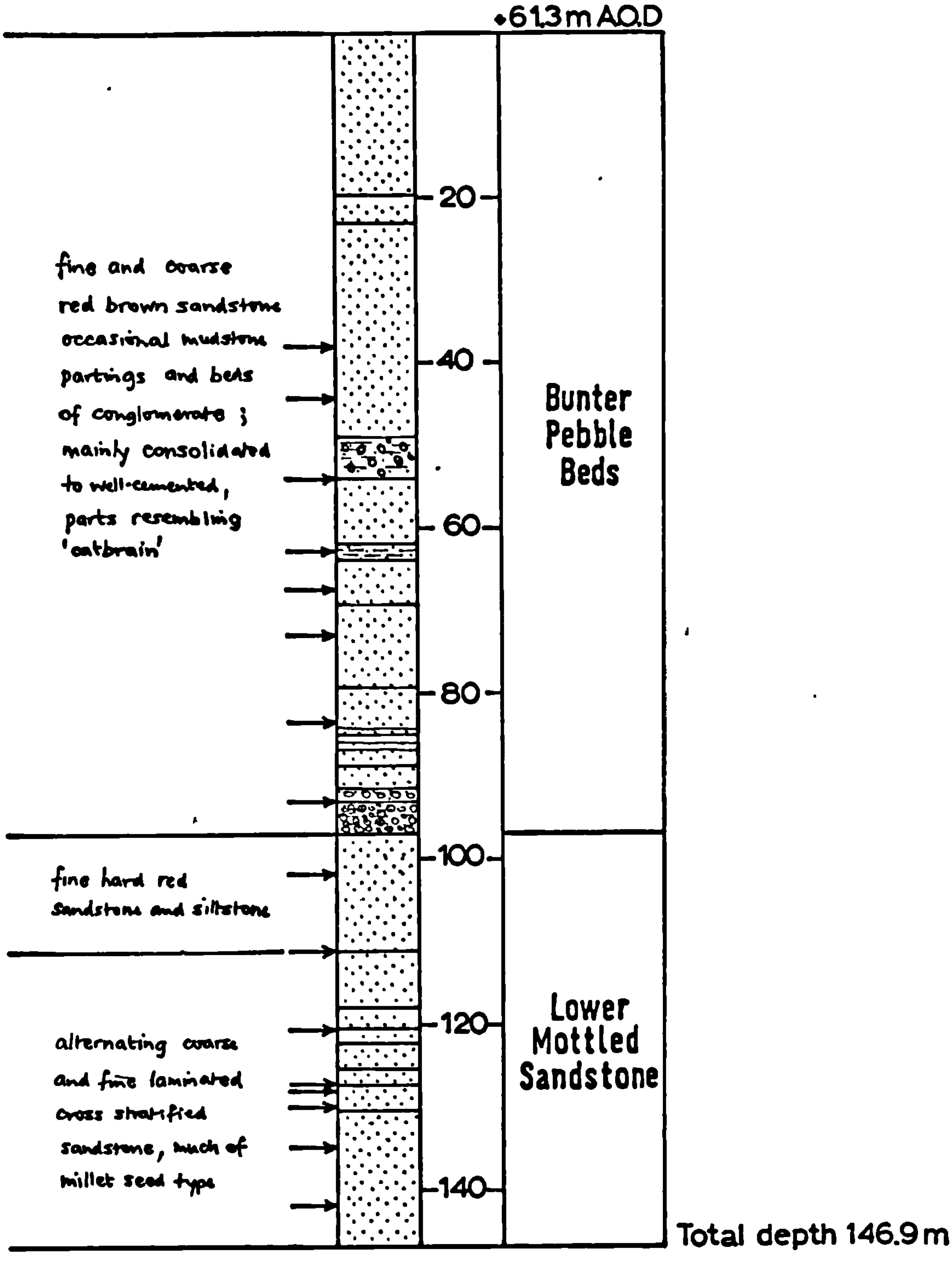


Fig.22Representative Well Logs : AREA 4 - BOLAS BRIDGE BH [1970] WELLINGTON, SALOP

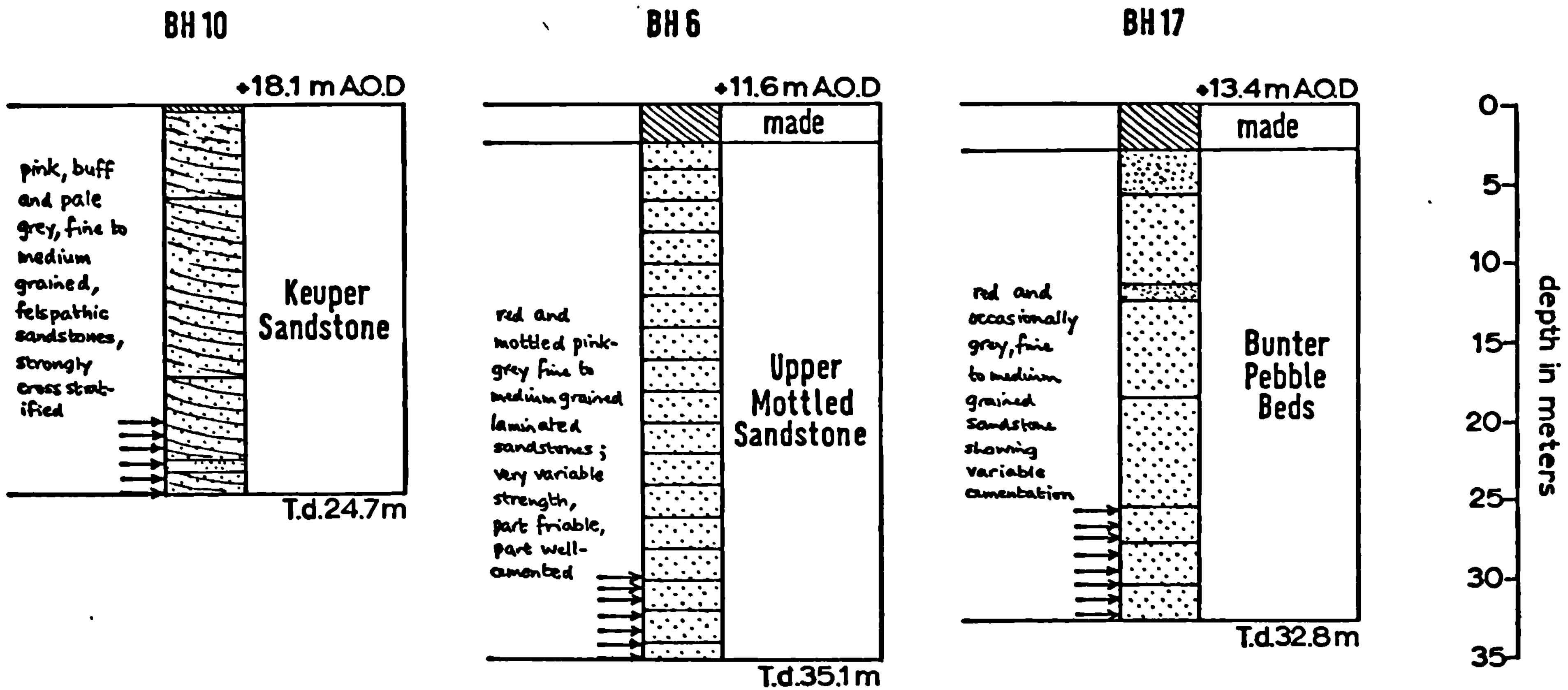


Fig.23 Representative Well Logs : AREA 5 - SITE INVESTIGATION BOREHOLES IN CENTRAL LIVERPOOL drilled for British Rail [1970]

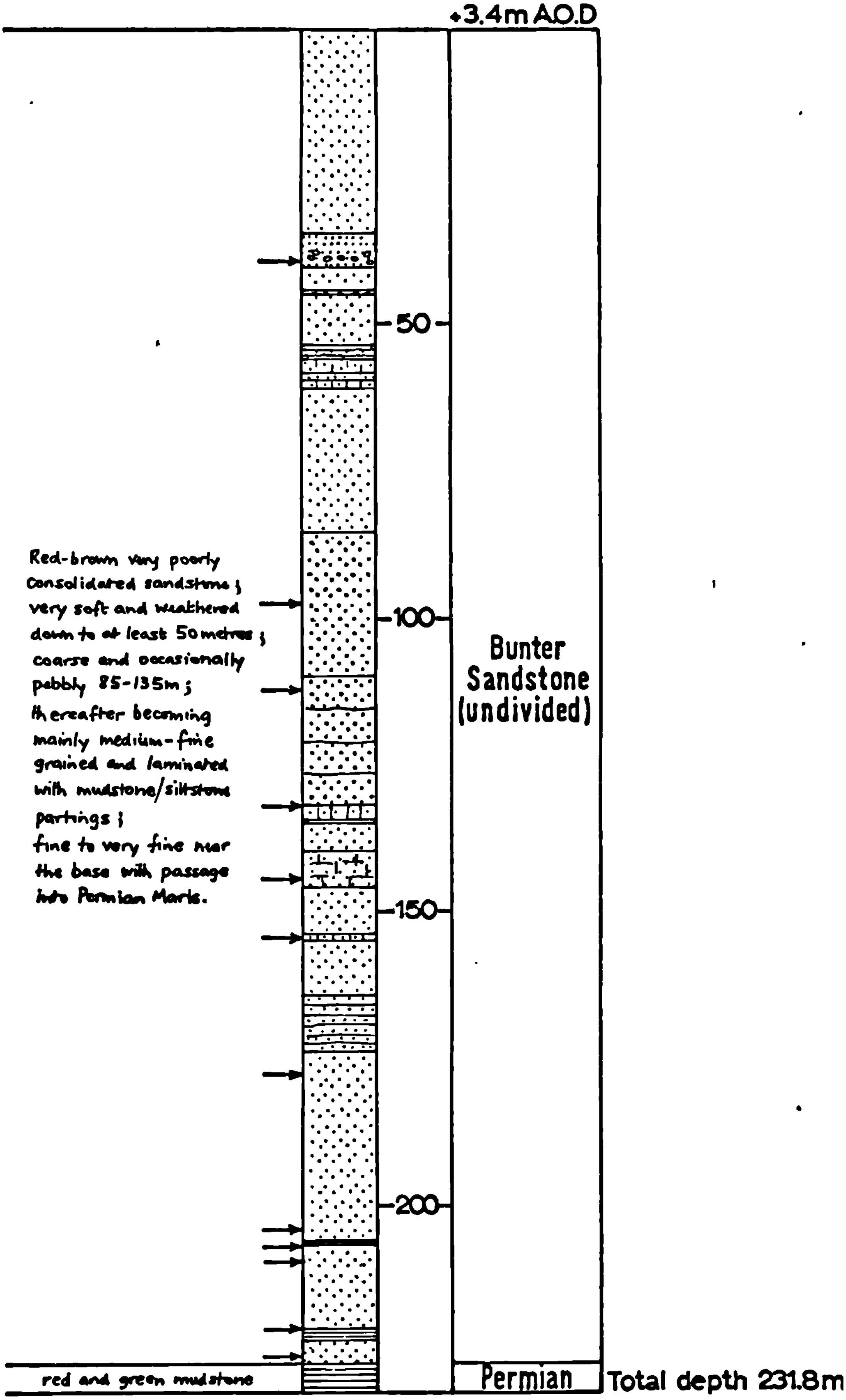


Fig.24 Representative Well Logs : AREA 6 - BOSTON PARK FARM B.H. [1969], DONCASTER, YORKS

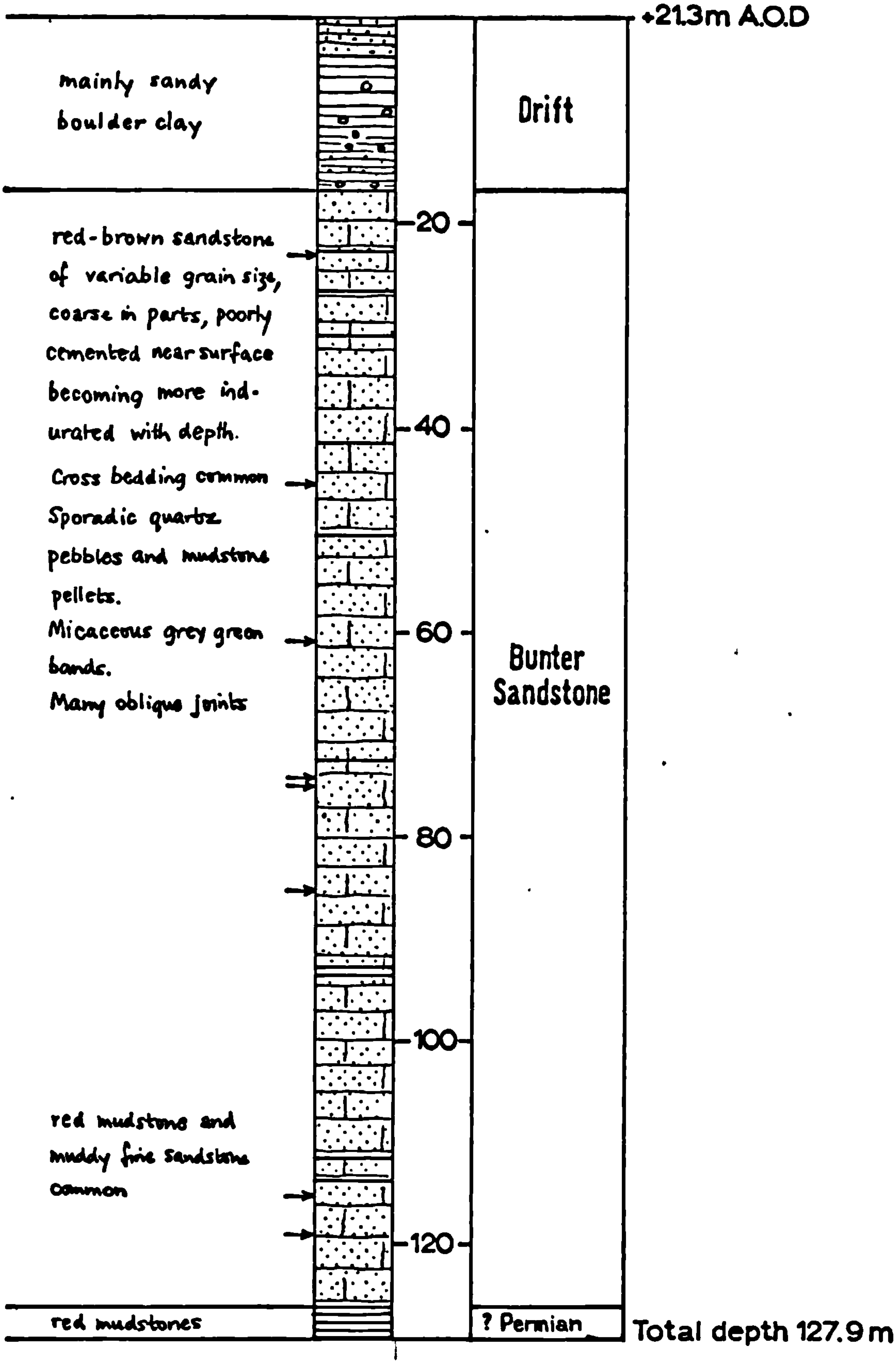


Fig.25 Representative Well Logs : AREA 7 - STUBBINS LANE B.H.[1968]
GARSTANG, LANCS

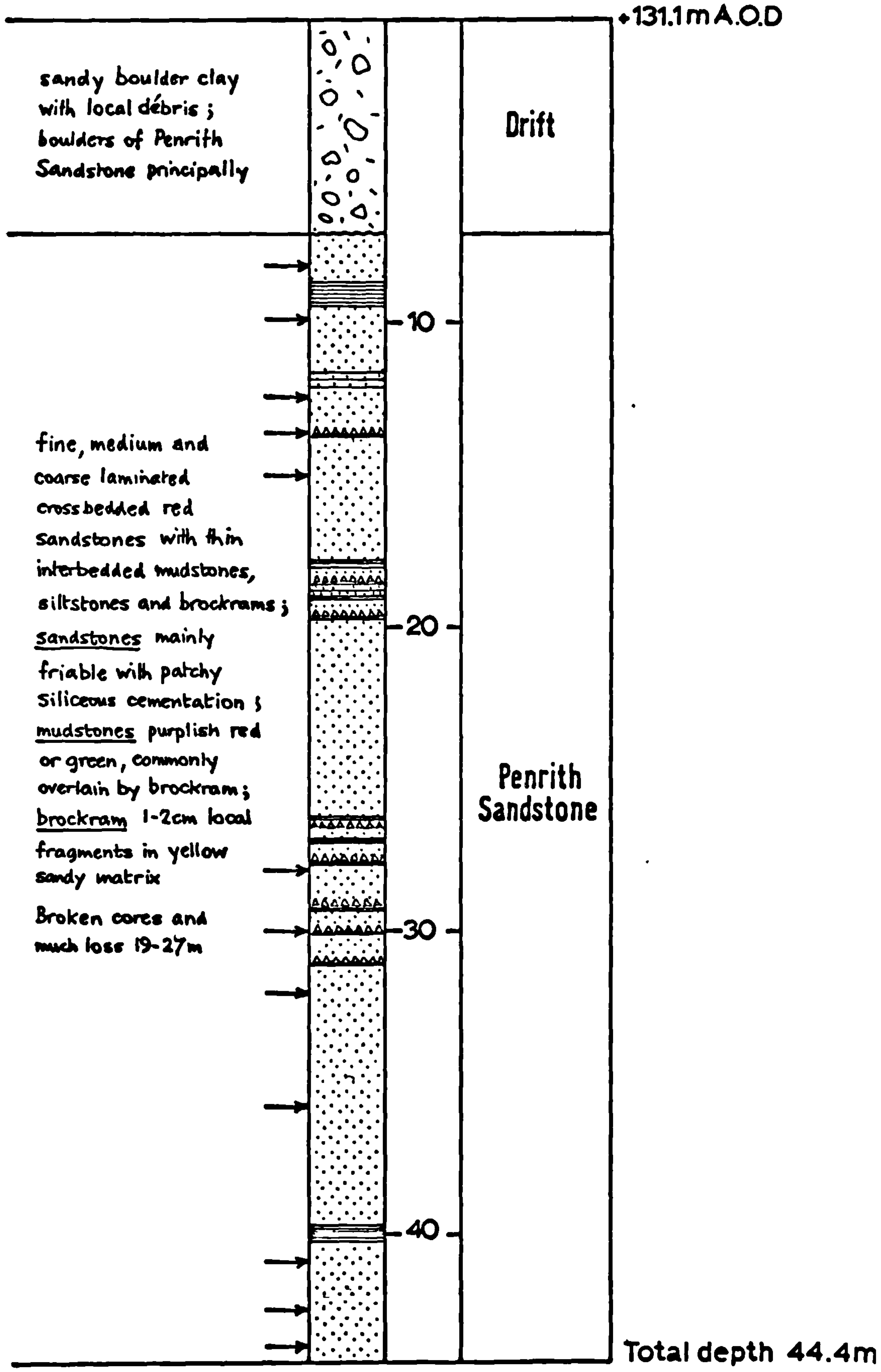


Fig26 Representative Well Logs : AREA 8 - BLACKMOSSPOOL BH [1968] CARLISLE, CUMBS

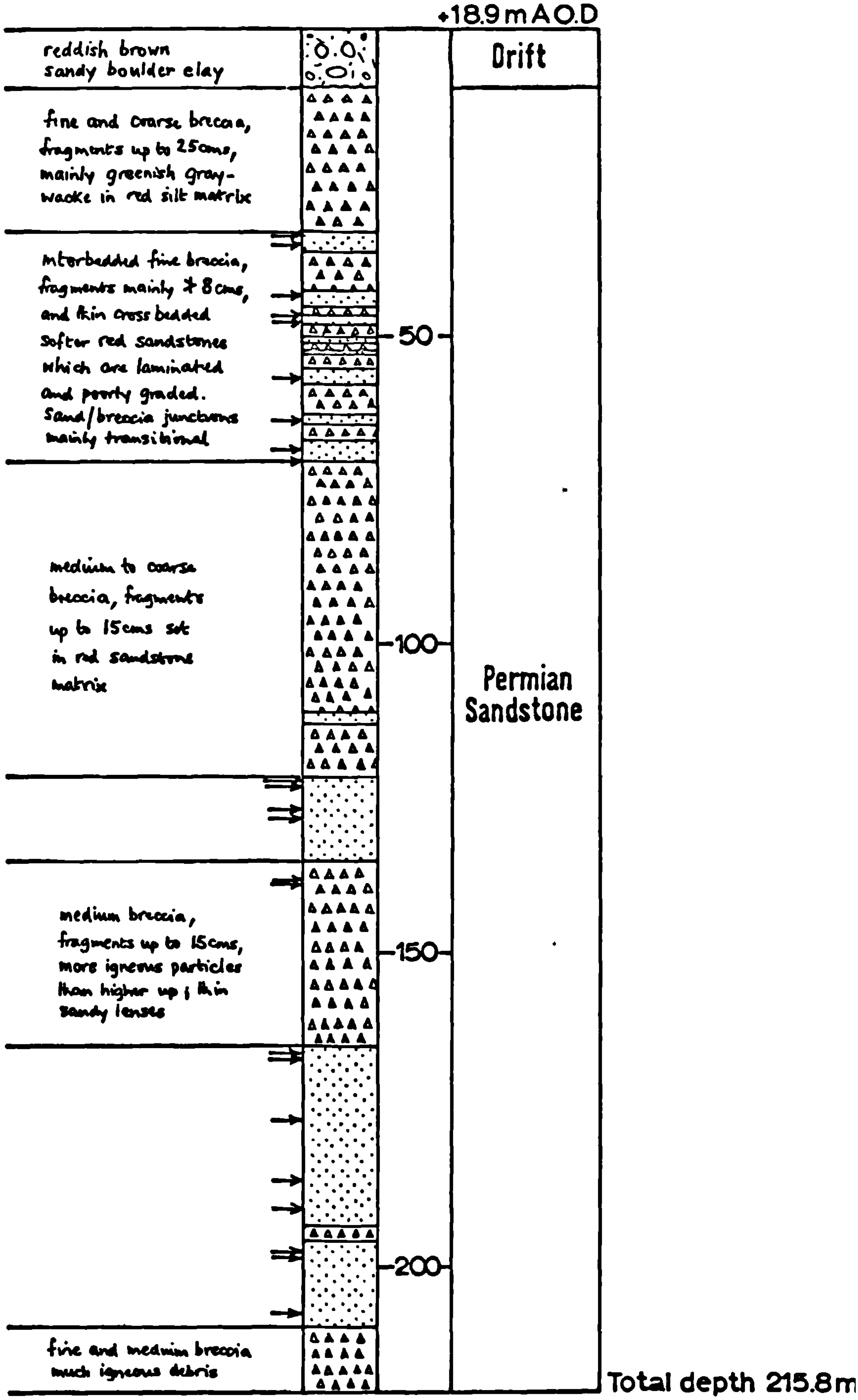


Fig.27 Representative Well Logs : AREA 9 - DUMFRIES FACTORY No 2 BH, drilled for ICI [1967]

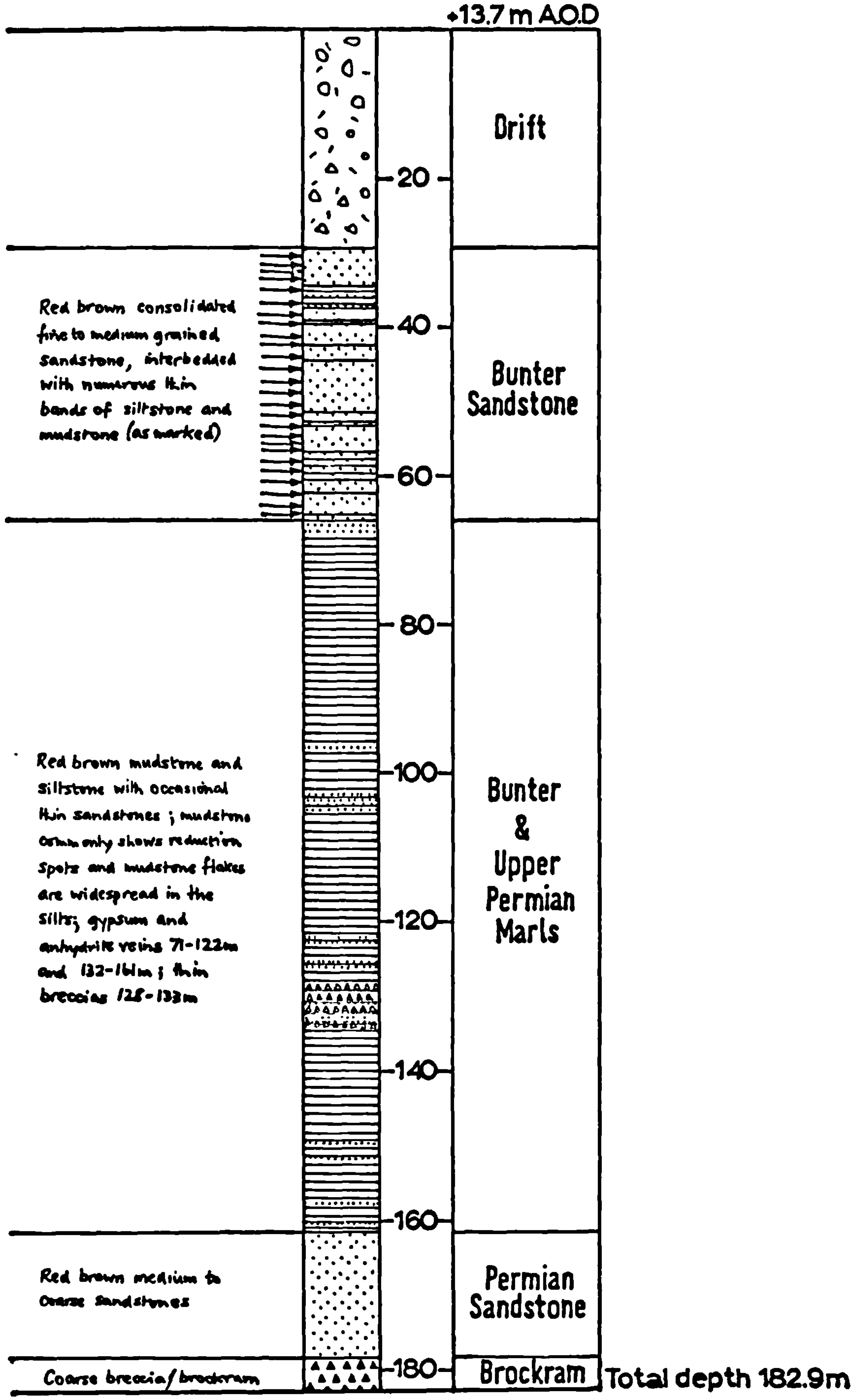


Fig.28 Representative Well Logs : AREA 10 - HAW HILL B.H. [1969]. COMBER, Co.DOWN

CHAPTER FOUR : Experimental methods

CHAPTER FOUR: EXPERIMENTAL METHODS

4.1. INTRODUCTION

The samples of Permo-Triassic rocks, the selection and distribution of which has been described above, were subjected to core analysis using specially modified versions of well established methods. Before describing these in detail, some statement of the underlying principles is required.

For reasons already given (p.45) it follows that where data from core analysis is being used to describe as far as is justifiable, the three dimensional distribution of physical property values in an aquifer, it is absolutely essential to consider large numbers of samples which have been subjected to standard procedures. Although results on some 3500 test specimens cut from 1065 samples are being synthesised in this thesis, it is not considered that the study as a whole constitutes anything but a preliminary attempt to define three dimensional variation in aquifer properties.

Owing to the large numbers of samples which must be considered if the work is to have any degree of statistical confidence, it follows that the test procedures should be:

i) standardised
ii) rapid and, therefore, relatively inexpensive
iii) simple to perform
iv) able to produce data of acceptable accuracy

The core analysis methods now to be described were conceived with these criteria firmly in view, and any advantages or disadvantages should be related to these considerations. The methods are concerned with the measurement of porosity, gas permeability, water permeability and centrifuge specific yield.

4.2. SAMPLE PREPARATION

The following quotation from the American Petroleum Institute Recommended Practice (1960) is appropriate at this point......

"The determination of reliable basic data depends upon the intelligent selection of test samples, the careful preparation of these samples for testing, and the use of test methods and equipment based on proved scientific principles".

This publication has provided much of the basis of the experimental work and it will be frequently referred to in this section. The high standard and completeness of this document is particularly noteworthy.

In the oil industry, core analysis is carried out either on the whole core sample (full diameter core analysis) or on smaller cylindrical samples which are cut out of the original specimen. In the present study, all the test specimens (in future referred to as "plugs") were cut from large samples, and no full diameter core analysis was attempted.

Two sizes of plugs were cut (i) cylinders of nominal 25 mm length and diameter (shown in PLATE 14A), and (ii) cylinders of nominal 75 mm length and diameter. Both were cut using an MF 4 Meddings Drilling Machine fitted with coolant jacket and diamond tipped coring drills (Habit Diamond Tools Limited). The coolant used was freshly drawn London tap water with no additives. Facing of the plugs was accomplished on a Cutrock Engineering BCM 200 Cutting Machine equipped with a 30 cm diamond blade, the same coolant being used. At the completion of coring and facing, the plugs were rinsed in tap water containing 10 mg/l NaOCl (sodium hypochlorite) to remove fines produced by the cutting process, and to sterilize the specimens. At the end of each day's work, the plugs were removed to an oven and dried at 95°C overnight.

These plugs were cut in a number of different axial directions which are indicated by means of index codes which follow the sample number, and which are tabulated in Table 3. The table provides a full explanation of the codes. In brief, plugs were cut wherever possible in the vertical plane and along two horizontal directions mutually at 90°. In the case of outcrop samples, the axes of the horizontal plugs were oriented in the field and labelled with a whole circle magnetic bearing for reference purposes. The direction of the horizontal plugs cut from cores could not be determined and these were conventionally referred to as HX and HY directions.

It was found that plugs suitable for testing could be produced from all but the most friable sandstone material by judicious selection of drilling speed and coolant pressure. Speeds of 3000 r.p.m. and a few p.s.i. coolant pressure were used when coring the more indurated and fine grained material; 1000 r.p.m. and very low pressure were used on the more friable samples. Facing was accomplished by hand, using a double-bladed hacksaw with the untrimmed plug held in a special jig.

TABLE 3

EXPLANATION OF PLUG INDEX CODES.

Code	Explanation
97V	- one only vertical plug cut from sample number 97
97V1	- first " " " " " " 97
97V2	- second " " " " " " 97 e
97H	- one only horizontal plug cut from sample number 97 bearing of direction unknown.
97H-45	- one only horizontal plug cut from sample number 97 in direction 45° Mag.
97H1-45	- first horizontal plug cut in direction 45° Mag.
97H2-45	- second " " " " " " " , et
97HX	- one only horizontal plug cut in X direction
97HY	- " " " " " " X + 90 (Y) directi
97HX1	- first " " " " X direction
97HX2	- second " " " " X " etc.et
97CS	- one only plug cut parallel to strike of cross-stratification
97CD	- one only plug cut parallel to dip of cross-stratification
97TT	- one only plug cut in true thickness direction, i.e. at 90° to cross-stratification.
97-1, 97-2, 97-3,	codes relating to a sequence of samples taken from the same run of borehole cores, commencing with the shallowest, and finishing with the deepest. Directional codes are suffixed, e.g. 97-3CS2, etc.

Mounting of the test plugs in lucite or some alternative plastic material was not carried out in this study, except on certain samples used in work on the reproducibility of the gas permeability and centrifuge specific yield measurements. There is no doubt that overall precision is improved by mounting, but the operation is time-consuming and some techniques require the use of high pressure hydraulic equipment which was not available.

4.3. POROSITY MEASUREMENT

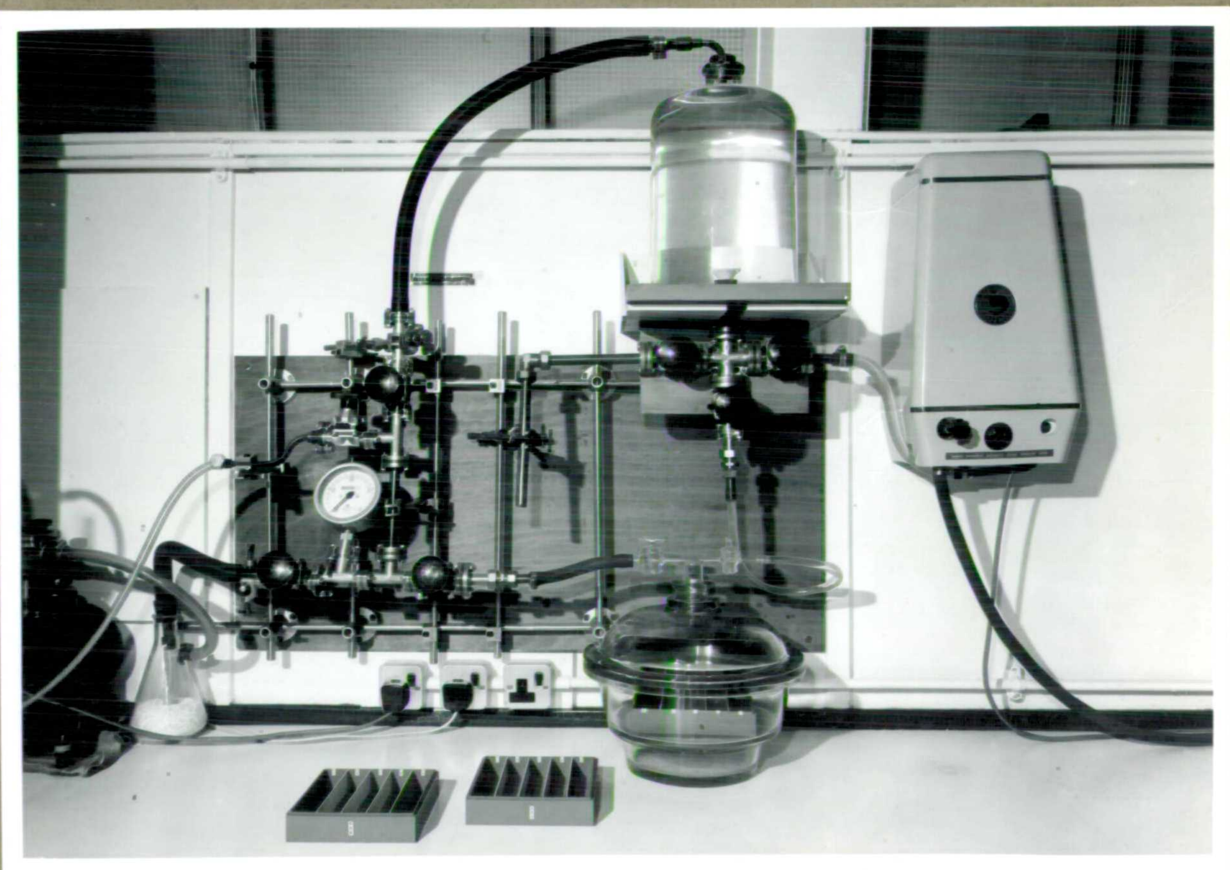
In this, the first of the procedures to be described, the total interconnected void space of the sample is measured and expressed as a percentage of bulk volume. This volume will be referred throughout the rest of this thesis simply as "porosity". It is not equivalent to either total porosity (which includes sealed voids) or "effective porosity" which in this thesis is referred to by its alternative name "specific yield".

To a great extent, confusion over the various types of porosity has arisen because different procedures measure different volumes. Thus, total porosity usually results when an unconsolidated granular sample is being dealt with using the wet method (API, 1960, p.27, Manger, 1963). For the present work, the Liquid Resaturation Method was adopted using water as the displacing liquid; this measures the interconnected void space of the sample, and does not involve crushing.

A. Storage drawer showing contents of ninety-six 25mm nominal diameter test plugs.

PLATE 14

B. Liquid Resaturation System used for the measurement of porosity



4.3.1. Equipment and Procedure

The oven dried plugs were allowed to cool to ambient temperature (20°C) and then were individually weighed dry in air using a Mettler P120 milligram balance. The plugs were placed after weighing in specially designed PVC baskets which will accommodate 25 specimens each. The baskets have solid sides and partitions, but their bases are perforated to facilitate slow upward saturation from below.

The baskets were then transferred to a large desiccator which was linked to a vacuum line by a quick-fit joint. The vacuum system was designed to enable both the saturating water to be deaerated and the desiccator containing the plugs to be evacuated. PLATE 14B shows the layout of the complete system. In routine testing of high permeability plugs, a vacuum of at least 5 torr was applied for a minimum period of 30 minutes, extending to 1-2 hours at the discretion of the operator if the material under test appeared to be "tight".

To provide the saturation liquid, mains water was fed into the reservoir after passing it through a column type Elgastat Deionizer. The water was deaerated by applying a vacuum to the reservoir and allowing the liquid to boil for a few minutes under the reduced pressure.

When the vacuum had been applied for the appropriate period of time, the desiccator was isolated and water allowed to be drawn into it from the reservoir.

The samples in the baskets rested above the bottom of the vessel and slow saturation under vacuum was effected by flooding from the bottom upwards, in order that air entrapment was reduced to a minimum. When the samples had been completely flooded, they were allowed to "soak" for a further 30-45 minutes under a reduced pressure.

The pressure in the desiccator was returned to atmospheric prior to measuring the weights of the individual plugs saturated with water in air. The milligram balance was again used. Particular care has to be taken to avoid weighing excess skin water on the plugs during the saturated measurement in air. Removal of excess water using blotting paper was not performed as many of the specimens were rather friable, and the process can cause suction drainage of the interior of the specimen which is highly undesirable.

Grain loss during porosity testing is a potentially serious source of error and the utmost care had to be taken to minimise grain loss from the more friable specimens.

The final weighing to determine the weights of the individual plugs totally immersed in water was performed by laying each plug on a brass support immersed in a water bath. For the present work, the support was suspended on the underside of the balance pan by means of fine, nylon fishing line. It is important that these suspension wires are as fine as possible since the movement of the support with different plugs laid on it will cause slight changes in its displacement weight, which for the purposes of calculation is assumed to be constant.

An identical procedure was adopted for the 75 mm size plugs, except that evacuation was generally applied for a minimum period of one hour, and only six samples were handled in one batch. Measurement was performed using a Torbal PL2 torsion balance reading to ± 0.1 gm.

4.3.2. Calculation and Accuracy

Porosity is calculated from the following equation which is based on the Archimedes principle:

$$\emptyset = \frac{S_1 - W}{S_1 - S_2} \times 100 \qquad (1)$$

in which $\emptyset$ is interconnected void space expressed as a percentage of bulk volume (porosity).

S_1 is the saturated weight of the sample in air, in grammes.

S_2 is the weight of the saturated sample when fully immersed in water, in grammes.

W is the weight of the dry sample in air, in grammes. It is easily seen that Eq.(1) assumes that the density of water equals unity and therefore, weights of water in grammes are numerically equal to volumes of water in cm^3. Since the density of water at ambient temperature in most laboratories (20°C) differs from unity by only - 0.18%, this assumption is considered justifiable.

Eq.(1) may be rearranged to produce density values inversely proportional to porosity.

Although these measurements are of limited significance in the groundwater field, they occasionally indicate compositional changes in the aquifer material which could affect the chemistry of the ground water. Accordingly, in routine work the density values were computed using the following equations, but space does not allow their significance to be assessed in this thesis:

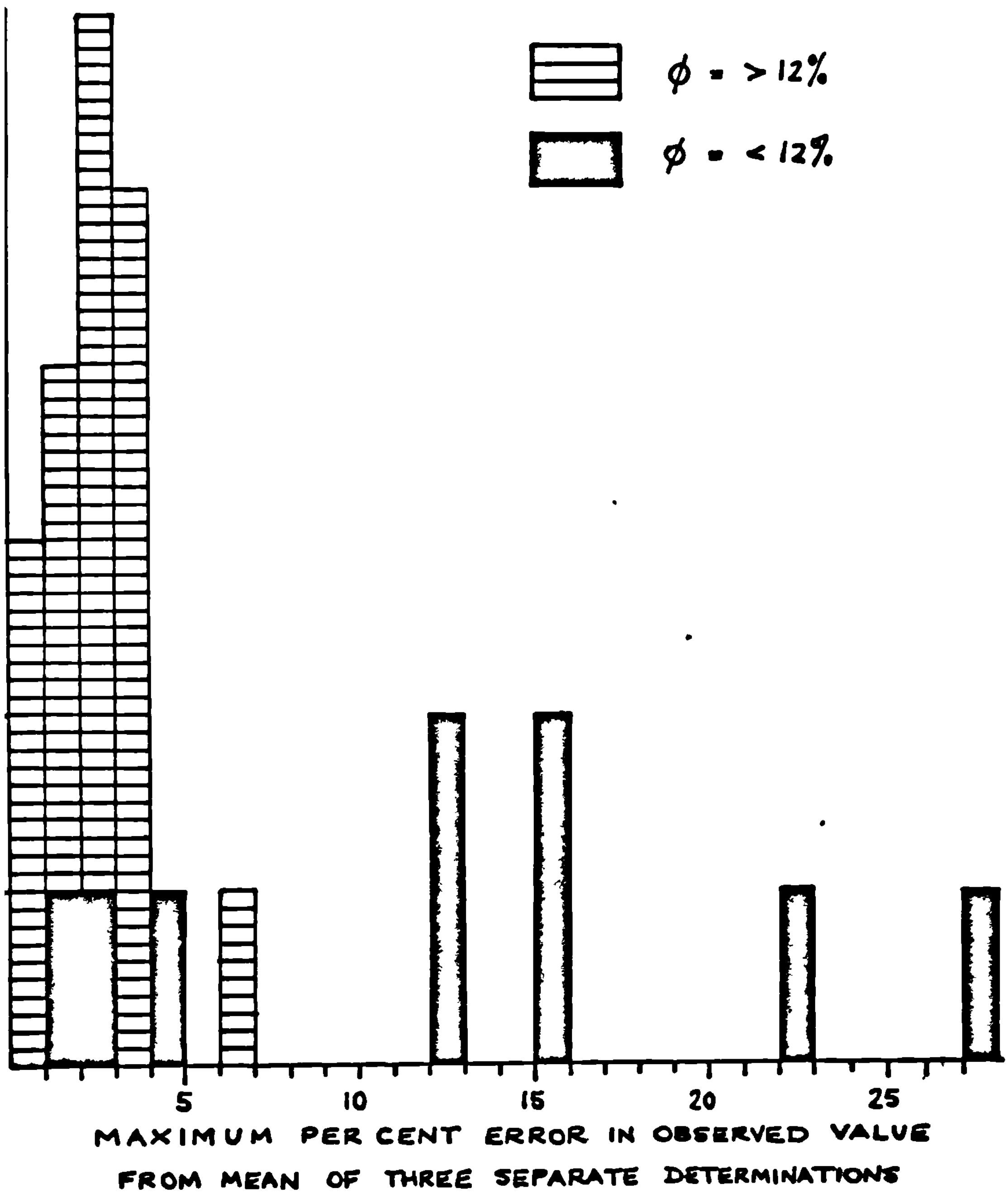
$$\text{bulk dry density} = \frac{W}{S_1 - S_2} \text{ gms. cc}^{-1} \tag{2}$$

$$\text{saturated density} = \frac{S_1}{S_1 - S_2} \text{ gms. cc}^{-1} \tag{3}$$

$$\text{grain density} = \frac{W}{W - S_2} \text{ gms. cc}^{-1} \tag{4}$$

In routine measurement, up to 50 samples per day can be examined, using the equipment and procedures described above. The calculation of Eq.(1) could therefore, occupy a great deal of valuable time. Accordingly, a short computer program was written in Fortran IV and all experimental data computed at the Atlas Computer Laboratory of Science Research Council. The program is given in Chapter Nine.

The accuracy of the porosity measurements quoted here has been investigated in a series of replication tests, the results being tabulated in Table 4, and plotted in fig.29.



3 Frequency distribution of error in porosity measurement.

Since the efficiency of the resaturation process is to some extent dependent on the permeability of the test plugs, and the permeability is largely dependent on porosity, it was considered essential to investigate replication in a batch of plugs whose porosity varied over a wide range. In theory, plugs with a low porosity and permeability should be more difficult to resaturate to exactly the same degree, and therefore, replication in these is likely to be less accurate. Table 4 and fig.29 indicate that this was in fact established. Replication in samples having porosity over 15% has a high probability of being within ± 4% of the mean value; in samples of less than 12% porosity, the accuracy using the liquid resaturation method is considerably inferior, and an arbitrary figure of ± 10% has been applied. In most of the samples examined, porosity was well in excess of 12% and the accuracy of ± 4% applies, which is considered satisfactory. Improvement of the accuracy of the values would necessitate a change in measurement technique, which in view of the friable nature of much of the material would almost certainly be more time consuming than the liquid resaturation method.

TABLE 4

REPLICATION OF POROSITY MEASUREMENTS

PLUG No.	ϕ_1	ϕ_2	ϕ_3	$\bar{\phi}$	Max. percentage deviation from mean value
398H287	3.7	4.4	6.0	4.7	+ 27.33
340H186	4.4	4.3	4.1	4.3	- 4.71
413V2	4.9	5.9	6.5	5.8	- 15.08
398H2-17	6.0	4.4	4.3	4.9	+ 22.45
491-6HY	7.0	6.8	6.9	6.9	- 1.74
40H130	8.0	8.3	8.2	8.2	- 2.20
329-10V2	9.1	11.1	11.0	10.4	- 12.58
329-6HY	10.0	12.8	12.7	11.8	- 15.54
462-5V1	11.0	6.4	6.9	8.1	+ 36.14
383-5HX2	12.0	10.0	9.9	10.6	+ 12.89
437-V1	13.0	13.6	13.3	13.3	- 2.33
329-9V4	14.0	15.6	15.2	15.0	- 6.35
397V1	15.0	15.6	15.9	15.5	- 3.16
491-5HX1	16.0	16.6	16.6	16.4	- 2.38
371H1-16	17.0	17.9	17.6	17.5	- 2.86
204V1	19.0	19.9	19.9	19.6	- 3.06
383-2HY	20.0	21.1	21.1	20.8	- 3.61
96V2	21.0	21.5	21.5	21.4	- 1.69
394H315	22.0	22.6	23.0	22.5	- 2.22
332V1	23.0	24.1	23.7	23.6	- 2.46
466-6HY2	24.0	24.1	24.3	24.1	- 0.54
41H310	25.0	25.3	25.2	25.2	- 0.71
96HY	26.0	26.2	25.7	26.0	- 0.96
330-1HY2	27.0	28.1	29.0	28.0	- 3.64
29V3	28.0	28.6	28.1	28.2	+ 1.38
466-7V1	29.0	29.6	29.1	29.2	+ 1.20
330-3HX2	30.0	28.6	30.5	29.7	- 3.67

ϕ_1 - first measurement ϕ_2 - second measurement

ϕ_3 - third measurement $\bar{\phi}$ - mean porosity value

4.4. GAS PERMEABILITY MEASUREMENT

The smaller sized plugs were tested for permeability to gas in a Gas Permeameter of the type widely used in the oil industry. The design and operation of such instruments has been the subject of a large amount of research by petroleum engineers, especially during the period immediately after the Second World War.

Direct methods of testing the permeability of consolidated rock to various liquids and gases began with the work of Melcher (1925), Glanville (1926), and Tickell et al, (1933). In the same year (1933), Fancher, Lewis and Barnes published a lengthy report dealing with all aspects of the physical properties of oil sands with particular reference to Pennsylvania. In this publication, a design for a Gas Permeameter appeared, which has survived with minor modifications up to the present day. This is now referred to as the Fancher instrument, and its use is approved in the A.P.I. Recommended Practice (1960) already referred to. At the time the I.G.S. project was begun, and up to the present time, the Fancher instrument is used in a high proportion of core analysis laboratories in the oil industry.

After the publication of the work of Fancher, Lewis and Barnes, attention was turned to the development of alternative direct methods of laboratory measurement of permeability.

In 1938, Hassler published his design for equipment to evaluate permeability in full diameter cores. This subsequently became known as the Hassler permeameter, in which a length of core is placed horizontally in a pressure vessel to which a tangential confining pressure may be applied by the use of a rubber or neoprene sleeve (see A.P.I.R.P. No.40, 1960, p.35). In this way, permeability can be evaluated over a wide range of confining pressures. Cells of this type were not used in the present study.

In the 1940's, there was a shift of emphasis to more theoretical studies of what actually happens when liquids and gases are passed through porous rock materials and the important work of Klinkenberg (1941) and Grunberg and Missan (1943), was published, followed by that of Heid et al, (1950). Much of this work was concerned with the problem of interpreting differences in the permeability of a rock sample to various gases and liquids. This topic is currently the subject of research amongst petroleum engineers, especially in connection with interactions which may take place between saline waters and rocks containing swelling clay materials.

By the middle of the 1950's sufficient research had been carried out and enough experience gained for the American Petroleum Institute to publish, in 1956, its Recommended Practice for determining the Permeability of Porous Media. This was written with the same thoroughness and rigorous attention to detail as the later work relating to general core analysis (1960).

In recent years techniques have tended to become standardised in order that data from different sources can be compared with cónfidence.

4.4.1. Equipment and Procedure

The Fancher instrument used in the present study is illustrated in PLATE 15B and is shown diagrammatically in Appendix 1 fig. 4 . It was designed by the British Petroleum Company, constructed by I.G.S. workshop staff, and assembled by the writer. Its construction follows the design criteria given in the A.P.I. Recommended Practice (p.14). The apparatus is based on Darcy's Law for the special case of isothermal steady state flow of gas through porous media. This is usually expressed in the following form:

$$k = \frac{2000\,\eta Q L p_2}{A(p_1^2 - p_2^2)} \qquad (5)$$

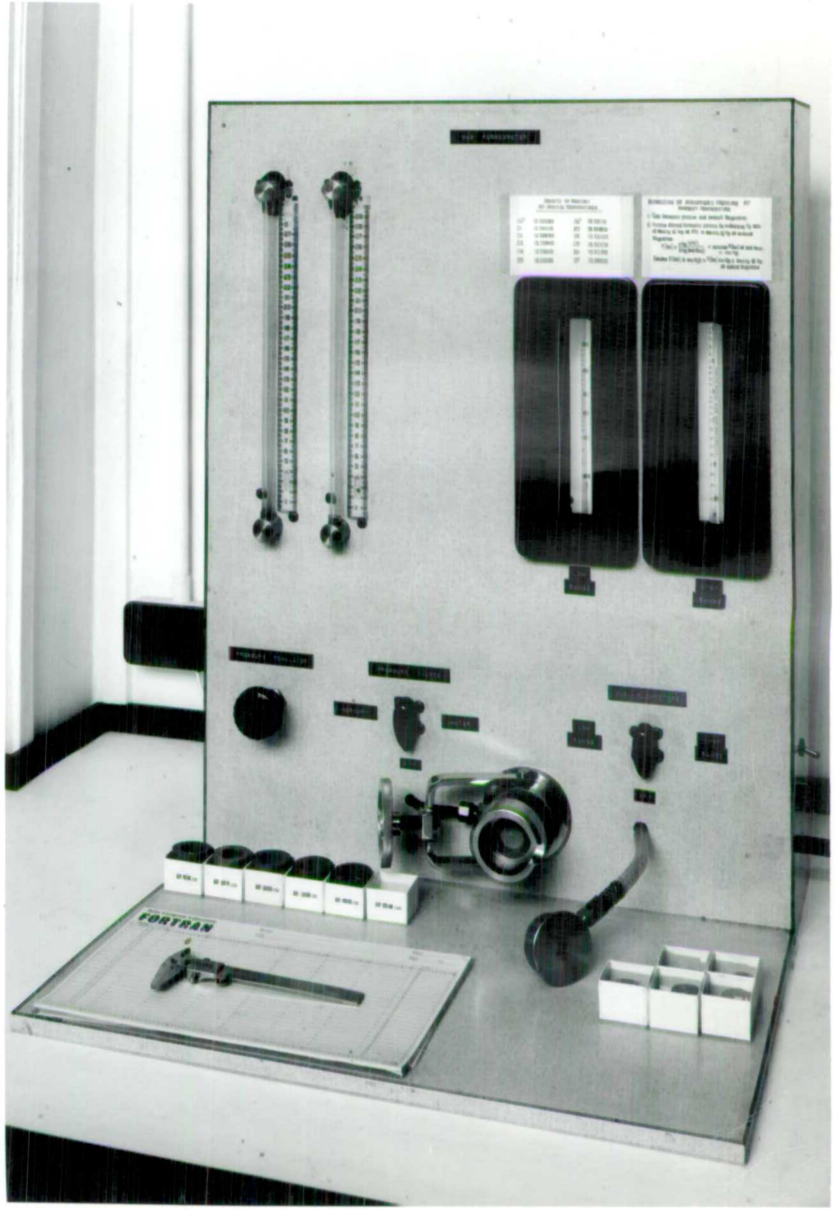
in which k is the intrinsic permeability of the porous medium, expressed in millidarcys

η is the viscosity of the gas in centipoises
Q is the discharge rate of the gas in $cm^3\ sec^{-1}$
L is the length of the plug in cm.
A is the cross-sectional area of the plug in cm^2
p_2 is the outlet gas pressure in atmospheres
p_1 is the inlet gas pressure in atmospheres

The darcy unit is precisely defined in the Recommended Practice (1956)(p.3) as follows: "A porous medium has a permeability of one darcy when a single phase fluid of one centipoise viscosity that completely fills the voids of the medium will flow through it under conditions of viscous

PLATE 15

A. Mk.III Water Permeability Testing System



B. IGS - BP Gas Permeameter

flow at a rate of one cubic centimetre per second per square centimetre of cross-sectional area under a pressure or equivalent hydraulic gradient of one atmosphere (76.0 cm Hg) per centimetre". A millidarcy is therefore equal to 10^{-3} darcys and is abbreviated in this thesis to md.

The derivation of Eq.(5) is dealt with adequately elsewhere (Muskat, 1949; A.P.I. R.P.No.27, 1956). Much work has been carried out in search of a theoretical justification of the empirical observation of Darcy (1856). Recent syntheses on this subject by de Wiest and by Rumer are to be found in de Wiest (1969).

Eq.(5) demonstrates that to obtain a solution for k, six variables must be measured. By selection of a standard gas for all measurements the viscosity term becomes a constant but each of the other five must be measured. The I.G.S./B.P. permeameter consists of a Fancher-type core holder, two upstream pressure manometers (one water, the other mercury), a high range and low range gas flowmeter, a source of compressed gas, an on-line drying tube and suitable valves and pressure regulators. The instrument was used in a laboratory, in which the termperature varied by $\pm$ 2°C.

In a routine test using compressed air as the test fluid, the sample plug was first calipered to obtain values for sample length, l and cross sectional area, A. The plug was then inserted into a rubber sealing ring tapped with a parallel-sided hole and having an outside taper of 1 in 8.

The rubber rings are a series of specially moulded stoppers, of varying hole sizes, to accommodate plugs of different diameters. Rings were used which were undersize, up to a maximum of 2% on the diameter, in order that a close-fit was obtained and side wall leakage along the rubber-rock contact eliminated.

In accordance with the Fancher-type design of the core holder, the plug in its rubber ring was pushed into a steel ring which had an internal taper matching that of the rubber ring. The assembly was then pushed into the core chamber and sealed by means of O-rings and a block and yoke (see PLATE 15B). The block was screwed up by means of the handwheel which was given a standard number of turns.

Once sealing was complete, gas was admitted from the air line and flow commenced. The inlet pressure was measured in one of the manometers, outlet pressure was read from the barometer and the gas discharge rate observed in one of the rotameters on the right-hand side of the instrument. It was found that flow rate and pressure achieved steady state conditions after only a few moments.

Certain precautions had to be taken to avoid erroneous results. Slightly misshapen or non-parallel sided plugs were not tested; nor were those exhibiting macroscopic cracks. Certain very friable plugs gave anomalously high values which have been excluded from the data section (Chapter Five). The effective range of the instrument is from 1 md to 23000 md.

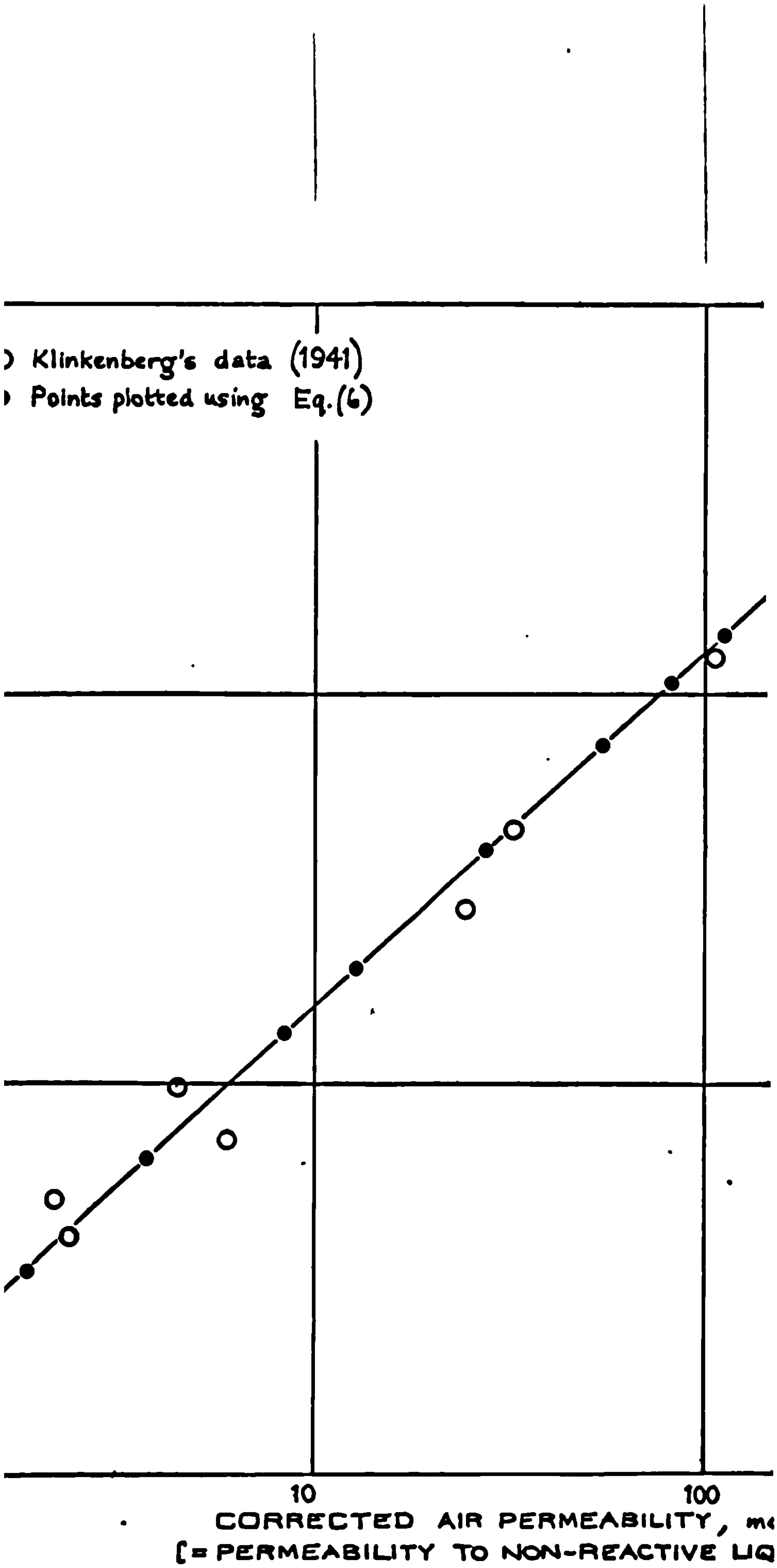
4.4.2. Calculation

Permeability in darcy units of intrinsic permeability was computed from Eq.(5) using a brief computer program written in Fortran IV language and given in Chapter Nine. This program included a facility to apply automatically a negative correction for the gas slippage phenomenon which was rigorously examined by Klinkenberg (1941). To simplify the correction process, Klinkenberg's experimental data relating to observed slippage using air as the test gas were replotted as in fig.30, and found to have an approximately linear relationship. The equation of this function was found to be on inspection:

$$\log_{10} k_c = 1.1 \log_{10} k_u - \log_{10} 2.1 \qquad (6)$$

in which k_c is the corrected lower value for intrinsic permeability and k_u is the uncorrected higher value. Fig.30 indicates a plot of Klinkenberg's own data from Table 9 of his paper (1941) over the range 1 md to 1000 md. Superimposed on it, is the straight line curve of Eq.(6) and some computed values using this function. Note that for convenience, k_c has been plotted on the abscissa.

It is considered that Eq.(6) fits Klinkenberg's data adequately for most routine laboratory measurements of permeability, at least for ground water purposes.
An alternative and more precise correction factor is discussed in the A.P.I. Recommended Practice (1956), based on experiments specially carried out for the publication.



orrection chart for Klinkenberg effect over the range 1

In work requiring a higher overall precision, this should probably be used in preference to Eq.(6). The equation is:

$$kc = \frac{k_u}{1 + \frac{b}{Pm}} \tag{7}$$

in which k_c and k_u have the same meanings as in Eq.(6), Pm is the mean pressure at which the gas is flowing and $b = 0.777\ k_c^{-0.39}$. A discussion of the procedure for applying the Klinkenberg correction using Eq.(7) is given in the Recommended Practice (1956).

The object of applying this correction by either of the methods given above, is to convert the observed permeability to gas to the permeability to a non-reactive liquid. Since the work now being described is to a large extent concerned with determination of rates of flow of ground water through predominantly medium grained continental sandstones, the correction of the k values to a figure appropriate for a non-reactive liquid is clearly an important one which should be applied. The computer program automatically applies the correction to all solutions of Eq.(5) which have a value of less than 1000 millidarcies. The error involved in assuming that the gas values are identical to non-reactive liquid values where k is greater than 1000 millidarcies, is within the limits of experimental error. Fig.30 indicates that the size of the error is approximately +5%.

It should be noted that Eq.(6) is valid up to the point on the curve shown in fig.30 at which $k_c = k_u = 1667.99$ md, or in other words, the point at which the Klinkenberg effect becomes zero. For convenience, an arbitrary limit of 1000 md has been taken, beyond which the correction has not been applied as its magnitude is well within the limits of experimental error.

It should be noted that although the units of permeability used in this work are those of intrinsic permeability, the correction must nevertheless be applied whenever gas is being used in the testing of samples of permeability less than 1000 md. This is because the phenomenon is related to non-Darcy behaviour of the fluid being used to provide solutions of Eq.(5). A full analysis of the mechanism of the slip phenomenon and its implications is given by Klinkenberg (1941) and his work was, to some degree, extended by Heid et al, (1950).

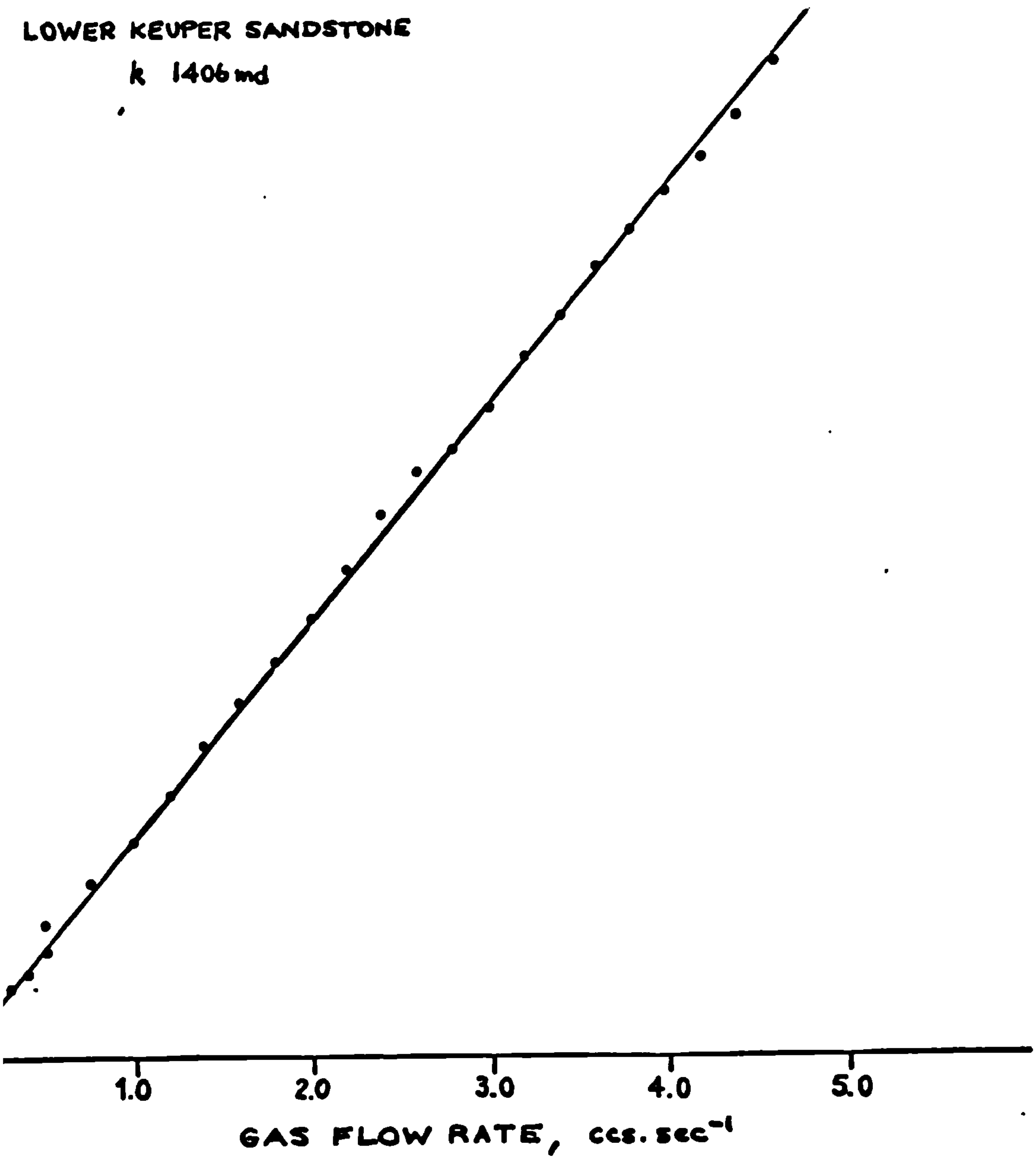
4.4.3. Accuracy

There is virtually no published data on the accuracy of laboratory permeability measurements. With regard to the accuracy of the Fancher-type gas instrument, comparison has already been made of the relative advantage of examining large numbers of samples with a moderate precision over small numbers of samples with a very high accuracy. An analysis of the experimental error in values determined with this apparatus was made in two stages: i) instrument errors and ii) operator error.

i) <u>Instrument error</u> - This was investigated in the course of an experimental check to demonstrate the empirical validity of Darcy's Law using the gas instrument. The resulting graph of discharge rate plotted against pressure gradient appears in fig.31. It closely approximates to a linear function of the form $y = mx + c$, and demonstrates that Darcy's Law appears to be valid over the range of pressure gradient studied, in an average medium grained red sandstone of 25-30% porosity. If the permeability of the specimen is computed from the points plotted in fig.31, and a frequency distribution diagram drawn of these permeability values, the scatter shown in fig.32 emerges. This could be described as approximately Gaussian with a tendency to skewness in the higher values. The mean permeability value is 1406 md with a standard deviation of 33 md or 2.4%.

ii) <u>Operator</u> - - To attempt to assess operator error, a number of replication tests were carried out by three different operators on a group of samples which exhibited a wide range of permeability. Each of 22 plugs was tested twice by each operator, and the results, expressed in millidarcies, are given in Table 5. As far as was practicable, each operator subjected the plugs to the procedure described above. The six values obtained for each specimen are averaged in col.8 of the Table and the maximum departure of any single value from this mean, either positive or negative, appears in col.9.

ɛck data showing the validity of Darcy's Law using the IGS-BP Gas Permeameter



Col.No.1.	2	3	4	5	6	7	8	9	10
PLUG No.	1st OPERATOR		2nd OPERATOR		3rd OPERATOR		ARITHMETIC MEAN VALUE	MAXIMUM DEVIATION	% DEVIATION FROM MEAN
	RUN 1	RUN 2	RUN 1	RUN 2	RUN 1	RUN 2			
359-1V	3	3	3	5	5	6	4.2	1.8	42.8
359-1H1235	72	81	60	70	81	80	74	14	9.5
359-1H2235	36	49	36	45	57	53	46	10	19.6
359-1H2325	129	143	117	190	150	146	146	44	30.0
359-2V2	635	761	772	797	909	805	780	145	18.6
359-2H298	2842	2244	2104	2282	2526	2637	2439	403	16.6
359-3H213	508	442	n.d.	456	539	503	490	49	10.0
359-3H303	846	780	685	782	846	814	792	107	13.5
359-4V	59	51	51	60	61	n.d.	56	5	8.9
359-4H230	716	677	656	905	745	731	738	167	22.6
359-4H320	1077	1316	801	1085	875	883	1006	205	20.3
359-5V	1	1	1	2	1	2	1.3	0.7	-
359-6V	215	205	206	234	278	263	234	44	18.9
359-6H65	128	131	114	141	133	140	131	17	13.0
359-6H155	477	445	421	465	473	463	457	36	7.9
359-7V	38	24	23	33	34	30	30	8	26.7
359-7H1110	267	251	217	297	279	282	266	49	18.4
359-7H2110	192	227	173	219	239	227	213	40	18.8
359-8V1	942	827	743	862	920	805	850	107	12.6
359-8V2	891	903	663	773	883	768	814	151	18.6
359-8H70	511	546	362	432	507	436	466	104	22.3
359-8H160	701	852	613	674	747	702	715	137	19.2

All values are in millidarcies.

This deviation is expressed as a percentage of the mean of the 6 values in col.10, and these percentages range from 7.9 to 42.8. Neglecting the first sample, the average value of these percentage deviations is $\pm$ 17.3 per cent. This value is the average maximum expected error in any single measurement made by any of the operators using the gas instrument. Fig.33 demonstrates the frequency distribution of these maximum errors and it can be seen to approach a normal or Gaussian type.

The magnitude of this operator error is acceptable only in the particular field of study under discussion. In comparison with the magnitude of errors tolerated in other general laboratory procedures in scientific research, a figure of $\pm$ 17% would be more than enough to suggest that there was something basically wrong in the design or operation of the equipment. The source of the operator error almost certainly lies in the manual sealing operation, whereby the plug of rock is placed in the core chamber and a pressure-tight seal made with the block and yoke (see PLATE 15B). Owing to the significant compressibility of these rocks, and the considerable mechanical advantage which may be exerted by tightening the block and yoke, it is considered that compaction of the rock structure may occur and this is the root cause of the variation in apparent permeability with different operators.

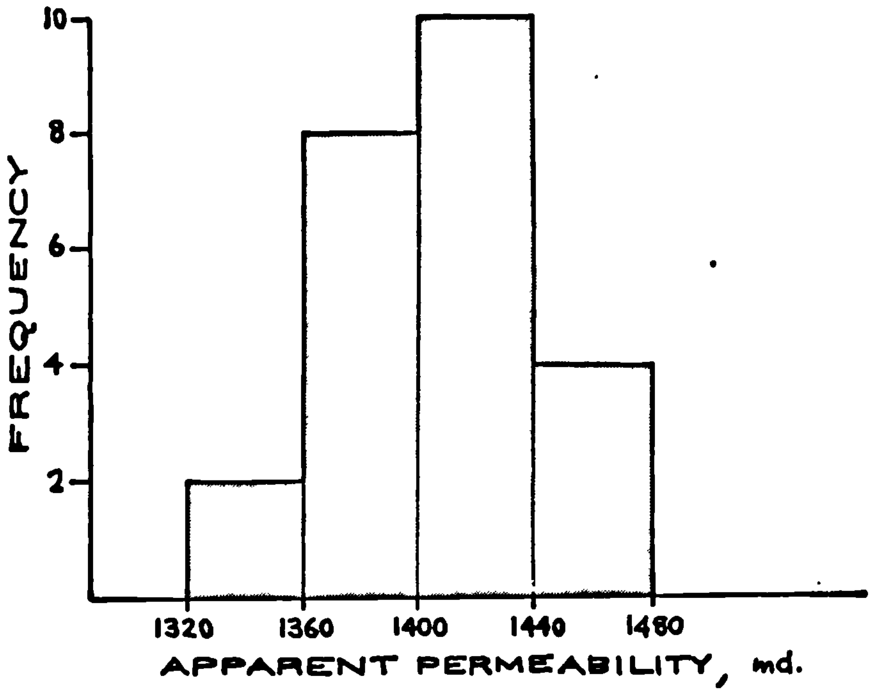


Fig. 32 Frequency distribution of k values computed from data presented in fig. 31.

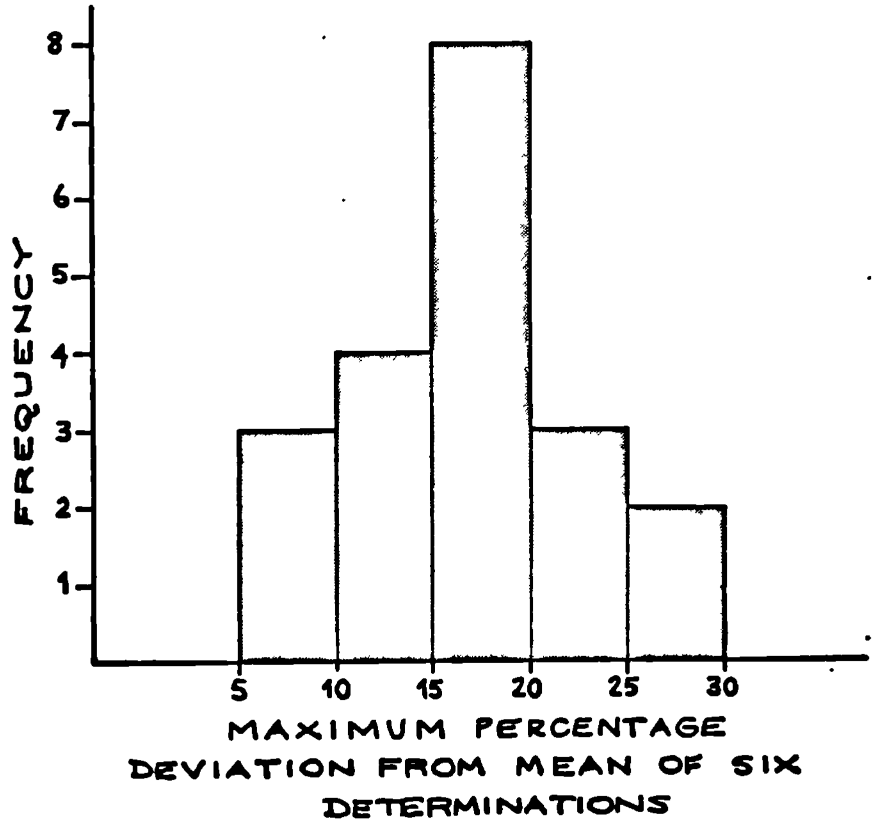
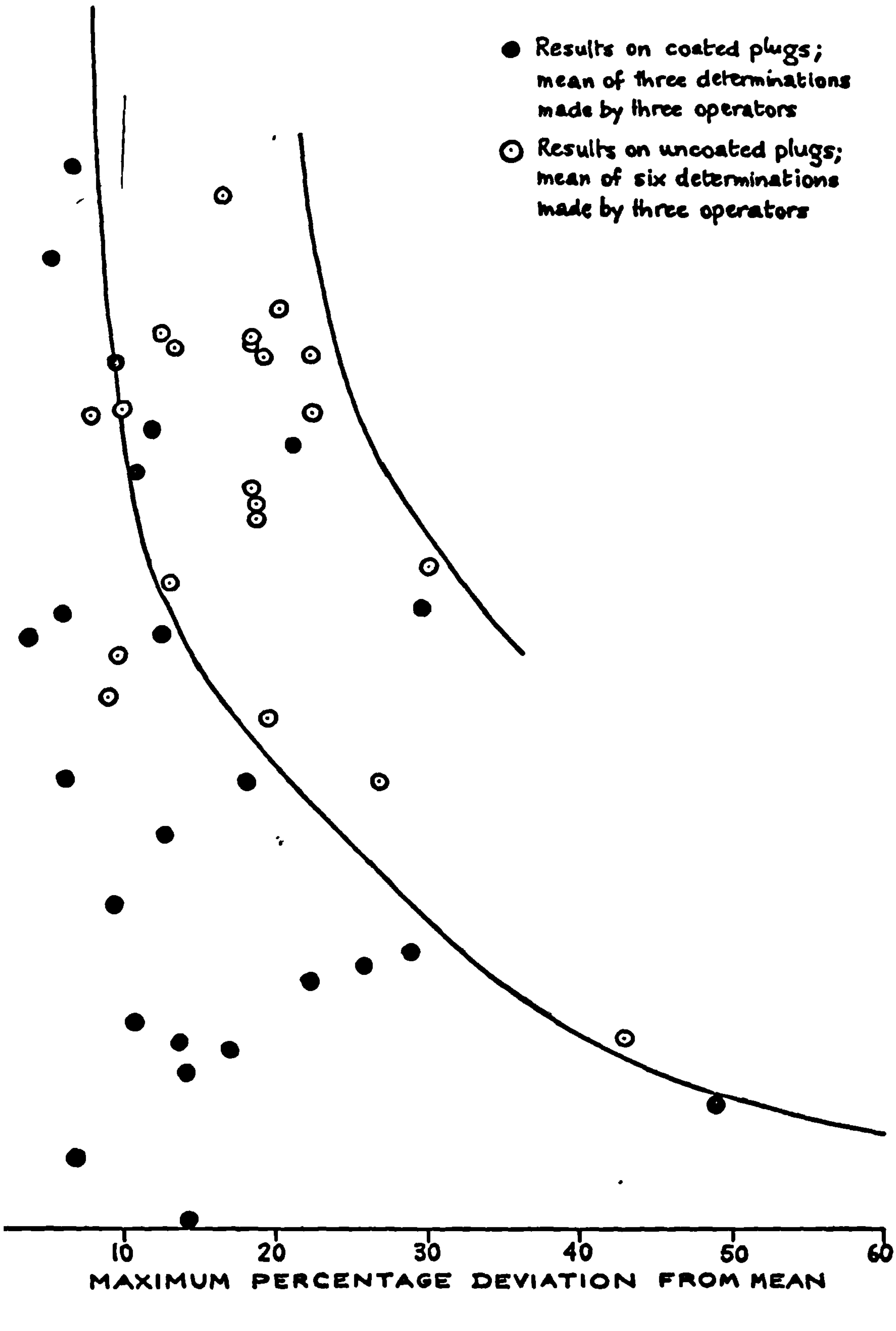


Fig. 33 Frequency distribution of maximum errors given in Table 4, col. 10.

In order to investigate, and perhaps reduce, the magnitude of the operator error, a second set of plugs was subjected to replication testing. The possibility of compressing the rock samples while they were being sealed in the rubber sleeve of the Fancher core holder was reduced to a minimum by coating each of the plugs with a thin (400 micron thick) film of epoxy resin (100 parts by weight Araldite SW 407 mixed with 20 parts by weight Araldite HY993). This particular compound is characterised by good sealing and low penetration properties. After the plugs had been coated, they were tested by three different operators in the air permeameter and the results (given in Table 6) then compared with those obtained in the previous uncoated replication tests. Fig.34 indicates that there was considerable improvement in the accuracy of the test data, with significant reduction in the maximum percent deviations from the mean values.

It seems very probable, therefore, that one of the principal sources of operator error using the Fancher core holder is the sealing operation, and that this can be reduced by rather time-consuming coating of the test samples before measurement. The error is virtually excluded in the Hassler Permeameter already referred to, in which a radial confining pressure is applied to the specimen by means of a flexible jacket, but it should be noted that a single measurement takes at least six times as long using this, compared with the less accurate Fancher device.



iagram illustrating improvement in accuracy of permeability
asurement obtained using coated specimens.

PLUG No.	1st OPERATOR k,md	2nd OPERATOR k,md	3 PERATOR md	ARITHMETIC MEAN VALUE	MAXIMUM DEVIATION	% DEVIATION FROM MEAN
681-3H	79.41	97.98	80	87.06	10.92	12.54
681-24H	1.91	3.82	.97	2.57	1.25	48.83
682-9H	29.25	31.43	2 .18	29.62	1.81	6.11
682-19H	1460.29	1455.99	15 7.16	1501.15	86.01	5.25
683-15H	620.01	750.58	682.11	684.23	64.22	9.39
683-16H	2928.80	2870.19	3197.57	2998.85	198.72	6.63
684-11H	308.17	436.91	336.41	360.50	76.41	21.20
684-21H	118.07	127.82	115.87	120.59	7.23	6.00
685-10H	5.76	9.63	8.88	8.09	2.33	28.80
685-20H	5.48	8.88	7.79	7.38	1.90	25.78
685-28H	5.35	7.90	6.17	6.47	1.43	22.04
685-38H	275.45	331.73	291.59	299.59	32.14	10.73
686-25H	4.93	5.20	4.30	4.81	0.51	10.60
688-9H	4.03	4.44	3.24	3.90	0.66	16.99
688-24H	1.74	1.85	1.60	1.73	0.12	6.94
688-44H	356.14	416.92	437.96	403.67	47.53	11.77
688-55H	85.21	85.40	90.19	86.93	3.26	3.75
688-65H	12.54	11.49	10.41	11.48	1.07	9.32
690-8H	0.47	0.39	0.37	0.41	0.06	14.63
697-5H	0.37	0.37	0.36	0.37	0.007	1.82
697-16H	1.15	1.16	0.92	1.08	0.16	14.55
697-26H	23.98	32.07	31.71	29.25	5.27	18.03
697-36H	3.88	4.61	3.66	4.05	0.56	13.83
697-46H	17.22	21.16	20.77	19.72	2.50	12.66
697-53H	3.14	3.74	2.94	3.27	0.47	14.26

4.5. WATER PERMEABILITY MEASUREMENTS

The larger sized plugs were tested for both water and gas permeability, with two objectives in mind:

i) to establish that the air permeability values obtained were, in fact, values of intrinsic permeability, and that they closely approximated to what the water permeability would be, and

ii) in the case of the least coherent sandrock samples, it was found that 75 mm diameter test plugs could frequently be cut from material from which it was impossible to produce 25 mm diameter test plugs. These samples have been found to have the highest permeability.

The apparatus used for the water permeability determination in orthodox petroleum core analysis is the Hassler cell for cores larger than about 35 mm diameter; this is the cell which has provision for the application of a radial confining pressure. Unfortunately, a cell of this type was not available at the time the measurement programme was begun, and a cheaper alternative system of testing had to be devised, which could accommodate consolidated non-disturbed samples of the sandstones. A series of experiments was undertaken over a period of s in the course of which various technical problems were overcome, the most important of which was the problem of reduction of apparent permeability with time.

These experiments may be divided into 3 stages of development.

4.5.1. First Series of Experiments

The apparatus shown in fig.35 and fig.36, was used for the preliminary tests which were primarily concerned with the determination of the reproducibility of a water permeability determination using a simple form of constant pressure instrument. The most important part of the equipment, the coreholder or cell, is a modified version of the Engineering Laboratory Equipment Ltd. High Pressure Permeability Cell, originally designed by A.F.Mendoza of Ground Engineering Limited.

i) Instrument details: The E.L.E. cell has been modified in two respects - the original head plate fitted with two thumb clamps has been replaced by a detachable tapped block (see fig.35). When in place, it is secured by a thumb screw and brass yoke which bear down on the cylindrical core-plug sealed in a thermoplastic (Vinomold) compression sleeve. The cell in this form approximates very closely in design to the Fancher-type permeability cell (Fancher, Lewis and Barnes, 1933). The tapped block has an inlet port for the testing fluid, which opens centrally above a sintered brass filter disk of average pore-size, 45 microns. Two manometer tappings arranged diametrically opposite one another open at the margins of the disk and these allow the precise pressure at the base of the disk (and therefore, at the top surface of the sample) to d off two manometers which are connected by f x le tuoin he cell.

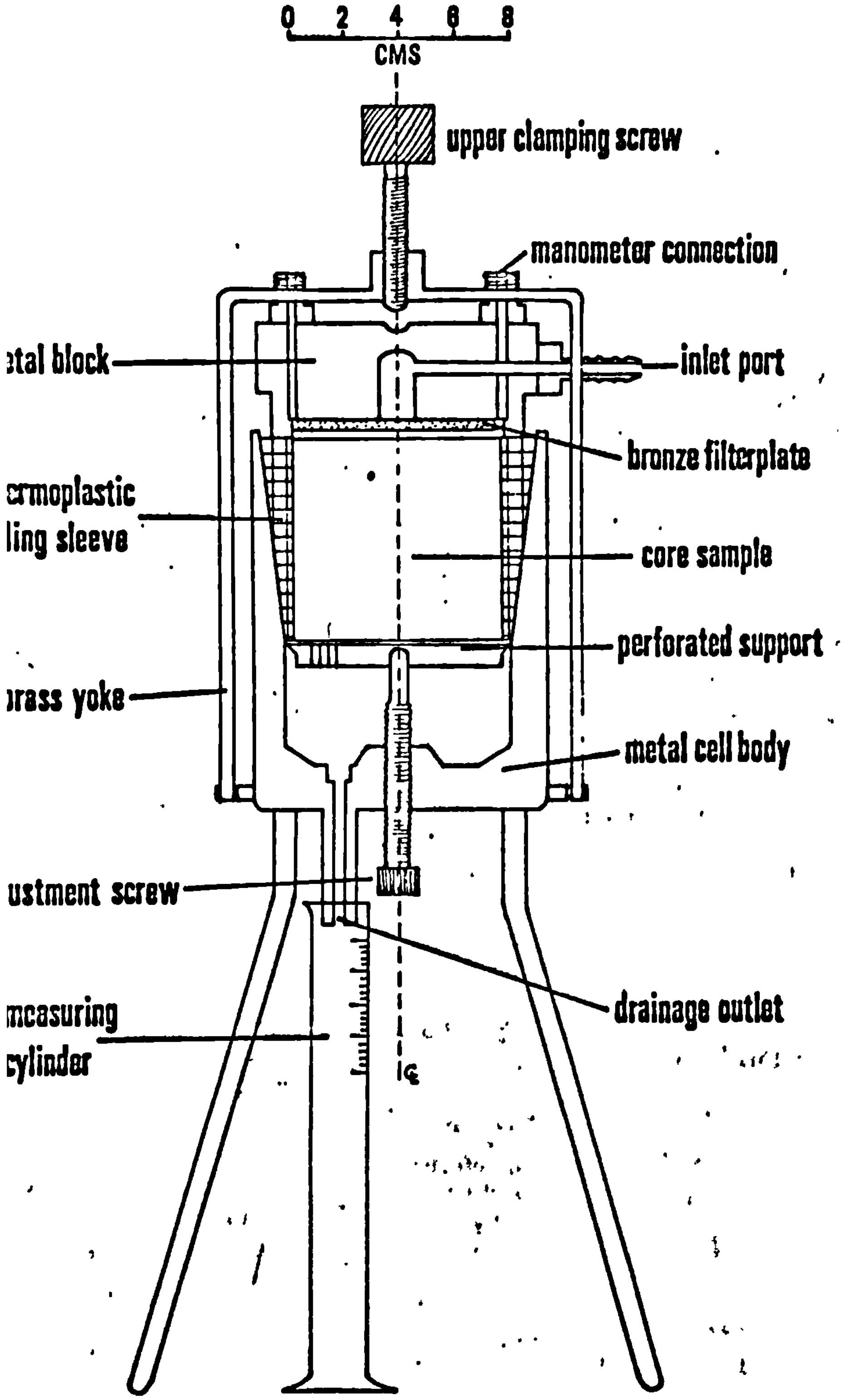


Fig. 35 I. G. S. -Fancher type permeability cell

The rock core is sealed in a detachable H.M.C. 18 Grade Vinomold compression sleeve, which for the purpose of these tests was varied in diameter from fit size to 3.2 mm (⅛") undersize on the diameter. The effect of this change in tightness on the permeability results will be discussed below.

Finally, below the core, sealed in its tapered ring lies a perforated plate. Its position can be altered by use of the lower adjustment screw and at the commencement of a test run, this plate is raised so that it just comes into contact with the base of the specimen. Its main function is to stabilise the rate of fluid discharge from the outlet point at the base of the cell.

ii) Test water and pressure control: Various types of water were used in the first series of experiments. Initially, unfiltered deionized London tap water was employed. This was changed early in the tests to filtered deionized water having an electrical conductivity ranging between 5 and 60 micromhos with a pH of 5.5. The filtration equipment consisted of a Millepore XX67 22 litre stainless steel pressure vessel couplec up to a 44 cu.ft. nitrogen gas cylinder. Fluid was supplied at 10 p.s.i. from the pressure vessel to a standard Millepore filt holder. The earlier tests used water from which particles larger than 5 microns had been excluded, whereas the later tests used water cleared of particles larger than 5 microns. Towards the end of these tests boiled water was employed, since there was a suspicion that some of the anomalous results might have been caused by the exsolution of dissolved gases in the water while it was permeating the sample

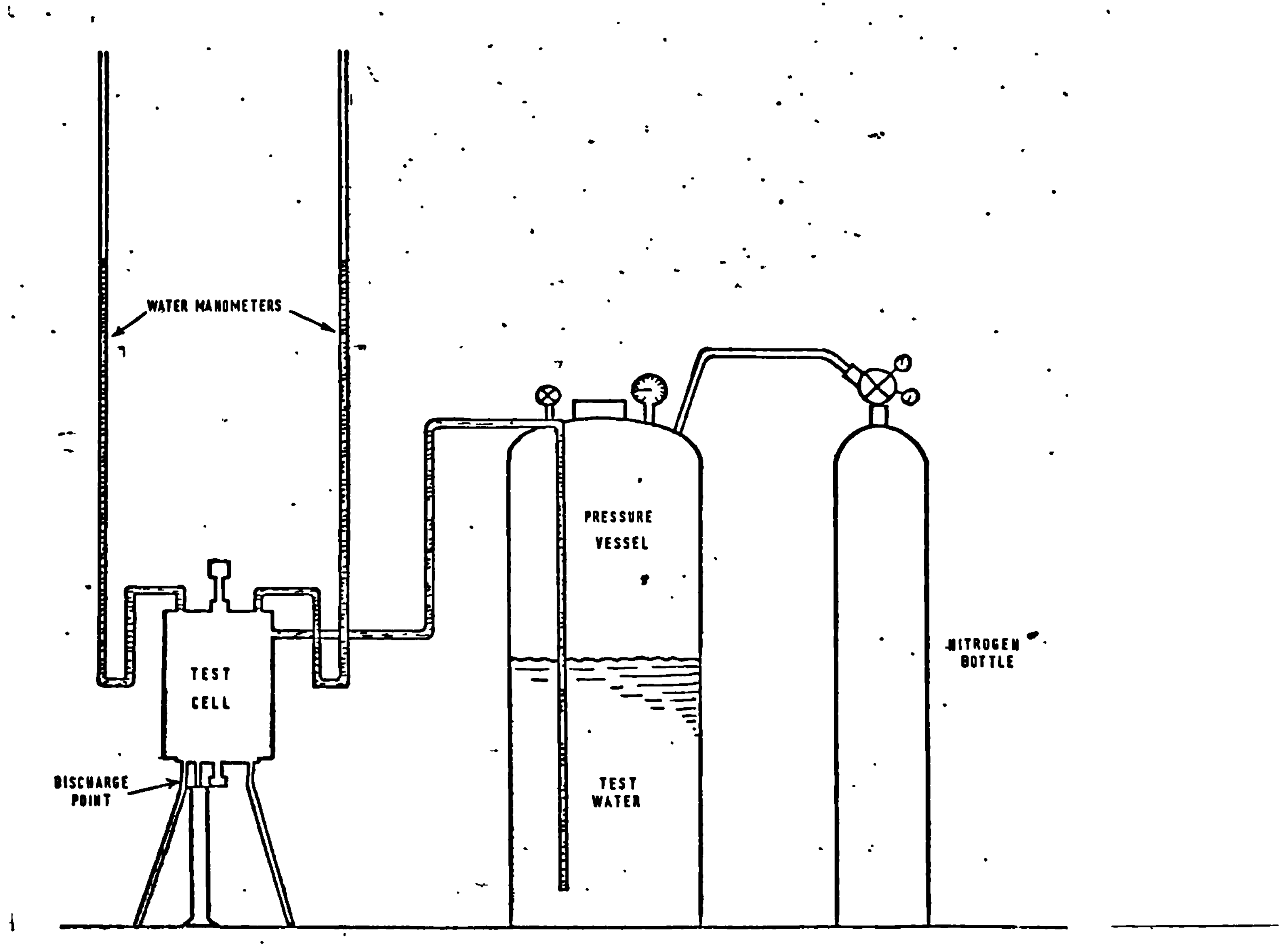


Fig.36 Mk I Water Permeability Testing System.

Some tests were run using filtered groundwater of pH 7.5 from a borehole in the Bunter formation at Bellington, Worcs.

The fluid pressure during the tests was directly controlled by the nitrogen in the Millepore pressure vessel which was filled with the testing fluid. The general arrangement of the equipment is shown in Fig.36. Sensitive control was afforded by the system and changes in head of as little as 0.5 cm. were readily effected. The range of pressure employed in the tests was from approximately 10 cm. to 75 cm. water.

iii) Sample Material: A sequence of 6.65 cm. (2.625") diameter cores from a borehole in Permo-Triassic sandstones at Kennel Bridge, Comber, Northern Ireland (Irish Grid Reference: J455700) were used in the tests as these were readily available and of convenient dimensions. Their lithology was also generally typical of the sandstone aquifers for which reproducible data are required.

The lengths of the cores varied from 5.14 cm. to 7.73 cm. Porosity and density data are tabulated below. Many iterative tests were carried out on specimens Nos. 326-5 and 326-6.

TABLE 7

CORE DATA

SAMPLE No.	DEPTH IN BOREHOLE IN FT.	BULK DRY DENSITY gm. cc^{-1}	SATURATED DENSITY gm. cc^{-1}	GRAIN DENSITY gm. cc^{-1}	EFFECTIVE POROSITY* %
326-1	168	1.83	2.14	2.67	31.6
326-2	175	1.95	2.22	2.66	26.8
326-3	182	2.23	2.40	2.70	17.5
326-4	186	1.87	2.15	2.60	28.0
326-5	196	2.03	2.27	2.68	24.1
326-6	201	1.92	2.20	2.68	28.2
326-7	207	1.99	2.23	2.62	24.1
326-8	212	1.92	2.21	2.68	28.1
326-9	217	2.21	2.37	2.63	15.7

* defined as interconnected void space expressed as a percentage of bulk volume.

iv) Experimental Procedure: The sample to be tested was first evacuated to approximately 15 mm Hg. for a few minutes, then saturated under this vacuum for a period of up to four hours in deionized water, using the vacuum apparatus shown in PLATE 14B. The sample was then removed from the saturation chamber and a thermoplastic compression sleeve of appropriate size was fitted over it; it was then placed in the body of the permeability cell without allowing aeration to take place. To ensure this, water was poured onto the top of the cell containing the sample until it reached the brim, and then the tapped block with fluid already flowing into it was rapidly placed in position and clamped down using the upper clamping scre

The manometer tubes were connected to the cell last of all, and these were found to provide an excellent escape route for any air which may have become trapped in the top of the cell during the sealing process. Once the sample was sealed, pressure and discharge was allowed to stabilise; in practice, the apparatus usually came "into control" within 2 minutes of beginning the test. Test runs consisted of precisely measuring pressure in the two manometer tubes and the discharge from the outlet point at approximately 5-10 cm intervals of head. Individual tests were made over periods of from 30 minutes up to 3 hours, depending on the object of the test. Fig.37 shows typical curves obtained during these tests. An important aspect of the procedure at this stage was the fact that between tests the specimen was kept under distilled water. There was no drying out, and resaturation during these tests.

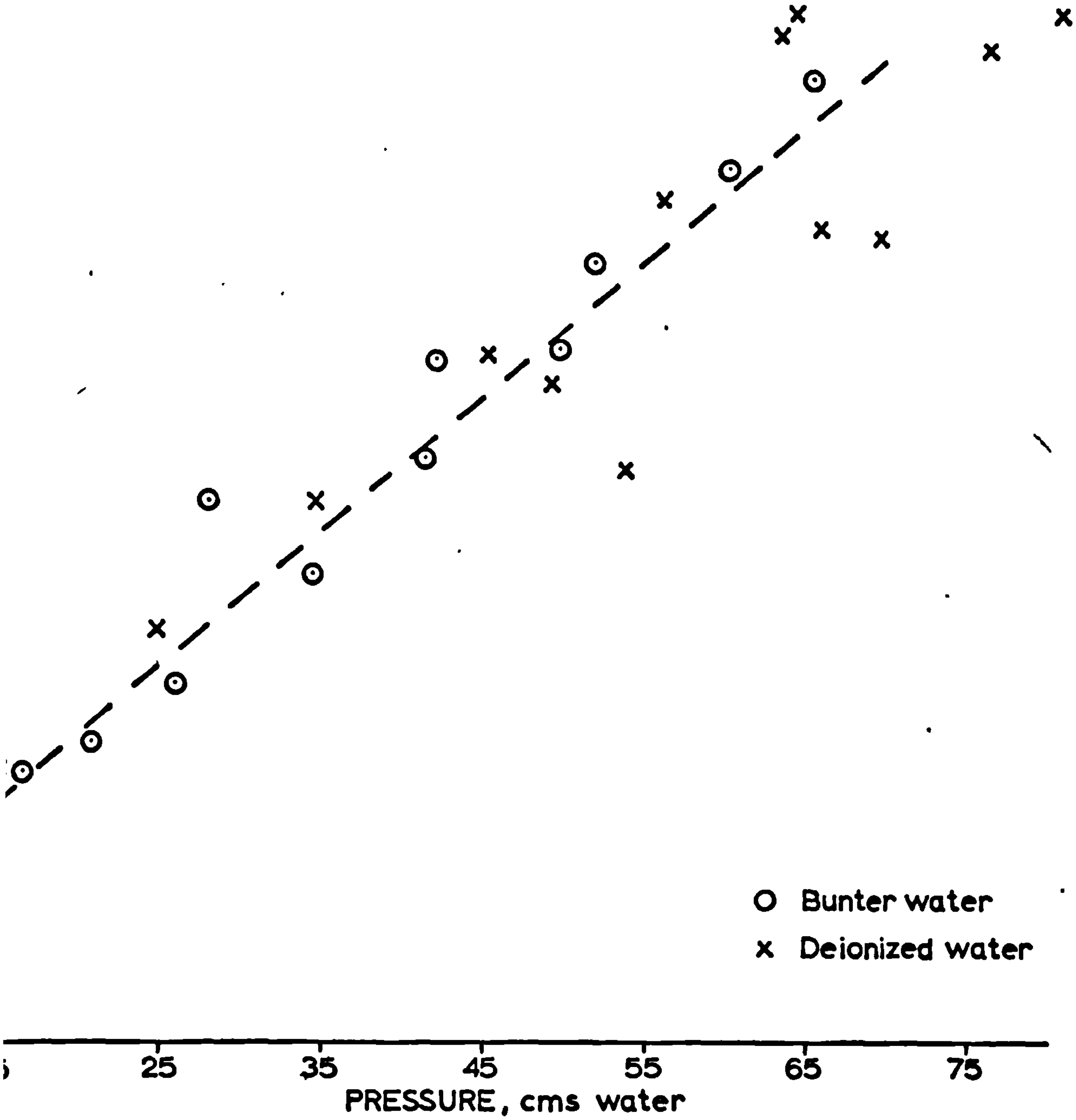
The first series of tests were carried out with a view to determining the effect on the calculated permeability of the following factors:-

1. Effect of change in tightness of the compression sleeve.

2. Effect of removal of sample from the compression sleeve and subsequent replacement in the same sleeve.

3. Effect of rotating the sample in the sleeve, vertically or horizontally.

4. Effect of altering tightness of upper clamping screw, or the lower filter adjustment screw.



7 Sample No.326-6 : test data showing reaction to different liquids.

5. Effect of using water of differing chemical composition and filtration quality in the testing process.

6. Effect of period of testing on the permeability rate.

7. Effect of dehydration and resaturation of the sample on its permeability.

Above all, the tests were intended to determine the margin of experimental error likely to occur in any permeability value quoted for particular specimens. It will be demonstrated that although the margin of experimental error using the measurement system described here is low, long-term changes of the rate of permeability under constant head with time of a partly irreversible nature were found to present a serious problem, which had to be understood in order for the system to be used satisfactorily on a routine basis.

v) Observations and Results:

Sleeve Tightness - The rate of discharge under a constant head of 40 cm water for specimen 326-6 was determined for various sizes of sleeve. With a sleeve of the same internal diameter as the diameter of the core plug, an average of six short repeat tests give a rate of 28.5 cc/min. Using a 1.6 mm (1/16") under size (on the diameter) sleeve, two repeat tests give a rate of 10.0 cc/min. falling off after a lapse of one day to 7.0 cc/min. Constant flow rate conditions over a period of five days were obtained with the fit size sleeve which incidentally did not have a flat upper contact surface.

In view of the very obvious decline in rate observed when a tighter sleeve was being employed, it is felt that possibly leakage down the walls of the core plug produced a stabilisation of the flow rate at about 22 cc/min. and the expected decline in flow rate owing to other factors discussed below was not observed. Certainly the reduction in the rate caused apparently by the use of a tight sleeve, is very significant, and standardisation of sleeve tightness for routine tests is clearly necessary.

The effect of sleeve tightness was also studied with specimen 326-5 with similar results. The rate of discharge (40 cm water head) with a sleeve of same i/d as the diameter of the plug was found to be between 20 and 25 cc/min. With a tighter sleeve (1.6 mm undersize onthe diameter) the flow rate initially fell to 10 cc/min. and after a period of further tests, the rate continued to fall to a minimum of approx. 4 cc/min.

Correlation of the results using a sleeve with results from a waxed-in sample were attempted, but as poor contact between the wax and the saturated sample was achieved, this study was abandoned. Some form of correlation of results with a sealed-in sample might, perhaps, have been carried out in order to demonstrate conclusively that side wall leakage when using the Vinomold sleeves does not occur to any significant extent.

However, tests with very low permeability material from the Permian of the South of Scotland demonstrated that no sidewall leakage occurs where 1.6 mm undersize sleeves are used at pressures up to 150 cm H_2O.

Removal and Replacement of Sample in Sleeve in Cell - In a series of tests with specimen no. 326-6, no significant changes in the measured head/discharge relationship were observed when the sample was removed and immediately replaced in the sleeve in the cell. Care was taken not to allow aeration of the specimen to occur while these operations were carried out. As a matter of procedure, however, it is thought that the upper surface of the sample should be flush with the upper surface of the compression sleeve.

Rotation of the Specimen in the Sleeve Vertically or Horizontally - Here again, no significant change in the rate of discharge was observed in specimen no. 326-6. The changes were made during the period of testing when approximately constant head/discharge conditions were obtained, and a sleeve of same i/d as the diameter of the core was used.

Adjustment of Upper Clamping Screw and Lower Filter Adjustment Screw - There is evidence that sidewall leakage past the Vinomold sleeve can occur if there is insufficient tension on the upper clamping screw which seals the tapped block with inlet port to the Vinomold sleeve containing the specimen.

In a test with 326-6, a flow rate of 38.9 cc/min was recorded at a water manometer pressure of 39.75 cm. When the upper clamping screw was tightened the rate fell immediately to 29.9 cc/min and remained there even if further pressure was applied. In practice, the upper screw should be tightened to a point at which it can no longer be readily tightened by two fingers alone. This will apply more than sufficient pressure to seal the compression sleeve in the taper of the cell (see fig.35). A check as to the presence of leakage around the metal/plastic seal at the base of the tapped block may easily be made by observing if leakage is occurring in the annular space between the tapped block and the rim of the cell.

With regard to the lower filter screw, the position of the filter plate has no effect on the rate of discharge unless it is forced against the underside of the specimen. Care must be taken to lower the filter plate beyond the bottom of the tapered portion of the cell, so that when pressure is applied at the top, the sleeve and specimen can slip slightly downwards in the taper. The filter should then be raised until the adjustment screw is finger tight.

Relative Merits of Different Testing Fluids - In considering this aspect of the testing procedure, it should be stated that during the limited tests described here, no significant changes in the flow rate under a constant head were observed, which were directly related to change of testing fluid.

This can be seen for example, in fig.37. Much further work is, however, required in order to demonstrate this conclusively. However, it is considered desirable that, with regard to filtration quality, the test fluid should be of as high a standard as borehole water. There was evidence that the deionized water being used in the laboratory contained suspended matter, chiefly of organic origin and this fact, coupled with the discovery that this water clogged within 10 mins, a 45 micron pressure filter, led to the decision to conduct all further tests with filtered test water.

With regard to the chemical composition of the test fluid, it is pertinent to quote the following passage from the American Petroleum Institute Recommended Practice (No.27) - For Determining Permeability of Porous Media (1952):

> "The choice of a test fluid for a particular medium must be made with the properties of fluid and medium in mind both separately and together, as well as the particular purpose for which the resulting permeability will be used".

The results obtained using the apparatus described here have been used in correlation work with the results of pumping test analysis, and therefore should represent rates of flow of <u>formation water</u> through saturated permeable rock. Thus, it may be argued that in laboratory tests, formation water should be used as this will have a chemical composition theoretically in equilibrium with the surrounding geochemical environment.

Relationship between Permeability and Period of Testing - The marked decline in apparent permeability observed in specimen no.326-5 and shown on fig.38, is an effect which has been studied extensively, particularly by Heid et al, 1950 and Johnson, 1963. The effect has been attributed to a number of causes of which the following appear to be the more important:

1. Clogging of flow channels by particulate matter, e.g. microorganisms (Allison, 1947).
2. Migration of fines to clog flow channels when a sample is subjected to a hydraulic gradient especially perhaps platy mineral grains, loosely bonded with the matrix (Bodman and Harradine, 1938, Payne, 1968).
3. De-gassing of dissolved gases in the testing fluids and migration of bubbles to block flow channels. (Christiansen, 1944, Smith and Browning 1946, and Gupta and Swartzendruber, 1964).
4. Swelling of clay minerals to block flow channels, caused by the testing fluid not being at chemical equilibrium with the porous medium. (Tignor, 1957, Baptist and Sweeney, 1955, Bardon and Jacquin, 1969, Degallier et al,1969).
5. The development of a layer of stationary fluid absorbed on the walls of the flow channels. (Heid and others, 1950, discussion therein).

In the first series of experiments, only indirect evidence was obtained as to which of these causes was likely to have been responsible for the reduction in flow. Since the specimens used were tested repeatedly without being dried out, and resaturated beforehand, it was considered

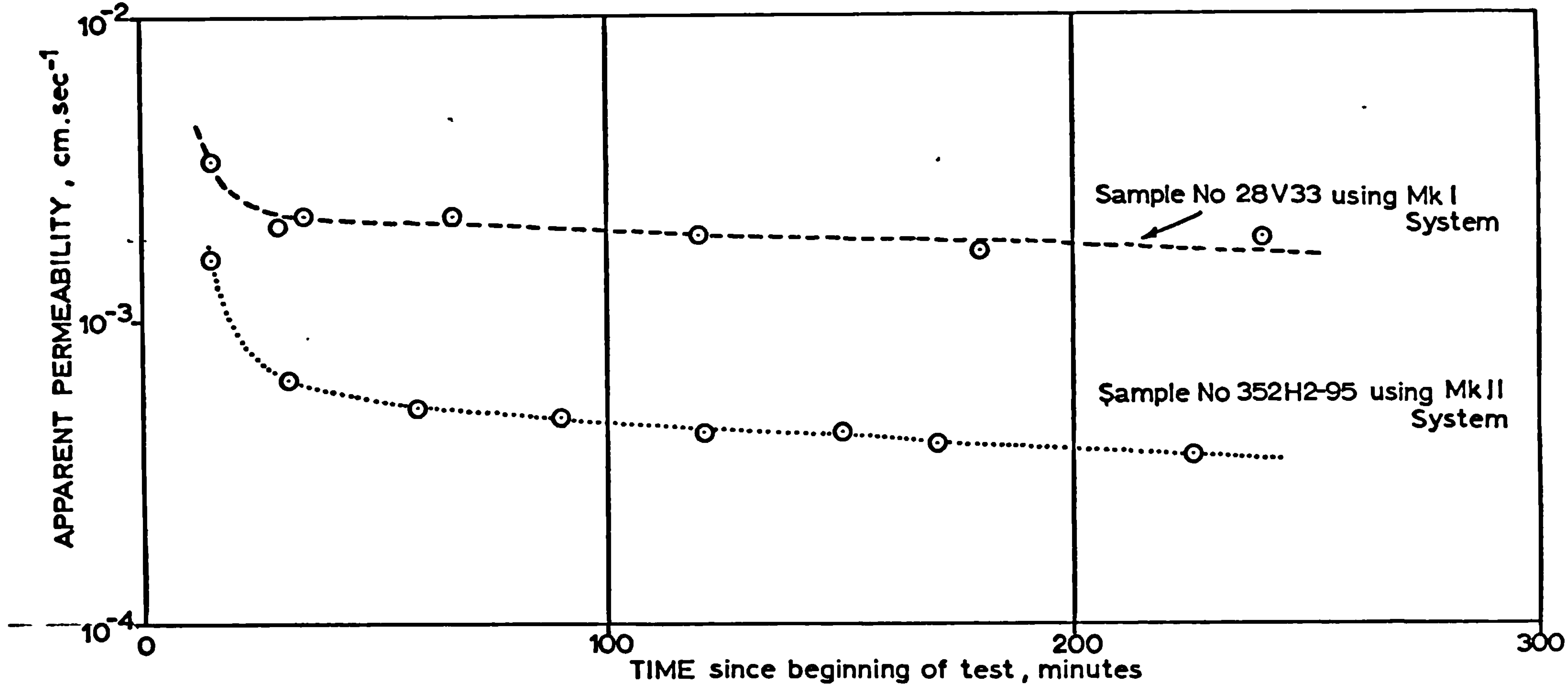


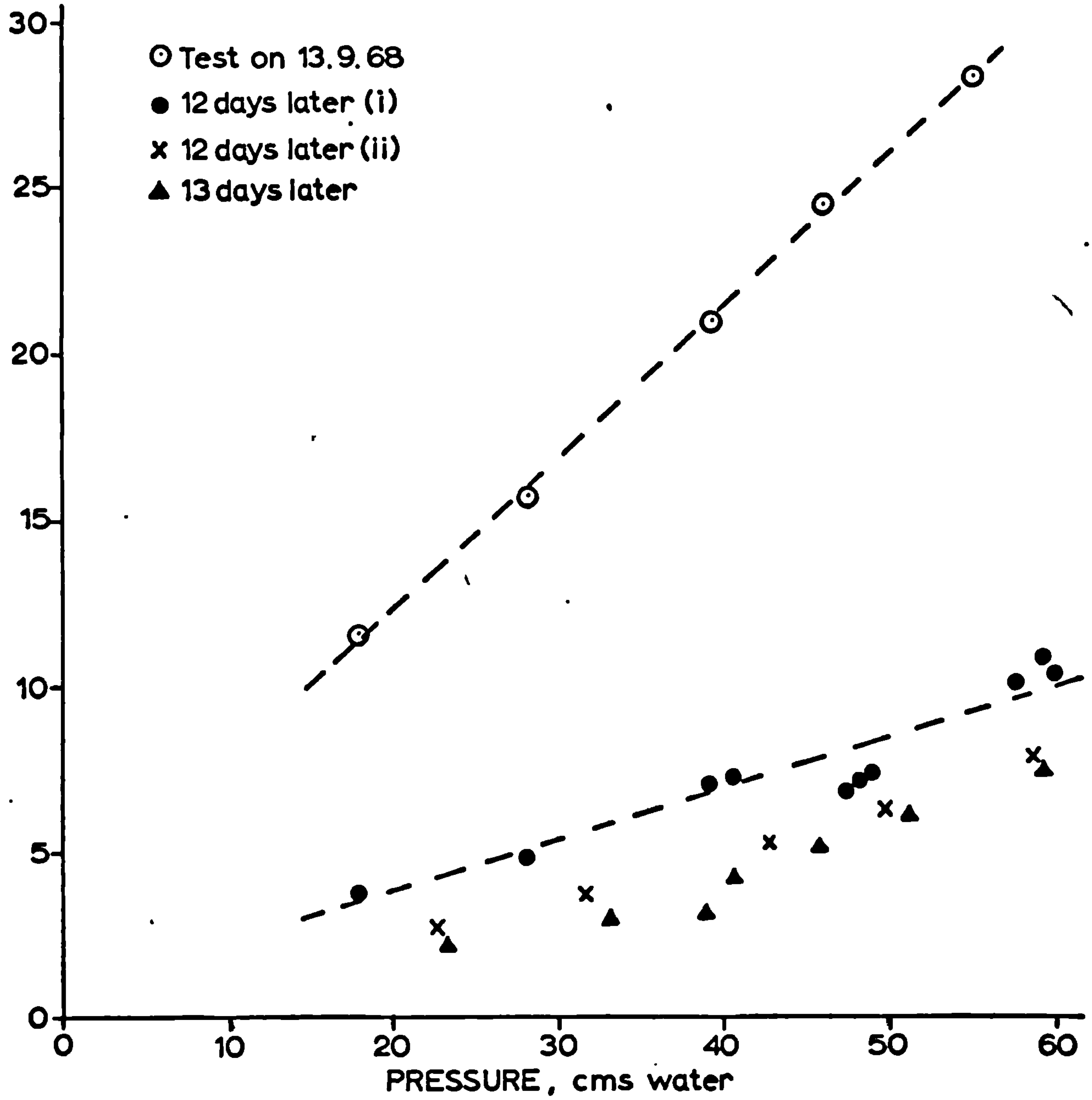
Fig.38 Comparison of relationship between apparent permeability and time using the Mk I and Mk II Test Systems

that virtually any combination of the five possible causes might have been operating, and these would have to be systematically excluded one by one.

It was considered that one point might be of some significance. With reference to figs. 39 and 40, it can be seen that the Darcy Law plots for individual tests deteriorate with time from good linearity in the early tests (after recent resaturation) to increasing curvature in the later tests, by which time the specimen had been saturated for up to two weeks. This might have been explained by either changes in the state of saturation, growth in the pores of microorganisms or swelling of clay minerals.

Effect of dehydration and resaturation on apparent permeability -

It was deduced, that for the five factors causing changes in apparent permeability, Nos. 1,2 and 4 would be experimentally irreversible, and 3 and 5 should be reversible. In order to investigate this, core no.326-5 was dried after 17 days saturation to 100^{o}C for 24 hours, and subsequently re-evacuated and resaturated under 15 mm vacuum for a period of four hours. The flow rate at the commencement of the retesting under a head of 40 cm was 13.5 cc/min which compares with c.21 cc/min when the specimen was first tested. The deterioration in permeability was therefore demonstrated to be of a partly irreversible nature such as might be caused by either of factors 1, 2 and 4.



'ig.39 Sample No.326 -5 : replication tests before dehydration and resaturation.

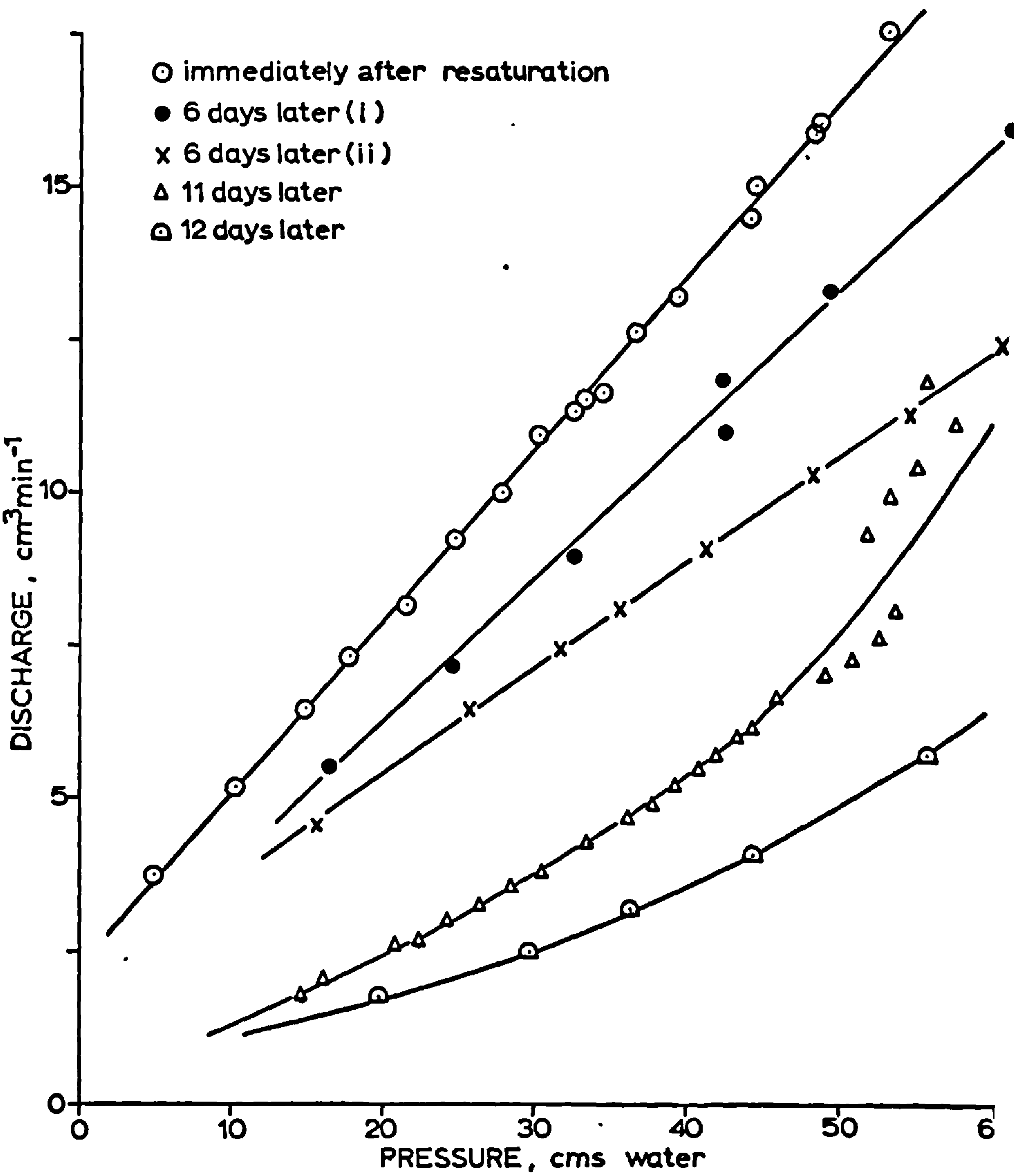


Fig.40 Sample No. 326-5 : replication tests after dehydration and resaturation.

That the deterioration was also partly <u>reversible</u> implies that factors 3 and 5 may have been partly responsible.

Further tests were clearly required to take the development a further stage forward.

4.5.2. The Second Experiment

This was intended to determine whether decline in apparent permeability continued indefinitely during a long period test, or whether a final minimum value could be reached, such as had been achieved by Heid et al, (1950) working on low permeability oil reservoir rocks and Johnson on various grades of sands (1963).

i) Sample material and testing water: For the purpose of this test, a core of 7.53 cm diameter and length 6.89 cm was cut from the centre of a borehole core sample taken from the Keuper Sandstone at a depth of 183 m in the Sugarbrook No. 1BH (SO 96036815) in Worcestershire.

The testing fluid used in this experiment was boiled, filtered, deionized London tap water. It was boiled to remove dissolved gases because it was thought they could be coming out of solution and blocking the flow channels, thereby reducing permeability (factor 3). The water was then passed through a 5 micron filter which was coupled to the Millepore XX67 22-litre stainless steel pressure vessel. The water was supplied to the filter holder at 10 p.s.i. using a nitrogen gas cylinder which was also coupled to the pressure vessel.

The arrangement of the apparatus was as in the first series of tests, and is shown in fig.36.

<u>ii) Experimental Procedure and Results</u>: The experimental procedure followed was identical to that described above in section 4.5.1. After the sample had been saturated in deionized water, under vacuum for four hours, it was placed in a thermoplastic compression sleeve, which was 1.6 mm under size on the diameter so as to eliminate sidewall leakage.

The test run consisted of measuring the pressure in the two manometer tubes and the weighed discharge from the outlet point in cc/min. These readings were repeated at approximately hourly intervals during the first day of testing and towards the later stages of the test at more infrequent intervals.

The sample was left under continuous test for a period of 288 hours. During this time, the maintenance of continuous water flow necessitated the use of a temporary reservoir syphon system, but the rate of discharge in the later stages became so slow that water supply was not a severe problem.

As was found in previous replication tests, there was a dramatic decline in the apparent permeability during the course of the experiment which became less marked after the first 50 hours, but a constant minimum value was not obtained. As fig.41 illustrates, the total fall in apparent permeability was from about 3×10^{-3} cm sec^{-1} to about 3×10^{-5} cm sec^{-1} - a factor of 100.

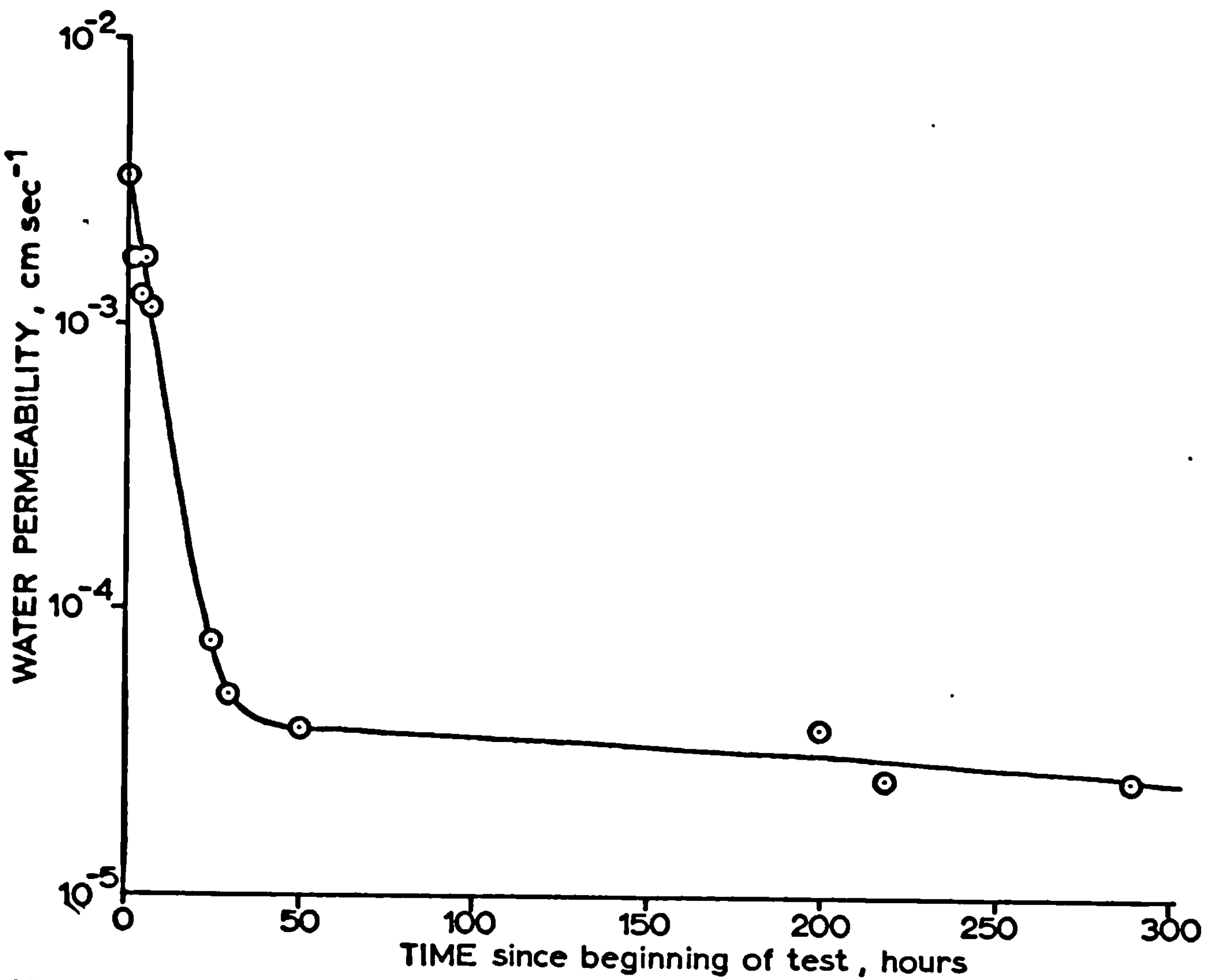


Fig.41 Sample No.28V33 : relationship between permeability and time.

The question to be answered was which of factors 1 - 5 was principally responsible for the change in permeability. It was judged that factors 1 and 3 ought to have been eliminated because the test water had been both boiled and filtered, and that therefore, factors 2, 4 or 5 remained to be excluded. However, careful examination of the top filter plate and the underside of the tapped block after this and previous tests revealed the presence of an unidentified green slime which suggested that in spite of the careful preparation of the test water, micro-organisms were present in the water in considerable numbers. It was felt that these might be responsible for the declining rate in permeability. Accordingly, five samples of the testing water, at various stages of its preparation, were taken for bacteriological examination at the beginning of the 2nd experiment. As can be seen from TABLE 8 below, the results were of great interest.

TABLE 8

MICRO-ORGANISM CONTENT - TEST WATER

DESCRIPTION OF SAMPLES	NUTRIENT AGAR COUNTS/ML 37°C	22°C
Drinking water unfiltered	3	13
Non-drinking water unfiltered	2	246
Discharge from Elgastat deionized	7	128
Filtered, deionized, boiled water	300+	300+
Discharge from deionized water reservoir	300+	300+

Following these results it was decided that as soon as the test was completed, the rock sample itself should be examined for evidence of micro-biological contamination. At the end of the test, a sample of the discharge from the cell was taken, the rock was removed from the cell and divided horizontally into three sections - upper, middle and lower - each of which was carefully crushed in tap water. A suspension of rock particles in water was taken from each section for bacteriological examination, and also a sample of the tap water used in the elutriation of the rock. Finally, the upper filter was carefully washed and a sample taken from the washings. The results obtained are shown in TABLE 9 below.

TABLE 9

MICRO-ORGANISM CONTENT - TEST SAMPLE PORE WATER

DESCRIPTION OF SAMPLES	NUTRIENT AGAR COUNTS/ML 37°C	NUTRIENT AGAR COUNTS/ML 22°C
Discharge from testing cell	7×10^4	10.8×10^4
Tap water used for elutriation	40	27
Top section of rock - Sample 1	2×10^3	24.6×10^3
Top section of rock - Sample 2	7.9×10^3	20.2×10^3
Middle section of rock	7×10^3	12×10^3
Lower section of rock	50×10^3	37×10^3
Upper filter plate	16×10^2	52×10^2

iii) Conclusion: From these results, it was clear that the next stage in the development of a satisfactory water permeability testing procedure should be the design of a sterile system which would exclude all possibility of bacterial contamination, and allow the investigation of the other factors, which might be causing decline in apparent permeability.

In conclusion, therefore, the second experiment suggested that clogging of pore channels by micro-organisms might explain the observed drop in permeability rate shown in fig.41.

4.5.3. Third Series of Experiments

The third series of experiments were preceded by work on the design of a system which, whilst including the Fancher cell, would incorporate on-line sterilizing filtration of the test water which at the present time is by far the most reliable method of removing microbiological contamination in water systems, without introducing noxious and sometimes reactive chemicals, not normally present in ground water.

At the time the system was designed, it was thought that bacterial growth was responsible for the entire decline in apparent permeability with time experienced during previous experiments.

The third series of tests indicated that this was not so, and that another of the 5 factors was principally responsible.

i) Design of System: The Mk.I System shown in fig.36 was modified to incorporate the following features:

1. Testing fluid to be tap water of drinking quality.
2. Primary filtration essential, followed by on-line sterilising filtration removing all particles larger than 0.22 microns.
3. Pressure reservoir of testing water to be small and easily cleaned.

These requirements dictated the design of the Mk.II and the Mk.III Systems shown in fig.42 and PLATE 15A, and culminated in the Mk.IV System of fig.43.

In the Mk.IV System, freshly boiled and cooled tap water is placed in the primary reservoir and passed immediately through a primary filter of the ceramic candle type where particles down to 1 micron size are removed. It then drains into the smaller secondary reservoir, a 1 U.S. gallon size Millepore Pressure Vessel. The vessel is coupled to a nitrogen gas cylinder; when it is full, the water flow is stopped and the vessel pressurised to about 30 p.s.i.g. Water flows through the on-line Millepore Filter and water free of particles larger than 0.22 microns flows to the head of the testing cell.

In practice, a number of difficulties have to be overcome.

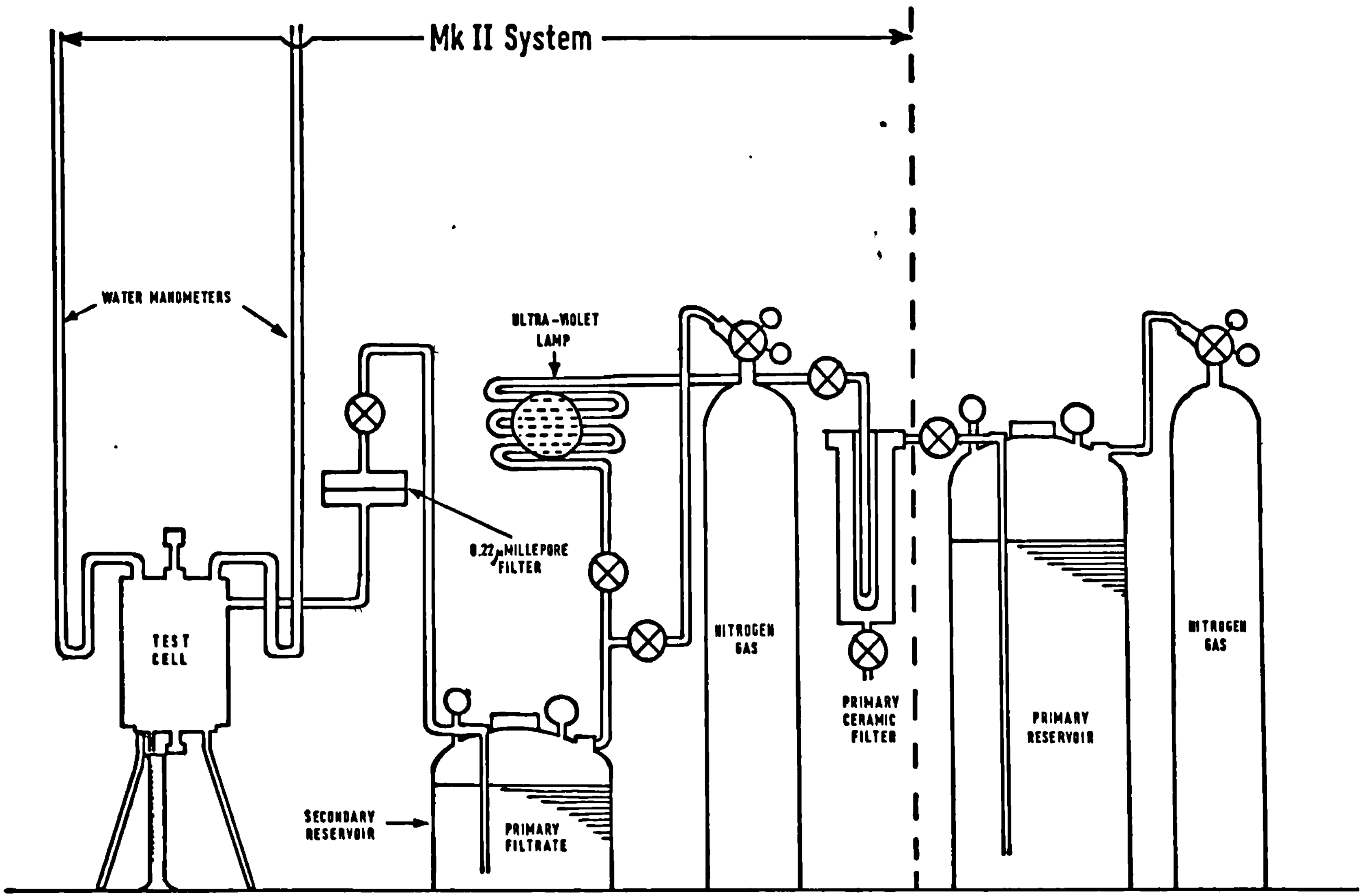


Fig.42 Mk III Water Permeability Testing System with sterilizing filtration

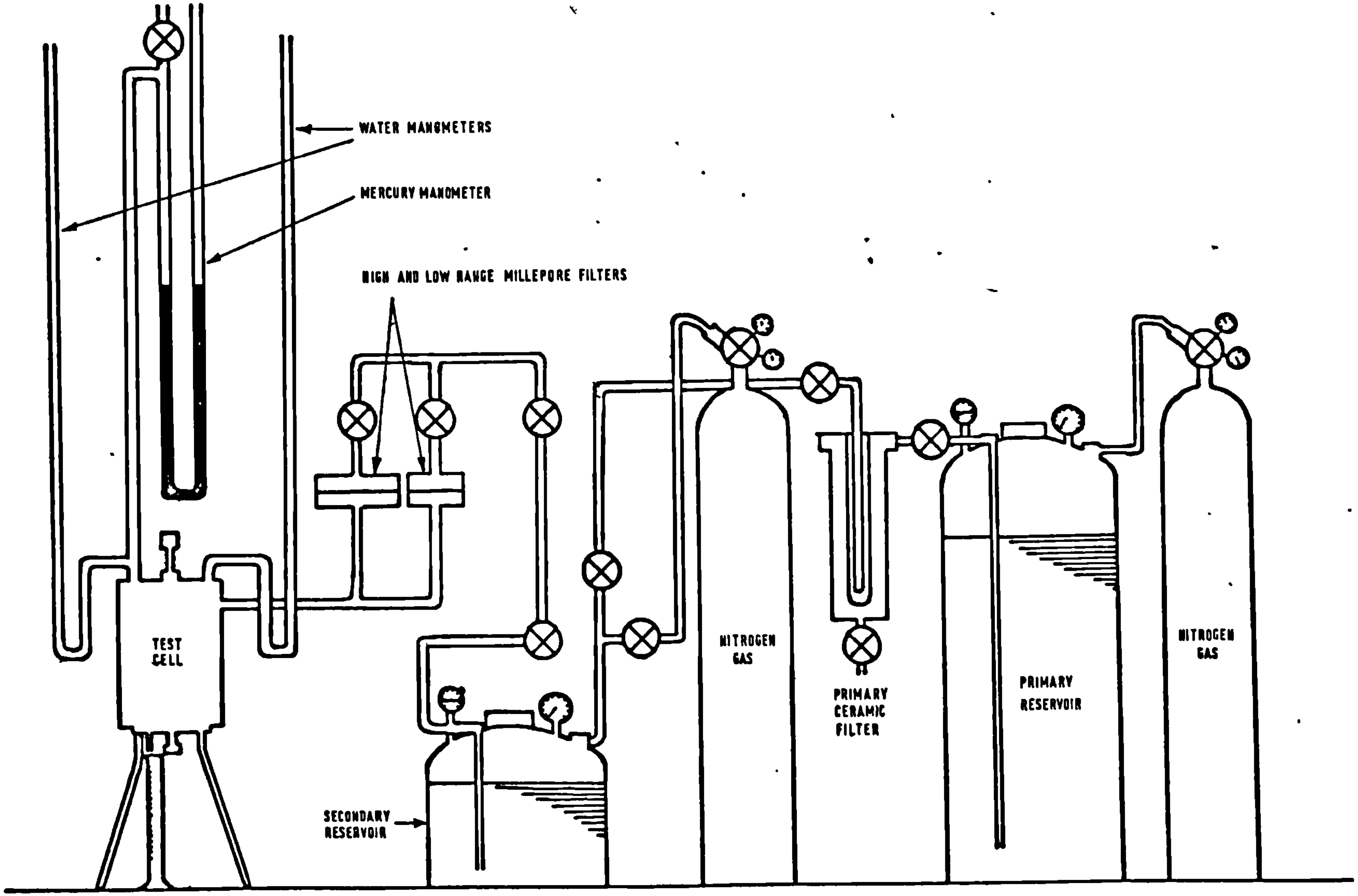


Fig.43 Mk IV Water Permeability Testing System with sterilizing filtration

To ensure that the system remains in a sterile condition after a test has been run, the primary filters and the brass filters in the testing chamber are oven dried to remove all organic contamination inside them. As a routine precaution, a 10 mg/l flushing solution of sodium hypochlorite has been found very effective in eliminating the growth of bacteria in the lines. The passage of 10 litres of this solution through the lines, over a period of about 30 minutes will remove all bacterial contamination, as the following Nutrient Agar counts indicate.

TABLE 10

EFFECTIVENESS OF SODIUM HYPOCHLORITE SOLUTION AS A STERILANT

DESCRIPTION OF SAMPLES	NUTRIENT AGAR 37°C	COUNTS/ml 22°C
10 mg/l Sodium hypochlorite solution, 3 days old	0	0
Tap water	17	1550
Discharge from primary filter	126	109
Discharge from Pressure Reservoir	580	630
Discharge from upper block of testing chamber	140000	109000
Sample of flushing solution	0	0
Discharge from upper block after completion of flush	0	0

Difficulty was encountered in obtaining sufficient pressure downstream of the Millepore Filter to provide constant head conditions on the testing chamber.

It was found that if a 0.22 micron Millepore Filter was used in the secondary filter, then 40 p.s.i. did not produce enough flow to the chamber at a measurable head. In practice, using a 0.22 micron sterilizing filter, about 60-70 p.s.i. will be required if adequate flow is to be induced, especially if highly permeable samples are under test. This pressure is rather high, and has the tendency of forcing nitrogen into solution in the test water with obviously undesirable results. A second Millepore filter of larger cross section was therefore, added to the equipment, this being one of the principal modifications in the Mk.IV System. The other alteration was the addition of a mercury manometer tube which enables higher supply pressures to be used and, therefore, lower permeability material to be tested in the system. These modifications effectively increased the range of permeability which the system can measure from 10^{-6} - 10^{-3} cm. sec^{-1} to approximately 10^{-7} - 10^{-2} cm. sec^{-1}.

ii) Experimental Procedure: When the system had been assembled in the manner shown in fig. 43, a number of replication tests were carried out, using the following procedure. This procedure was subsequently adopted for all the water permeability tests conducted for this Project:-

1. The specimen, was weighed dry, evacuated for a period of 30 minutes, and saturated under about a 15 torr vacuum (corresponding to the vapour point of water at room temperature) in the apparatus shown in PLATE 14B.

2. The pressure reservoir was filled from the tap water supply line.

3. The reservoir was closed and pressurized, and a fresh filter inserted in the Secondary Millepore Filter.

4. The specimen was transferred from the vacuum chamber, rapidly reweighed and then placed in a Vinomold compression sleeve (1.6 mm under size on the diameter) and positioned in the testing chamber.

5. Flow was started from the system by opening the valve upstream of the Millepore Filter.

6. When flow issued from the upper filter plate in the block of the test-cell, the block was clamped down on the top of the specimen and the test commenced.

7. The presence of air locks in the head of the cell was determined by unclipping the manometer tubes and holding them horizontal for a few moments. Any trapped air then automatically emerged.

8. The first measurement of permeability was made as soon as steady state conditions were prevailing in the manometer tubes; and preferably not later than 2-3 minutes after the beginning of the test. The levels in the tubes should be identical. Any difference in the levels is an indication of air bubbles present in the head of the test chamber. Head and discharge was measured every five minutes during the tests.

9. At the end of each test, the specimen was reweighed. The standard laboratory version of Darcy's Law for isothermal viscous flow through saturated porous media was used in the calculation of permeability as hydraulic conductivity:

$$k = \frac{Ql}{Ath} G \qquad (8)$$

in which k is hydraulic conductivity in cm/sec units at 15.5^{o}C.

Q is discharge from the test chamber in cm^3 at a head of h cms (mean reading of the two manometer tubes),

l is length of the sample in cms.,
A is its cross sectional area in cm^2.
t is in seconds, and
G is a temperature correction factor.

The tests of reproducibility were made using a 75 mm diameter rock core of 77 mm length of Lower Keuper Sandstone from Helsby, Cheshire (SJ49117541). It has an interconnected porosity of 23.8 per cent. Air permeability tests on control plugs cut from the same sample in horizontal directions gave values of 2138,2297 and 2310 millidarcies with porosities of 23.7, 24.5 and 24.1 per cent. The test sample number was 352H2-95.

Altogether 11 separate tests were conducted (numbered 37-48), but only 7 of the tests produced reproducibility data which was strictly comparable. The permeability against time curves observed during these experiments are shown in Fig.44, and refer to Test Numbers 37, 38, 39, 43, 45, 47 and 48. The specimen was dried out overnight, resaturated and reweighed at the beginning of each new test. The most striking feature is the tendency for each test to have approximately the same initial apparent permeability.

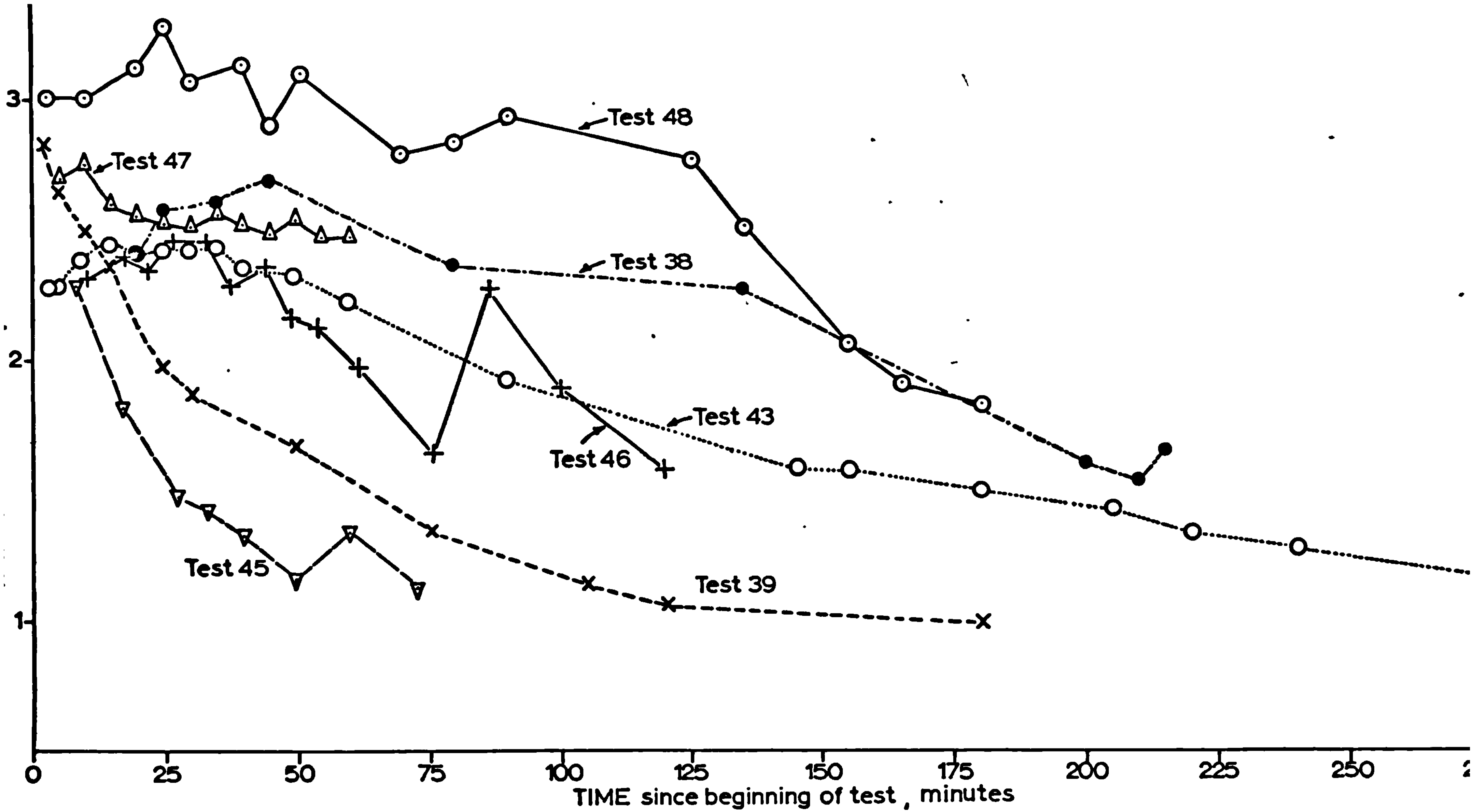


Fig.44 Sample No. 352H2-95 : relationship between permeability and time observed during 7 repeat tests.

iii) Results: Table 10 indicates a summary of results obtained during the replication tests, and it requires some explanatory comments. With regard to Test 37; in this first experiment with the Mark III System, in-chamber evacuation and resaturation was attempted, and from the initial permeability value it is clear from subsequent tests that a poor level of saturation was achieved, using this method, probably a saturation of about 93.5 per cent. For the determination of 100 per cent saturation, the highest uptake of water by the sample in the evacuation and resaturation apparatus (PLATE 14B) was used. This value was 79.1 cm^3 and, as can be seen from Table 11, not all the initial saturations corresponded to this figure. This was because in Tests 43-46 the specimen was resting not on the perforated disk in the dessicator, but on the bottom of the dessicator vessel in which position the pore channels opening at the base of the specimen would have been restricted. In Test 47, the specimen was again resaturated while resting on the perforated disk.

The saturation figures, then, are based on the assumption that a water content of 79.1 cm^3 corresponds to full saturation. In fact, it was the maximum saturation which could be readily achieved under experimental conditions.

In Table 10, values for initial and final permeabilities are given together with the observed saturations at these permeability values.

SUMMARY OF RESULTS USING THE Mk.III WATER PERMEABILITY SYSTEM

Sample in all cases was 352H2-95						
TEST No.	LENGTH OF EVACUATION BEFORE SATURATION	DURATION OF TEST	INITIAL SATURATION* per cent	INITIAL PERMEABILITY** cm. sec^{-1}	FINAL SATURATION per cent	FINAL PERMEABILITY cm. sec^{-1}
37	30 mins.	3 hrs.45 m.	93.5	1.59×10^{-3}	77.8	3.60×10^{-4}
38	15 mins.	3 hrs.45 m.	100	2.67×10^{-3}	93.7	1.65×10^{-3}
39	30 mins.	3 hrs.	100	2.83×10^{-3}	90.4	9.95×10^{-4}
40	45 mins.	3 hrs.	100	3.02×10^{-3}	95.6	2.30×10^{-3}
41	45 mins.	5 mins.	100	-	-	-
42	no new evacuation	45 mins.	100	-	97.0	2.69×10^{-3}
43	no new evacuation	4 hrs.50 min.	98	2.27×10^{-3}	93.0	1.14×10^{-3}
44	30 mins.	1 hr.	99	2.67×10^{-3}	97.1	2.03×10^{-3}
45	30 mins.	1 hr.15 mins.	97	2.27×10^{-3}	91.0	1.12×10^{-3}
46	30 mins.	2 hrs.	99.1	2.70×10^{-3}	97.8	2.26×10^{-3}
47	30 mins.	1 hr.	100	2.71×10^{-3}	98.5	2.48×10^{-3}
48	30 mins.	3 hrs.	100	3.02×10^{-3}	97.1	1.84×10^{-3}

* SATURATION (Vol.of water present/Vol.of voids) x 100.

** as Hydraulic conductivity, k.

The losses in weight to reduce the saturation of the test specimen by 10 per cent were of the order of 8 gms in 750, or slightly over 1 per cent, and these very small but critical losses were readily measured using a PL2 Torbal Torsion Balance. If these small weight losses had not been noticed, then the problem of decline in permeability would not have been explained.

Test 40 is omitted from fig.44 as severe degassing of the test water occurred in the apparatus during the test, and only initial and final permeabilities and saturations are considered reliable.

Test 41 was abandoned owing to filtration difficulties and Test 42 was conducted to study the effect of testing under non-isothermal conditions. In Test 42, the final saturation and permeability are considered valid, as isothermal fluid flow conditions were obtained at the end of the test.

In Test 44, a carbon dioxide flush was attempted prior to saturation, in order to assist the achievement of full saturation, according to the method described by Christiansen, Fireman and Allison, 1946, and Chu, Davidson and Wickstrom, 1955. A significantly higher degree of saturation was not, however, obtained, but the technique deserves further consideration and experimentation.

iv) The Permeability - Saturation Relationship: The data presented in Table 10 are plotted in fig.45, which shows that a linear relationship has been established between saturation and observed water permeability which may be extrapolated to 100% saturation with confidence.

It is apparent from fig.45 that the true saturated permeability of the medium may be deduced from the linear function $Y = 0.2x + 0.87$, in which Y is the observed permeability and x is the water saturation. The points plotted in fig.45 have been derived from the precise paired measurements of saturation and permeability, and they have been fitted on to the indicated line using the least squares method. To enable this to be done an assumption had to be made, viz., that the relationship was linear over the saturation interval 90-100%; this is considered to be a justifiable assumption (vide, Muskat, 1949, pp.276-277).

Using this line, the true saturated water permeability of the sample is 2.87×10^{-3} cm sec^{-1}, and the five values obtained at full saturation have a standard deviation of only 0.015 or about 0.5%. The values obtained were in fact 2.67, 2.71, 2.83, 3.02 and 3.02×10^{-3} cm sec^{-1}. These values were obtained in completely separate tests with two different operators. They are quoted here as conclusive evidence that with careful use, the Mark III Water Permeability Testing System (and its successor the Mk.IV System) is capable of

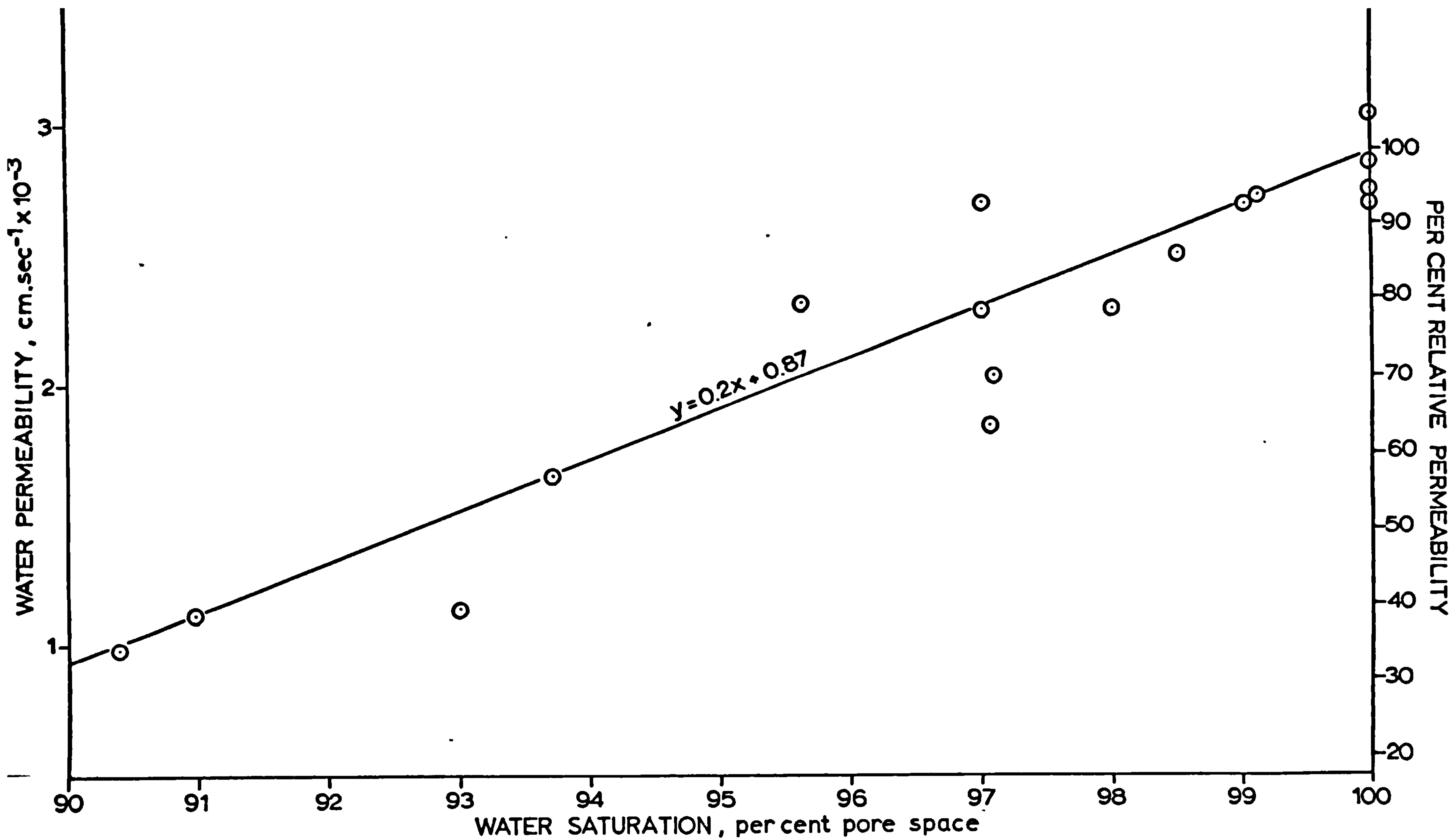


Fig. 45 Sample No 352H2-95 : graph showing relationship between permeability and saturation

producing water permeability values for saturated rock with a high degree of experimental accuracy.

v. Conclusions: The reduction in apparent water permeability has been found to be reversible in the case of Sample no. 352H2-95, and it is therefore considered that on the evidence above, the reduction is caused primarily by clogging of pore channels by exsolved gases. If the reduction had been found to be partly irreversible, then clearly some other explanation would need to be sought, such as migration of fines or bacterial growth; but from the data obtained on this apparently non-reactive sandstone, and from the observed relationship between saturation and permeability (fig.45), it is considered that the effect is primarily an indication of unsaturated permeability.

Unfortunately there is no way of determining precisely the spatial distribution of the exsolved gas bubbles which developed in the specimen during these tests, nor can their presence be demonstrated except by loss of weight of the sample. The change in density due to their presence is very slight, but it might be detected using a very finely collimated gamma-ray attenuation device such as the GRAPE instrument (described in Tech.Rept.No.65-8U . Marathon Oil Company, Denver). From the physical principles underlying the technique, one would predict that the majority of the bubbles develop in the upper part of the test specimen, closest to the

.nflow interface where the test water experiences a sudden .oss of hydrostatic pressure.

It is considered that the observed reduction in ›ermeability of a fairly coarse homogeneous Triassic sandstone :or a drop in saturation of only 10% is of some practical ;ignificance; the permeability in fact, fell by about 70% for :his drop in saturation. In terms of volume for volume lisplacement of water by air, this amounts to only about 2.4 ›er cent of the total bulk volume of the formation. An air :ontent of this magnitude is likely to be present in the zone ›f annual fluctuation of ground water level, and also within :he cones of depression of pumping wells where it must ;ignificantly reduce intergranular flow.

<u>vi) Equipment Details</u>: the Mk.IV System is made up from the following principal components:-

1. Nitrogen gas cylinders - 2200 p.s.i.g. 40 cu.ft. size fitted with 0-150 p.s.i.g. two stage pressure regulators.

2. Pressure Vessel Reservoirs - Millepore Stainless Steel Pressure Vessels, 1 and 5 U.S. gallon sizes.

3. Valves - Simplifix Klinger type, for ¼ inch nom. o/d copper tubing.

4. Filters: Primary: Saludor Pressure Filter. Secondary: Millepore 25 mm and 47 mm High Pressure Filter Holders with Millepore GSWP filters.

5. Test Chamber: I.G.S. - modified Clockhouse Engineering High Pressure Permeability Cell.

The total cost of the equipment is in the region of £350-£400.

4.6. CORRELATION BETWEEN AIR AND WATER PERMEABILITY

The water permeability testing system, which has been described at length above, was developed principally to investigate whether the Permo-Triassic sandstones react in the classical Darcy manner to the passage of different fluids through them. It was considered particularly important to study the degree of correlation beween values of permeability obtained using air and those derived using water. Provided no evidence was found to suggest the presence of non-Darcy behaviour, the measurements made using the more rapid gas permeameter could then be used with confidence to provide permeability data on flow of ground water through aquifers.

4.6.1. Procedure

Eighty 75 mm plugs, representing most of the stratigraphic subdivisions of the Permo-Trias, and exhibiting a wide range of facies were cut in horizontal and vertical directions from both outcrop and borehole samples. The permeability of the plugs covered the full range established in the main study. Each of the plugs was tested using the I.G.S. Fancher cell assembly shown in fig.35, which, for the purpose of the air correlation work, was coupled up to the gas permeameter instrument panel shown in PLATE 15B.

ressure gradients and sample dimensions were measured in the usual way, and to cope with the greater discharge of gas from the larger size plugs, an additional high range rotameter was inserted in the instrument panel (not shown in PLATE 15B). Gas permeability was calculated in the usual manner using Eq. (5), the result being expressed in millidarcies.

After being tested using gas, the plugs were subjected to a water permeability test using the Mark IV Testing System described above. The test water used was either deaerated deionized tap water or distilled water. Each plug was tested in the same sealing sleeve in both tests. Water permeability was calculated using Eq.(8), and the result again expressed in millidarcies.

1.6.2. Results and Conclusions

There are certain serious experimental difficulties which should be borne in mind when the following results are considered. These have already been mentioned in the previous section (p.89), but certain of them require additional emphasis here.

Firstly, it is essential to distinguish between genuine non-Darcy behaviour and experimental error. The former occurs where the physical resistance of the porous medium to the flow of a particular fluid is exerted in a different manner to its resistance to some other fluid.

The classic example of this effect is seen in sands containing swelling clay minerals of the bentonite type, which alter their volume in accordance with the salinity of the pore water, with the result that the apparent permeability of the sand to say brine and to fresh water changes very considerably, an effect which has been extensively studied, particularly by Baptist and Sweeney (1955) and many others .

On the other hand, certain commonplace sources of experimental error may imply that some form of non-Darcy behaviour is present; in the context of the present study, the presence of incomplete saturation when using water as the test fluid is probably the most fundamental of these, and this will result in a k_W value consistently lower than the k_G value. It is considered that, particularly in the finer grained sandstones where the capillaries are very small in diameter, it may be physically impossible to fill all the pore space in the sample with water when using a vacuum technique. An intractable part of the problem is related to the rather high vapour pressure of water at room temperature, which means that the lowest pressure which can be obtained in the pore space of a specimen as it is being saturated under vacuum is only of the order of 15 torr. Much lower pressure could be achieved by using a resaturating liquid of lower vapour pressure, such as kerosene, but this is unsuitable for work in which the physical properties relative to water are of paramount importance.

Secondly, much of the rock material being subjected to these tests was unusually coarse grained and friable. It is possible that the passage of gas through cores in a particularly weak state of consolidation may physically alter the geometry of some of the flow channels, causing irreversible changes in the permeability of the medium. A subsequent test using water which has a much higher density and viscosity may produce rather different values. In this respect it is interesting to note that water is 832 times denser than air at 20°C and 760 mm pressure, and 55 times more viscous. Very little is known of the detailed force fields existing in the pore channel system during orthodox Darcy flow, let alone during non-Darcy flow. Bearing in mind the inherent statistical element in the Darcy equation which means, in practical terms, that the discharge rate of fluid over a unit cross section of permeable material is the average of all the discharge rates from each capillary channel, it is hardly surprising that different frictional resistance is experienced with different fluids. One would expect that the best hope of demonstrating experimentally the existence of true Darcy flow conditions would lie in testing extremely large specimens of aquifer material containing millions of channels, provided the problem of saturation could be overcome.

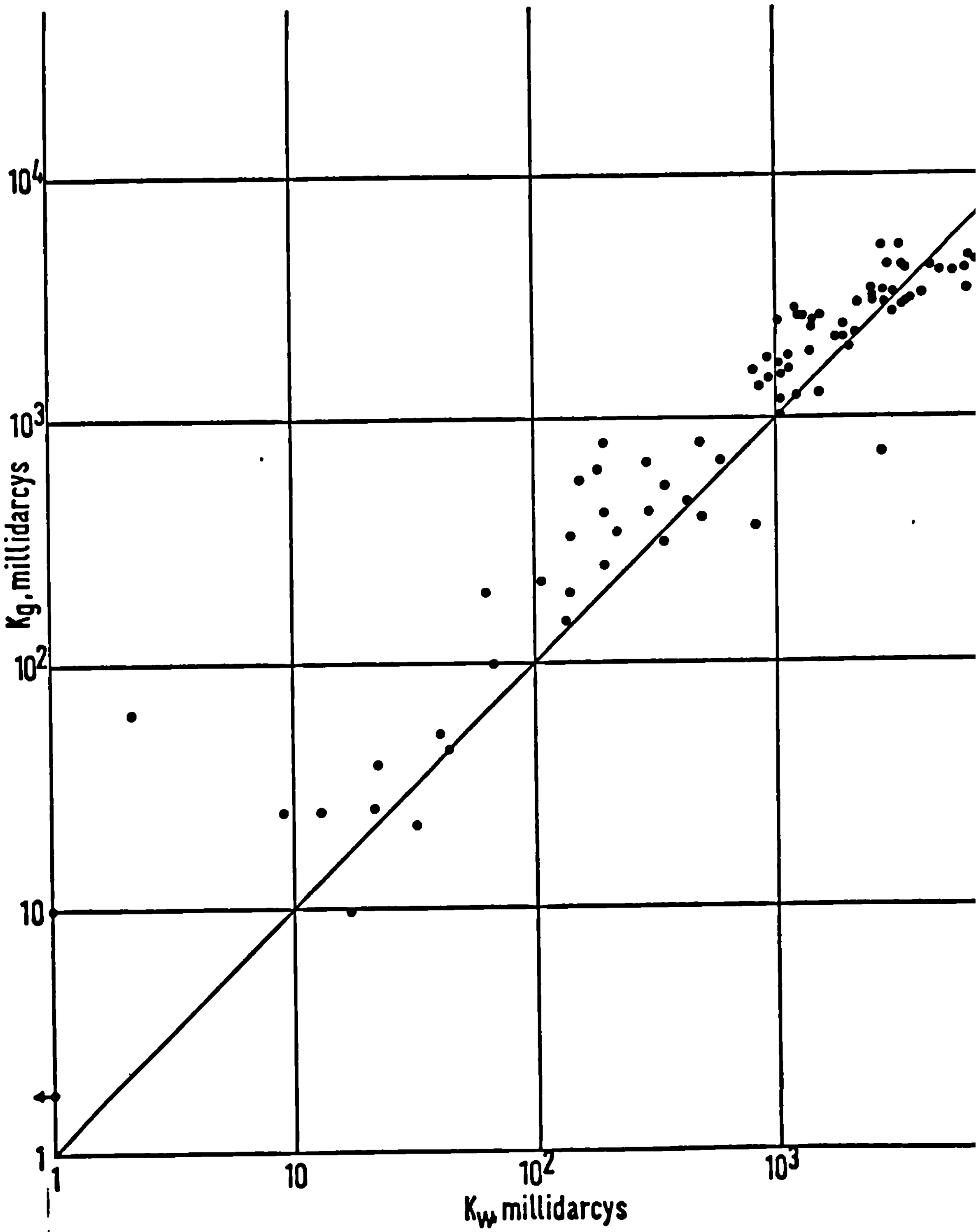


Fig.46 Correlation of gas permeability [K_g] and water permeability [K_W] in eighty 75mm plugs

Turning to fig.46, which summarises the results of the air-water correlation study on a log-log basis, the following conclusions can be drawn:

i) there is a marked degree of correlation between k_W and k_G values

ii) the correlation is marginally closer at the higher, and therefore hydrogeologically more significant end of the permeability scale.

iii) there is a general tendency for water values to be slightly lower than the gas figures, except at values beyond about 2000 md, where an inverse relationship may apply.

In fig.47, the degree of correlation is analysed on the basis of kw/kG ratios, which have been plotted on a histogram. The margin of maximum expected experimental error is $\pm$ 20% and therefore, it can be seen that the peak of the distribution, occurring at a kw/kG value of 0.6-0.79 is outside the limits of experimental error. The distribution of values is rather wide with only 35% of the ratio values falling within the limits of experimental error. The histogram does, however, indicate that there is no tendency to skewness in the distribution, nor any suggestion that the k_W values show a particularly strong tendency to be markedly below the k_G values.

In the writer's opinion, the position of the peak of the distribution is readily explained by the problem of resaturation under vacuum mentioned at the beginning of this section.

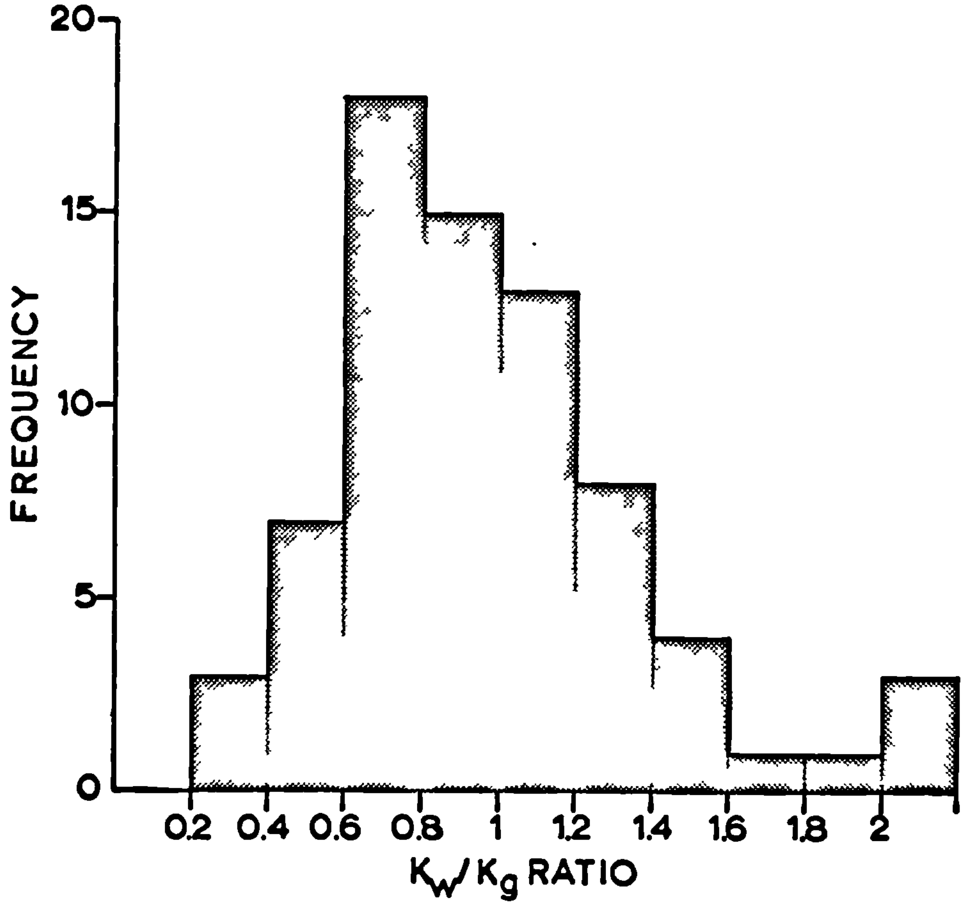


Fig.47 Frequency distribution of values of K_w/K_g ratio.

This problem is one which clearly deserves a great deal of careful study at research level, taking into account all of the five principal causes of lack of correlation mentioned on p.89 . Nevertheless, it is considered that on the basis of the data presented in figs.46 and 47, no convincing evidence has been found to suggest that any serious departure exists between permeability values obtained using air and those using water, provided both are expressed in the darcy unit of intrinsic permeability. Non-Darcy behaviour has not been established, and there seem to be very few reasons why it should be present in these chemically relatively stable rocks.

4.7. MEASUREMENT OF SPECIFIC YIELD

4.7.1. Introduction

The measurement of the specific yield of earth materials is a subject which has attracted a great deal of attention since its importance in groundwater and irrigation studies was first recognised at the turn of the century. The specific yield of a rock or soil is defined as the quantity of water which a unit volume of the material will yield by gravity, expressed as a percentage of its bulk volume. The volume of water retained against gravity expressed as a percentage of bulk volume is referred to as the specific retention of the material, and specific yield plus specific retention therefore equals porosity.

The importance of specific yield lies in the fact that knowledge of its value for a particular material enables estimates to be made of the quantity of water which that material, under confined or water-table conditions, will drain by gravity to a pumped well. These estimates are used in the determination of the groundwater resources available in a particular area, and attempts to measure the property have been made in a number of widely different ways.

Johnson (1967) has provided by far the best summary of previous work on specific yield measurements, both in the field and in the laboratory, practically all of the data and scientific literature being of American origan. He divides the various techniques which have been applied in the following manner:

Laboratory Methods:
- i) Sample saturation and drainage (column drainage).
- ii) Correlation with particle size
- iii) Centrifuge moisture equivalent (CME)
- iv) Moisture tension techniques.

Field Methods:
- i) Field saturation and drainage
- ii) Sampling after lowering of water table
- iii) Pumping method
- iv) Recharge method

It is not necessary to describe each of these methods in detail as this has already been done by Johnson.

In the same 1967 paper, he has also summarised many of the published values of specific yield for various materials and these are of considerable value for reference purposes.

The work undertaken in the present study, was carried out in the knowledge that there is a total absence of published data on the specific yield of the Permo-Triassic sandstones of U.K. and for that matter, of many other aquifers in this country. The selection of an appropriate measurement method was, therefore, made on the grounds of practicability, rapidity and accuracy.

Turning to Johnson's list of laboratory methods, it was considered that the centrifuge moisture equivalent test was probably the most suitable technique to adopt for the measurement of the drainage characteristics of large numbers of small test samples. The column drainage method has always been used with unconsolidated samples and is not very suitable for use with rock material. In the absence of much particle size data, the correlation method was also inappropriate and the moisture tension method, while being probably the most accurate and scientific technique is very time consuming and prone to experimental problems associated with moisture equilibrium and hysteresis.

Accordingly, the centrifuge moisture equivalent test was investigated to establish whether it could be adapted to produce reliable specific yield data on consolidated, but often friable rock samples as a routine core analysis procedure.

4.7.2. Previous work on the Centrifuge Method

The earliest work describing the results of centrifuging soil materials was published by Briggs and McLane in 1907; in this paper the concept of moisture equivalent was originally defined as the moisture which a soil would retain against a centrifugal force 3000 times that of gravity. Three years later, Briggs (1910) suggested that a 1000 g force could be used and subsequently, this moisture content was referred to as the moisture equivalent of the soil, expressed as percentage by weight. The selection of the 1000 g force appears to have been entirely arbitrary, but Stearns (1927) elaborated on the effect which a force of this magnitude might be expected to produce. By using the analogy that if a material could lift under natural conditions water against gravity to a height of 100 inches (254 cm) (as a capillary fringe), then by subjecting such a material to a 1000 g force, the capillary fringe could be artificially reduced to 0.1 inch (0.25 cm) (or negligible proportions). In other words, the centrifuge test reduced the moisture content of an initially saturated sample to what it would be just above the capillary fringe under natural conditions in the ground. However, the height of the capillary fringe developed in any particular earth material is related to the capillary characteristics of that material, and, therefore, samples will respond to the 1000 g force in differing ways.

Prill (1961), however, came to the conclusion that the water retention obtained by centrifuging is at least comparable to that obtained by gravity drainage of long columns.

In the present study, it was considered desirable that an attempt should be made to obtain specific yield values which are of direct application in groundwater investigations, rather than produce moisture equivalent data by means of the purely arbitrary CME test. This led to the consideration of other earlier work in the field which had tackled the force problem from a different approach.

In 1937, Schaffer, Wallace and Garwood, working at the Building Research Station, published the results of a study on Portland Stone in which the centrifuge method had been used to obtain what now would be called pF curves. They compared directly results from the centrifuge with hydrostatic (moisture tension) data and came to the conclusion that "the functional relation between water content and pressure deficiency is the same for the centrifuge and hydrostatic methods". More important still they derived the following equation which described the applied tension at any distance from the centrifuge rotor at any speed of the rotor:

$$T = \frac{W^2}{2g} \left({r_1}^2 - {r_2}^2\right) \qquad (9)$$

in which T is the tension in centimetres of water at point radius r

W is the angular velocity in radians per second

g is acceleration of gravity in centimetres per second per second

r_1 is the distance of the bottom of a sample from the centrifuge axis

r_2 is the distance of any point in the sample from the centrifuge axis

This equation was taken up by Richards and Weaver who in 1944 published some of the first curves on soils for application in irrigation work. They discussed the implications of the Schaffer equation, and concluded that the standard moisture equivalent test in a 10 mm high sample applies a tension of between 100 and 1000 cms water. They also considered that the gradient of tension developed in a sample during centrifuging is linear, provided the sample is homogeneous. Eq.(9) has been used in the present study to compute applied tensions.

The most recent information on the centrifuge test was published by Johnson Prill and Morris (1963) who, after a series of very thorough experiments, demonstrated that temperature control of the centrifuge is essential if reproducible results are to be obtained. Their paper also considered column drainage and its relation with centrifuge moisture content. It is one of the publications produced as a result of the United States Geological Survey special research study into specific yield currently being undertaken at the Hydrological Laboratory in Denver, Colorado.

As far as the author is aware, the centrifuge has not been used before for the measurement of specific yield of consolidated aquifers. Mention should, however, be made of the work of McCullough, Albaugh and Jones (1944), Hassler and Brunner (1945) and Slobod, Chambers and Prehn (1951) who used a combination of a temperature stabilised centrifuge and stroboscope to determine capillary pressure curves for the air/water system in oil reservoir rocks. These are the only papers on this subject known to the author which have appeared in the petroleum engineering literature.

4.7.3. EQUIPMENT

The specific yield tests were carried out using an MSE Mistral 2L centrifuge, shown in Plates 16A and 16B, which, following the work of Johnson, Prill and Morris (1963) was a refrigerated model. This particular version allows the bowl temperature to be maintained constant within $\pm$ 1^{o}C over the range - 15^{o}C to +40^{o}C.

Vertically oriented plugs were centrifuged using the special eight place swing out head, shown in operating position in Plate 16A. Each of the buckets contains a removable perforated raised base in anodized steel on which the stainless steel plug holder rests. The plug holder also has a perforated base to allow bottom drainage to take place from the plug, one of which is shown in position on the left of Plate 16A. Each bucket is provided with a cap which fits loosely so that air pressure inside and outside the bucket remains constant during

A. The M.S.E. Mistral 2L Refrigerated Centrifuge

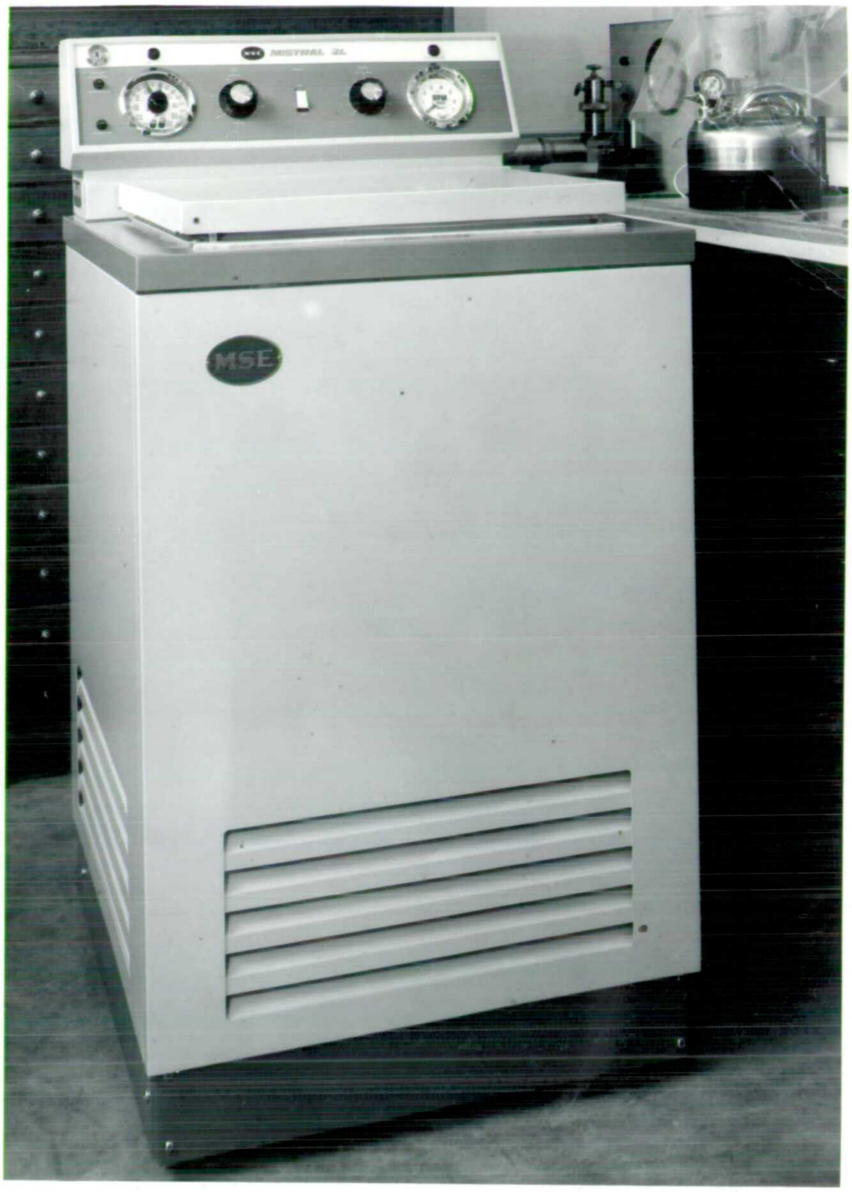
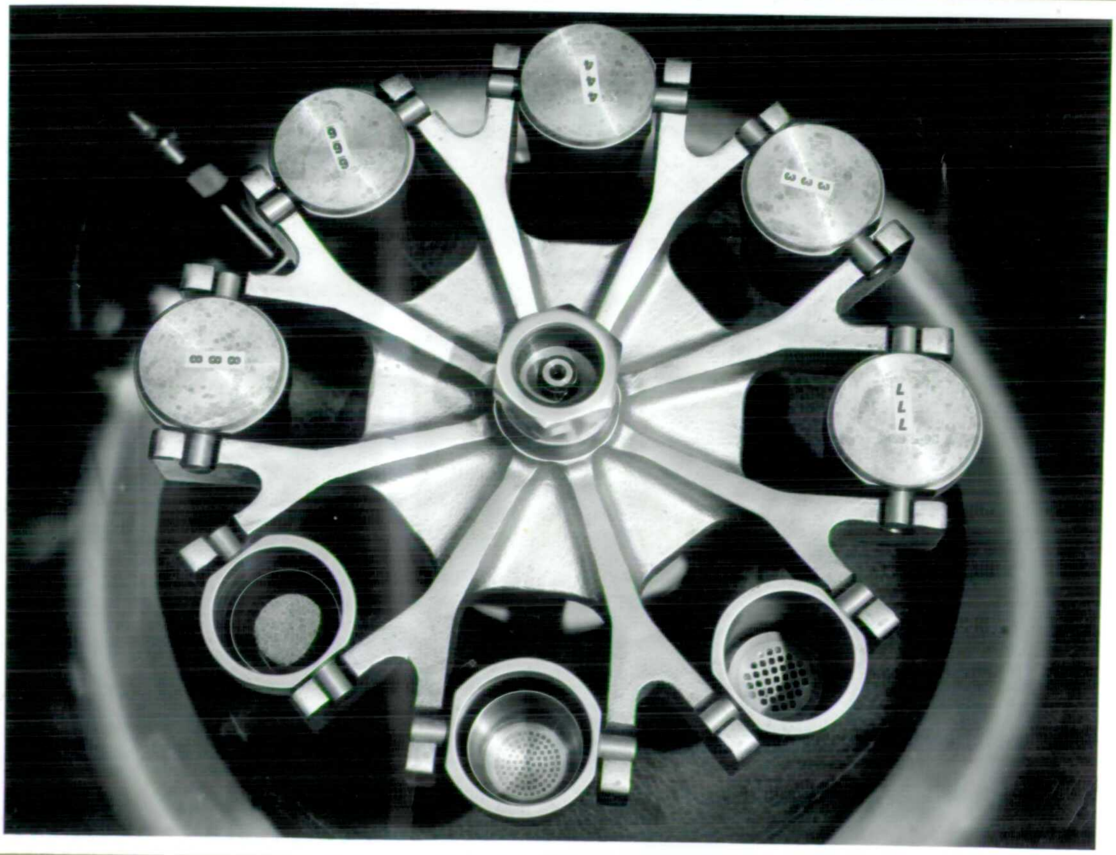


PLATE 16

B. Internal view of angle head assembly for centrifuge specific yield experiments



4.7.4. PROCEDURE

The operation of the test was very simple. When the bowl temperature of the centrifuge had been brought to the standard temperature of 15.5°C., the water-saturated rock plugs were placed in the plug holders in the buckets and centrifuging was carried out at a fixed speed and a constant temperature for a predetermined period of time. At the end of this period, the centrifuge was stopped, and the plugs removed from the machine and reweighed. The apparent loss in weight caused by drainage of pore water from the plugs was converted to a volume and this expressed as a percentage of bulk volume to give a value for "centrifuge specific yield".

Certain problems, however, had to be overcome to ensure that all the samples were subjected to the test in exactly the same manner. The most important of these were the following :-

i) Balancing the centrifuge head

ii) Effect of sample height and speed of rotation on induced moisture tension (capillary pressure)

iii) Effect of duration of test on achievement of moisture equilibrium

iv) Effect of lateral drainage.

i. Balancing the centrifuge head

The running of a centrifuge with an unbalanced head can result in severe vibration and damage to samples as well as damage to the machine itself. Particular care was taken during this work to ensure that the head was properly balanced by selecting batches of plugs with approximately similar individual saturated weights. Final balancing of opposite buckets to within $\pm$ 0.1 gm was accomplished using 2 mm diameter glass beads which weigh 0.03 gm apiece. These can be easily accommodated below the perforated raised base in the centrifuge bucket, where they in no way hinder the process of induced drainage. Provided opposite buckets are balanced within 0.1gm, the pairs of buckets may differ in weight by as much as 1gm before evidence of imbalance during centrifuging begins to appear. Table 11A indicates a specimen laboratory test sheet, on which provision has been made for calculation of the required extra weight for balancing purposes. 'Basket position' refers to the location of the plug in the saturation basket used for porosity testing, which is the key to the identity of the plug. (It should be pointed out that the handling of relatively large numbers of unlabelled plugs poses special problems, which were successfully overcome using the basket system described on p.59).

ii. Effect of sample height and speed of rotation on induced moisture tension.

The plugs were centrifuged at a speed which would theoretically induce a moisture tension of $\frac{1}{3}$ atmosphere at the centre point of the sample. The selection of the particular value of $\frac{1}{3}$ atmosphere or 343 cms H_2O pressure was based on previous work on the moisture characteristic of medium grained sands which suggests that, under field conditions, gravitational flow of soil water in these material effectively ceases when the tension reaches between 1/10 and $\frac{1}{3}$ atmosphere. This value is given by Johnson, Prill and Morris (1963), referring to the earlier work of Coleman, 1947 and Richards and Weaver (1944). It is also quoted by Marshall (1959).

The Richards and Weaver equation referred to above, and on which the results reported here are based, enables the angular velocity to be computed, provided values are inserted for moisture tension, T and the radial distances, r_1 and r_2. Table 12 gives computed values of w and speed of rotation, R is revolutions per minute, based on T = 343 cms water tension, radial distance r, equal to 15.05 cms (constant for the head assembly shown in Plate 16A) and $14.05 \geqslant r_2 \geqslant 13.40$ cm In Fig. 48, the height of the test plug, h, is plotted against computed values of rotational speed, R, in revolutions per minute. It can be seen that as the sample height increases, the speed of rotation required decreases; this is because as the sample height becomes greater, the top and therefore the mid point of the specimen approaches closer to the centrifuge rotor. At a given speed, the force experienced by a centrifuged body increases towards the rotor; therefore, a reduction in speed is necessary to maintain the applied force at a constant level.

It follows that, during experimental work, all eight plugs being centrifuged together must be of the same height if they

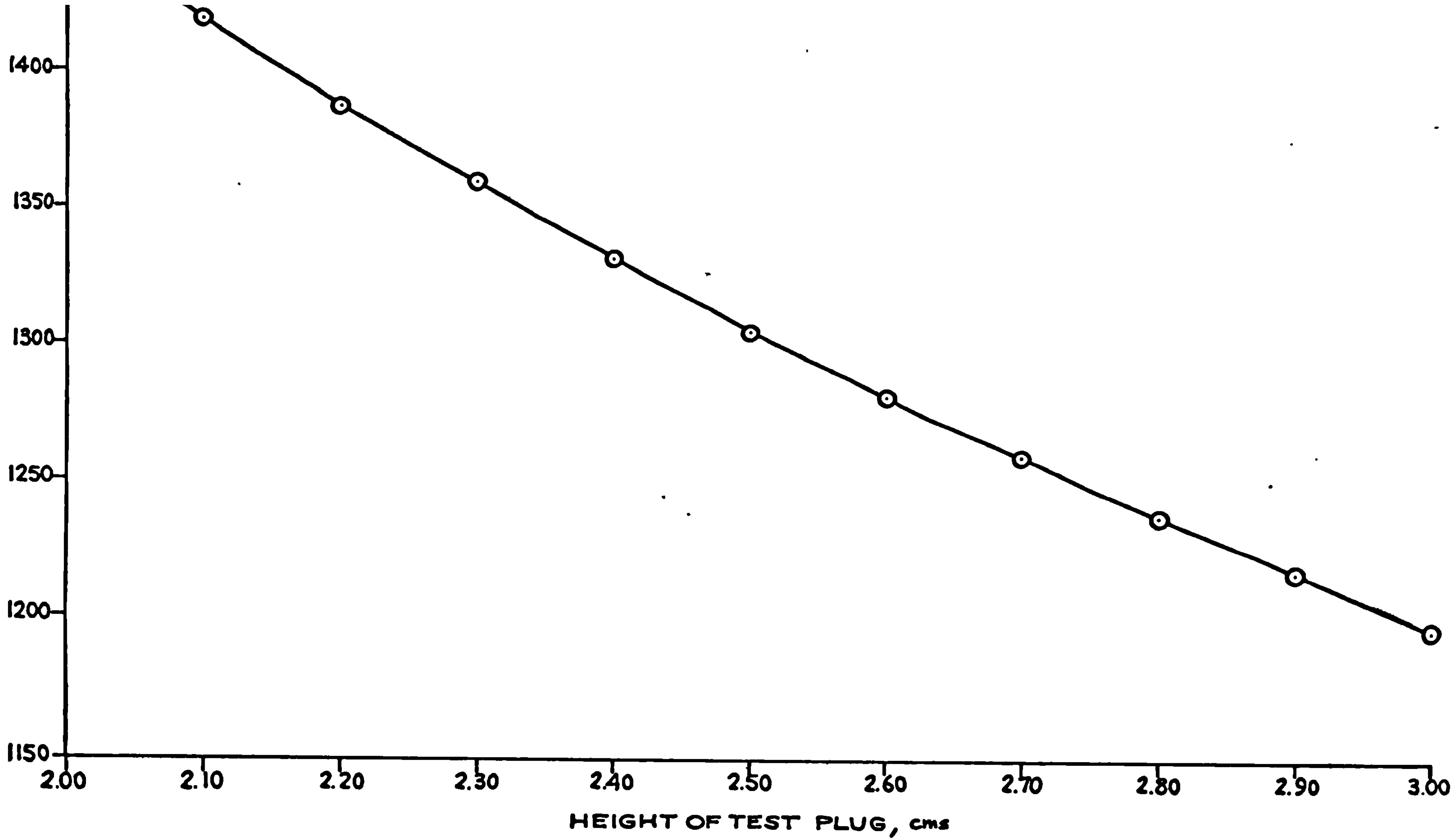


Fig.48 Relationship between height of test plug and rotational speed required to exert 1/3 atm. soil moisture tension.

are to experience the same force.

TABLE 12

VALUES OF ANGULAR VELOCITY AND SPEED OF ROTATION FOR DIFFERENT VALUES OF SAMPLE HEIGHT

Sample Height h cms	r_2	r_2^2	$r_1^2-r_2^2$	w^2	w	$R = \frac{w}{2\pi}$ r.p.s.	R r.p.
2.00	14.05	197.40	29.10	23125.98	152.07	24.20	1452
2.10	14.00	196.00	30.50	22064.46	148.54	23.64	1418
2.20	13.95	194.60	31.90	21096.11	145.25	23.12	1387
2.30	13.90	193.21	33.29	20215.26	142.18	22.63	1358
2.40	13.85	191.82	34.68	19405.02	139.30	22.17	1330
2.50	13.80	190.44	36.06	18662.40	136.61	21.74	1304
2.60	13.75	189.06	37.44	17974.52	134.07	21.34	1280
2.70	13.70	187.69	38.81	17340.02	131.68	20.96	1258
2.80	13.65	186.32	40.18	16748.78	129.42	20.60	1236
2.90	13.60	184.96	41.54	16200.43	127.28	20.26	1216
3.00	13.55	183.60	42.90	15686.85	125.25	19.93	1196
3.10	13.50	182.25	44.25	15208.27	123.32	19.63	1178
3.20	13.45	180.90	45.60	14758.03	121.48	19.33	1160
3.30	13.40	179.56	46.94	14336.73	119.74	19.06	1144

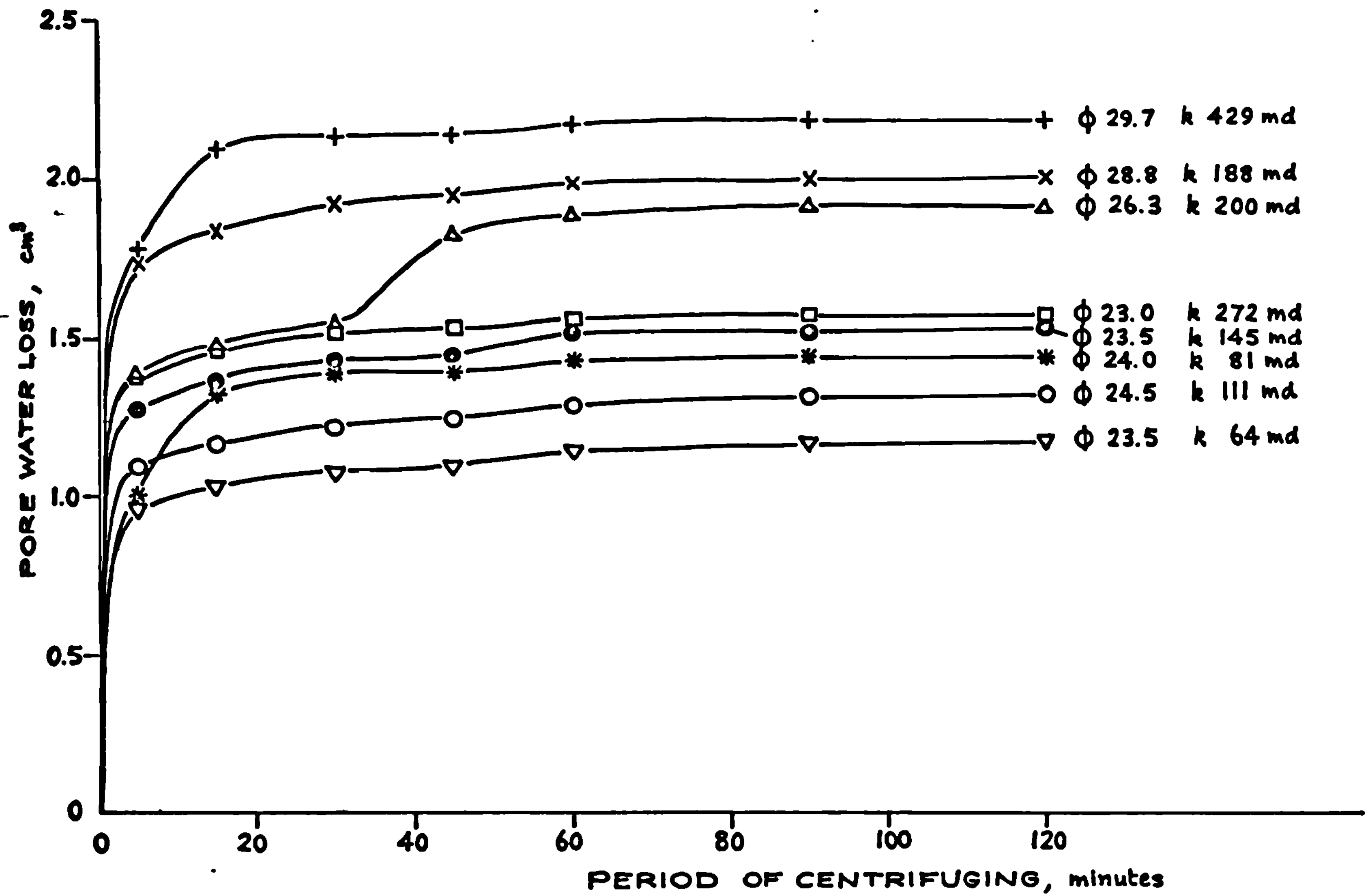
It is considered that the tolerance on this measurement can e within $\pm$ 0.05 cm before appreciable error is introduced.

One final point should be made in relation to the significance f Eq. (9). It is easily seen that if r, is set equal to $r_2 - h$ nd the equation solved for T, then a much higher value than 343 cm s obtained. Conversely if $r_1 = r_2$, then T = 0. Further calculation of the intermediate points would demonstrate the underlying assumption of this equation, viz. that in an isotropic sample, moisture tension decreases linearly with distance from the rotor, and is actually zero at the base of the specimen where seepage occurs. It also follows that if the tension is zero, then the specimen must be saturated at this point.

iii) <u>Effect of duration of test on achievement of moisture equilibrium.</u>

Studies were also made to establish the optimum period of centrifuging having regard to the cost of the measurements and the small number of samples which can be tested at one time. The original CME test employed an arbitrary one hour period which Johnson, Prill and Morris (1963) investigated. As might be expected, they found it to be adequate for coarse grained materials but too short for fine grained silts and cla

Fig. 49 presents data on the effect of duration of testing on 8 plugs of rather variable permeability and porosit The results were obtained during a 2-hour discontinuous test, and care was taken to measure the weights of each plug as rapidly as possible after each interval of time in order that capillary redistribution of moisture in the plugs, which might have affected the total pore water loss, was minimised. The diagram illustrates the very rapid drainage that occurs during



2.5
2.0
1.5
1.0
0.5
0
PORE WATER LOSS, cm³
0
20
40
60
80
100
120
PERIOD OF CENTRIFUGING, minutes
ϕ 29.7 k 429 md
ϕ 28.8 k 188 md
ϕ 26.3 k 200 md
ϕ 23.0 k 272 md
ϕ 23.5 k 145 md
ϕ 24.0 k 81 md
ϕ 24.5 k 111 md
ϕ 23.5 k 64 md

the first few minutes of centrifuging, which is followed by a much more gradual dewatering until virtual equilibrium is achieved after 1½ to 2 hours; in Fig. 49 an average 81% of the total pore water loss took place in the first 5 minutes of centrifuging.

On the basis of these results, it was decided that moisture tests should be run for two hours in order to ensure that equilibrium had been attained.

iv) <u>Effect of lateral drainage</u>

Many of the samples under examination displayed a markedly laminated structure, which was more noticeable in vertical plugs cut from them. Since there is abundant evidence of higher permeability in the direction parallel to the laminations, it was considered that there was a risk of lateral drainage taking place during centrifuging. Such a process of sideways movement of water could not take place under natural field conditions where each column of saturated aquifer adjoins other columns of saturated aquifer on all sides.

An experiment was, therefore, carried out to establish whether lateral drainage occurred. A batch of 8 plugs was centrifuged and afterwards the curved surface of the plugs was coated with a thin film of epoxy resin (the same mixture as used in the gas permeability test, see p.76). They were then centrifuged a second time and the results compared. Table 13 indicates the data obtained, and it can be seen that the water loss from coated plugs is significantly lower, owing to the exclusion of lateral drainage, which appears likely to take place even in plugs cut in the horizontal direction.

TABLE 13

EFFECT ON SPECIFIC YIELD OF COATING TEST PLUGS

Plug Code	Porosity per cent	Specific Yield		Change per cen
		Uncoated per cent	Coated per cent	
673-2H	23.60	12.08	10.69	-1.39
673-2V	23.20	11.54	10.26	-1.28
673-4V	25.22	14.65	13.29	-1.36
673-5V	22.46	13.16	11.86	-1.30
673-7V	22.24	13.76	12.45	-1.31
673-9V	27.52	17.49	15.67	-1.82
673-9H	28.40	17.56	16.27	-1.29
673-16V	22.38	10.61	9.60	-1.01

The investigation of these problems resulted in an improved testing procedure in which the simulation of natur[illegible] gravity drainage was made as precise as possible. The most important elements of the method may be summarised as follo[illegible]

1) the centrifuge should be precisely balanced and temperature controlled;

2) the tested samples must be of the same height and for comparative data, the speed of rotation should be varied according to this height;

3) the test should be carried out for a minimum period of 2 hours at a speed constant within $\pm$ 5%;

4) lateral drainage is a sizeable source of error when testing rock cores; it may be effectively minimised by the use of an epoxy resin coating.

4.7.5. Reproducibility of Measurements

The results of three repeat tests on eight plugs under identical conditions are tabulated in Table 14, with drainage expressed in this case as pore water loss. It is readily seen that the standard deviations of the values are small, and the figures for standard error indicate that measurements can be reproduced to within 1%. Undoubtedly, this superior accuracy is related to the high standard of performance of the Mistral 2L Centrifuge.

TABLE 14

RESULTS OF THREE REPEAT TESTS ON EIGHT SAMPLES

Plug Code	Pore water loss, gms			Standard deviation	Standard Er of mean
	1st Test	2nd Test	3rd Test		
28V12A	3.418	3.451	3.482	0.026	0.015
28V13A	3.274	3.263	3.257	0.007	0.004
28V14	3.222	3.371	3.332	0.063	0.036
28V16A	3.464	3.491	3.496	0.014	0.008
28V19B	3.362	3.361	3.356	0.005	0.003
28V20A	3.662	3.577	3.675	0.043	0.025
28V25	3.343	3.479	3.470	0.062	0.036
28V26B	3.263	3.271	3.313	0.032	0.018

4.7.6. Interpretation of Data

At this early stage and in the absence at the present time of a satisfactory calibration, it is difficult to judge whether the values of centrifuge specific yield obtained so far represent correct values of specific yield.

In the data sheets accompanying Chapter 6 will be found values on samples of medium to coarse grained Bunter sandstones from Area 2. These range from 7.8 to 27.0 per cent. The analyses by Water Resources Board of short duration (not more than 5 days) pumping tests produced specific yield values of approximately 5 per cent.

In the case of the samples listed in Table 13 which were fine grained Bunter Sandstone from Northern Ireland, pumping tests have suggested a value for specific yield of approximately 0.8 per cent, compared with the 10-15 per cent given by the centrifuge method. (Foster, 1969).

As a third example, centrifuge values on samples of the hard Chalk of East Yorkshire suggest a specific yield of about 0.3 - 1.0 per cent, where pumping tests have given values of 0.5 per cent - (Foster and Milton, 1971).

In these instances, there is a considerable discrepancy between the laboratory and the field values. However, the centrifuge figures are the right order of magnitude. Moreover, it cannot be denied that the analysis of pumping test data is often beset by difficulties which may result in the values of specific yield being appreciably in error. The writer considers that the centrifgue method deserves further consideration and that calibration of the technique using capillary pressure curves should be attempted as a logical development. The method offers a real opportunity of assessing rapidly on a routine basis the specific yield of both unconsolidated and consolidated materials.

CHAPTER FIVE : Correlation between lithology and aquifer properties

CHAPTER FIVE :

CORRELATION BETWEEN LITHOLOGY AND AQUIFER PROPERTIES

5.1. INTRODUCTION

The consideration in detail of the large amount of data which was generated during the course of the project, can be undertaken using two rather different lines of approach. In the face of an almost total lack of published information, it had been originally decided to study the whole of the British Permo-Triassic sandstone sequence; this has been largely accomplished although owing to the size of the problem at an essentially preliminary level. For this reason, the interpretation of the results may be tackled in two ways :

i) an interpretation in terms of lithology (This Chapter)

ii) an interpretation in terms of statistical probability (the following Chapter).

The following section describes in detail the manner in which the aquifer properties vary with the lithology. For this purpose, the sandstone subdivisions are considered on the basis of the Areas used in Chapter Two as the framework for the description of the stratigraphy. Within the Areas, formations are dealt with in ascending sequence. Each subsection is followed by a set of data sheets which form an appendix of results on each formation. These document the samples analysed and provide lithological descriptions in a shorthand, which is explained below. In this way, representative data on permeability, porosity, density and centrifuge specific yield can be obtained for any specified rock type, provided the description is based on a thorough examination of a sample under a binocular microscope. It is obviously not possible to estimate quantitative data in this manner with any high degree of confidence, but a preliminary examination of a sample at low magnification will allow an approximate estimate to be made, and it is hoped that the data sheets in this Thesis can be used in this respect as a work of reference.

TABLE 15

EXPLANATION OF LITHOLOGICAL SHORTHAND

b	breccia	dk	dark
bf	buff coloured	f	fine grained (Wentworth)
br	brown	fels	felspathic
c	coarse (Wentworth)	fr	friable, very poorly cemented
cav	cavernous, vuggy	gn	green
cg	conglomeratic	gy	grey
cn	clean	gyp	gypsiferous
con	consolidated, indurated	l	lustrous, glistenin
cs	cross-stratified		

lam : laminated

lt : light coloured

m : medium grained (Wentworth)

md : muddy

mdst : mudstone (Wentworth)

mf : containing mud flakes

mic : micaceous

ms : well rounded, or containing 'millet seed' grains.

mt : mottled colouration

o : orange

p : purple

pb : pebbly

pk : pink

r : red

sd : sand, sandston

slt : silt (Wentwort

vc : very coarse (Wentworth)

vf : very fine (Wentworth)

wc : well cemented

wg : well graded

wh : white

y : yellow

Also on the data sheets will be found, in the column 'depth or outcrop' the letters 'o/c' signifying surface outcrop, and 'm' signifying depth in metres.

5.2. NOTE ON PRESENTATION OF AQUIFER PROPERTY DATA

In the present study it was decided not to present aquifer property data either in the form of core analysis logs of the type used by petroleum service laboratories nor on a distribution map. In the first case, borehole cores have not been sampled at a sufficiently close interval for interpolation between points to be reliable; on the other hand, presentation of this type of data on maps is plainly misleading in the current state of knowledge. The results of much more intensive studies in the future may, however, be sufficiently detailed for either of these methods to be justified, particularly if these are based to a great extent on cored boreholes.

All permeability data has been given in the millidarcy unit which equals 0.966×10^{-6} cm.sec^{-1} (water), 0.966×10^{-8} m sec^{-1} or 1.71×10^{-2} Imperial gallons per day per square foot. For the convenience of the reader, one millidarcy is roughly equal therefore to 10^{-6} cm.sec.$^{-1}$ or 10^{-8}m.sec.$^{-1}$.

Finally, certain symbols used on the result sheets require explanation. Those values asterisked * are values for k_w on 75 mm cores in millidarcys; porosity and density values where given for these cores will also have been determined using the 75 mm core size. Those data suffixed ≠ are air permeability values on 75 mm cores. Data suffixed either * or ≠ have not been included in the probability distributions discussed in Chapter 6.

5.3. CORRELATION OF LITHOLOGY AND PROPERTIES, AREA BY AREA

BUNTER PEBBLE BEDS AREA 1

The Pebble Beds in this area live up to their name and they crop out over rather widely scattered districts with their true nature and extent beneath the later covering of Keuper rocks not being known in detail.

In the present study, only the sandstone units of the sequence could be subjected to core analysis and different techniques which will be described later (p.226) had to be adopted in order to determine the magnitude of intergranular permeability in the shingle beds. This type facies is particularly well developed around Birmingham and on Cannock Chase, and elsewhere close to the unconformity with pre-Triassic formations eg to the east of Burton-on-Trent.

The sandy beds interbedded with the shingle facies. were found to have a particularly high permeability, commonly between 6000 and 12000 md. Samples were examined from the Cannock Chase outcrop (Plate 2A) and from exposures near Burton-on-Trent. Porosity was also found to be very high, approaching the maximum (30-32%) for sands of this type. The magnitude of these values is a direct reflection of the clean and poorly consolidated nature of the sandstones at least at outcrop.

When subsurface samples are examined, it is found that there is only a slight tendency towards increased consolidation The cores examined from two boreholes drilled between the

Warwickshire and Leicestershire coalfields (see Fig.19), where virtually pebble-free sandstones assigned to the Pebble Beds subdivision occur beneath Keuper Sandstone, showed little evidence of either induration or cementation. Values of permeability obtained from these cores (samples No. 330-5 to 330-13 and 466-11 to 466-14) show much the same range established at outcrop, i.e. between 5000 and 18000 md. Porosity is again high at about 30%, perhaps fractionally lower than at outcrop. The most striking feature of many of these sands from the Bunter Pebble Beds is the cleanness and uniform grading, in marked contrast to the very poor grading of the intervening shingle units where these are developed.

The aquifer property values are reduced by cementation in the few localities where this has taken place. In this area, cemented samples were only obtained at Milford, Staffs (sample No. 612), at one horizon in the Appleby Parva BH (466-11) and at Ingleby, Derbyshire (518). It is possible that cementation is more widespread that these results suggest. When present, porosity is reduced to about 20% (cf reduction to 5-9 per cent in Area 3), and permeability may decrease to less than 1000 md.

AREA 1

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
330-5V1	cn m br sd	Newton Regis B.H., Tamworth, Staffs	SK 28220728	100 m	3534	2.16	29.2	
5V2				"	6004	2.14	31.3	
5V3				"	2071	2.17	29.2	
5HX1				"	7300	2.14	31.0	
5HX2				"	18934	2.14	31.1	
5HX3				"	5507	2.15	30.8	
5HX4				"	6410	2.15	30.4	
5HY1				"	5874	2.13	31.2	
5HY2				"	7114	2.13	31.2	
5HY3				"	8233	2.13	30.8	
330-6V2	c br-gy cn sd			102.0 m	12211	2.13	30.8	
6HX1				"	11337	2.13	30.9	
6HX2				"	13065	2.12	30.9	
6HY1				"	15040	2.13	31.4	

AREA 1

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
330-7HX	m fr br-r sd	Newton Regis B.H.,	SK 28220728	103.5m	-	2.32	20.8	
330-8V1	cn m r sd	Tamworth, Staffs		125.5m	4401	2.19	27.8	
8V2				"	5022	2.18	27.7	
8HX1				"	4227	2.19	27.8	
8HX2				"	4227	2.19	27.4	
8HY1				"	3705	2.21	26.7	
8HY2				"	18401	2.21	26.6	
330-9V	cn m fr r sd			131.0m	3822	2.22	26.0	
9HX1				"	3594	2.20	26.8	
9HX2				"	4124	2.21	26.5	
9HY				"	5181	2.22	26.0	
330-10V2	cn c fr r sd			136.0m	> 23000	2.15	29.7	
10HY				"	15385	2.14	30.2	
330-11V	m fr r-sd			146.0m	5016	2.19	27.4	

AREA I

Formation: BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
330-11HX2	m fr r sd	Newton Regis B.H., Tamworth, Staffs	SK 28220728	146.0m	3313	2.19	27.4	
11HY				..	4852	2.19	27.4	
330-12V	m-c cn r sd with patchy cementation			152.1m	4921	2.20	26.7	
12HX1				..	8509	2.20	26.7	
12HX2				..	6825	2.22	25.6	
12HY				..	8347	2.19	27.5	
330-13V	m fr r sd			163.5m	3528	2.15	29.9	
13HX1				..	4745	2.16	29.2	
13HX2				..	7463	2.15	29.7	
13HY				..	3124	2.16	29.4	
466-11V1	c-vc pb br sd with patchy cementation	Appleby Parva B.H., Leicestershire	SK 30670858	146.6m	2482	2.28	22.5	
11V2					2170	2.31	20.7	
11HX				..	3461	2.28	22.4	
466-12V1	m-c cn br-gy sd			155.1m	4672	2.19	27.7	

AREA 1 Formation: BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
466-12V3	m-c cn br-gy sd	Appleby Parva B.H., Leicestershire	SK 30670858	155.1m	3384	2.21	26.6	
12HX1				"	6375	2.19	27.5	
12HX2				"	4758	2.17	28.4	
12HY1				"	5365	2.18	27.9	
12HY2				"	3445	2.17	28.5	
466-13V1	f-m fr r sd			161.2m	852	2.20	27.4	
13V2				"	706	2.21	27.1	
13V3				"	1471	2.24	25.6	
13HX1				"	2172	2.20	27.5	
13HX2				"	1620	–	–	
13HY1				"	825	2.20	27.5	
13HY2				"	2286	2.20	27.2	
466-14V	c cn br-gy sd			169.1m	7147	2.15	29.7	
14HX				"	17283	2.14	30.2	

AREA 1 Formation: BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
514 HX		Repton, Derbyshire	SK30842614	o/c	4721	–	–	
HY				..	–	–	–	
515 V	gy-y m fr sd cn		SK30872616	o/c	6502	2.12	31.7	
H175				..	7033	2.14	30.5	
H265				..	8707	2.12	31.5	
516 V	br-y m cn fr sd		SK30982628	o/c	5436	2.11	32.1	
HX				[loose block]	4721	2.14	30.5	
HY				..	3878	2.14	30.5	
517 V	m-c br sd	Ticknall, Derbyshire	SK33872450	o/c	4257	2.18	28.3	
518 V	y con m sd	Ingleby, Derbyshire	SK34682666	o/c	1143	2.33	21.0	
H24				..	1934	2.34	19.8	
H294				..	2571	2.35	19.4	
611 V	f-c lt br sd patchy cement	Hopton, Staffordshire	SJ94582603	o/c	329	2.29	21.6	

AREA I

Formation: BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
611 H130	f-c lt br sd patchy cementation	Hopton, Staffs	SJ94582603	o/c	1147	2.28	22.5	
H220				..	1507	2.31	20.7	
612 V	m-c wc pk sd	Spring Hill, Milford, Staffs	SJ97702098	o/c	99	2.40	15.9	
H177				..	573	2.39	16.2	
H267				..	678	2.35	18.6	
615 V	cn m fr r sd	A5 at Hints; Staffs	SK15740335	o/c	3391	2.13	31.3	
H165				..	15042	2.11	31.8	
H255				..	–	2.11	32.3	
617 V	m-c dk br sd	Anglesey Canal, Ogley Hay, Staffs	SK05710604	o/c	2188	2.25	23.5	
H32				..	4095	2.25	23.3	
H302				..	7481	2.26	23.0	
634 V	fr m pk sd	Marlbrook Sand Pit, Bromsgrove, Worcs	SO97987470	o/c	39	2.13	30.1	
H258				..	1081	2.07	33.4	
705 V	dk r mdst	Dunnings Gravel	SJ97091243	o/c	<1	–	–	
	cn m-c	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	

AREA 1 Formation: BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
706 H260	cn m-c fr pk-gy sd	Dunnings Gravel Works, Huntington.	SJ97061233	o/c	13247	2.09	32.5	
H350				..	10043	2.13	31.1	
707V	cn fr m-c gy sd		SJ97021233	o/c	-	2.12	25.8	
H154				..	6755	-	-	
H244				..	11770	2.12	30.5	
712 V	fr m-c r sd		SJ96801213	o/c	7729	2.10	33.1	
H107				..	12253	2.12	31.4	
H1-197				..	-	2.03	32.1	
H2-197				..	10107	2.11	31.6	
H287				..	-	2.10	32.4	
715V	fr m-c r sd		SJ96751214	o/c	-	2.10	31.1	
H80				..	9930	2.10	33.0	
H170				..	-	2.09	30.1	
716 V	m-c fr r sd		SJ96751214	o/c	4355	2.13	31.2	

AREA I

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
716 H 360	m-c fr r sd	Dunnings Gravel Works, Huntington	SJ96751214	o/c	9214	2.09	31.8	
695-40V	m-c r sd	Webheath B.H., Redditch, Worcs	SP00986693	306.9m	3652	2.21	26.7	
40HX				"	6782	2.19	27.5	
40HY				"	3099	2.20	27.3	
696 A	f-m fr r sd	Sling Common, Belbroughton, Worcs	SO94657819	o/c	–	2.11	30.3	
B				"	724	2.12	30.4	
C				"	925	2.13	29.9	

As has already been stated (p 10), this subdivision is only present in the extreme west of this area where in the course of this study core samples were obtained from two boreholes. A few outcrop samples were also obtained near Bromsgrove but it is not considered that sufficient material has been examined from the Birmingham City area in order to come to any quantitative conclusions on the properties of the formation in that district.

The test results from the Webheath borehole, where practically a full section in the sand was penetrated below some 180 m of Keuper rocks, indicate that all gradations of red sandstone are present, ranging from very fine grained units through to clean medium grained beds. As might be expected, the aquifer properties alter with the grain size and degree of sorting. As a general rule, the sandstones are on the fine side and permeability is commonly between 100 and 1000 md with porosity about 25%.

In more detail, the very fine grained well-cemented or consolidated sandstones possess minimal permeability (as low as less than 1 md) and porosity reduced to 19 per cent (695-26 and 695-37). The dominant fine grained sands may be cemented (eg 695-31) in which case permeability lies between 10 and 100 md and porosity is again reduced to about 23 per cent. Some of the fine sands are, however, friable and well graded and in these beds permeability ranges up to 2000 md with porosity greatly increased to 32-33% (632 and 694). Next in gradation are the poorly graded fine to medium sands which in spite of moderate porosity (24%) show reduced permeability (500-1000 md), eg. sample 695-28). Finally at the coarse end of the scale, are the clean medium sands which appear to be more common near the base of the subdivision, as the underlying Pebble Beds are approached. These have the highest permeability, reaching 7-8000 md with porosity moderate to high. These clean sands were present both at Webheath (samples 695-27, 695-32 and 695-35), and in the Birmingham Tunnels Site Investigation BH (samples 743-1, 743-3 and 743-4).

Partial cementation of the sandstone along cross-stratification laminae appears to be a marked sedimentological characteristic of the Upper Mottled Sandstone subdivision in this area. It would be interesting to establish the general distribution of the medium grained clean sands in both vertical and lateral directions.

AREA 1

Formation: UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
632 VI	fr f cav r sd	Burcot, Bromsgrove, Worcs	SO98507152	o/c	2439	2.09	33.0	
H265				..	2328	2.09	32.6	
H355				..	1843	2.10	32.1	
694 V	f r sd	Vigo, near Bromsgrove, Worcs	SO98567138	o/c	1023	2.10	32.4	
H87				..	1196	2.09	33.0	
H357				..	1383	2.10	32.8	
695-23V	m con pk sd	Webheath B.H., Redditch, Worcs	SP00986693	c192.3m	2822	2.25	24.3	
23HX				..	1966	2.25	24.2	
23HY				..	2440	2.26	23.6	
695-24V	f-c wc lam pk sd			199.0m	132	2.33	20.0	
24HX				..	1309	2.32	20.6	
24HY				..	809	2.33	20.0	
695-25V	f con r sd with laminar veins			206.7m	80	2.25	23.8	
25HX				..	421	2.24	24.4	
25HY					[illegible]	2.25	24.1	

AREA 1 Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
695-26V	wc vf r sd mic mf	Webheath B.H., Redditch, Worcs	SP00986693	214.3m	2	2.26	24.2	
26HX				"	7	2.34	19.0	
26HY				"	26	2.26	24.3	
695-27V	m fr pk sd cn			221.9m	4986	2.17	29.1	
27HX				"	6396	2.17	28.9	
27HY				"	7733	2.16	29.3	
695-28V	f-m fr pk sd			229.5m	516	2.28	22.8	
28HX				"	532	2.26	23.6	
28HY				"	933	2.27	23.4	
695-30V	f-m fr pk sd & patchy cementation			245.4m	1239	2.24	24.7	
30HX				"	1462	2.26	23.9	
30HY				"	1631	2.25	24.1	
695-31V	f con r sd			251.2m	9	2.26	24.0	
31HX				"	79	2.28	22.9	
[illegible]					[illegible]	[illegible]	[illegible]	

AREA 1

Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
695-32V	m fr cn r sd	Webheath B.H., Redditch, Worcs	SP00986693	258.8 m	5206	2.17	28.9	
32HX				-	7034	2.18	28.5	
32HY				-	5235	2.20	27.1	
695-33V	f r sd cs with laminar cementation mf			264.0 m	1159	2.20	27.2	
33HX				-	873	2.25	24.9	
33HY				-	1547	2.22	26.3	
695-34V	vf-f fr r sd			271.3 m	69	2.19	27.9	
34HX1				..	148	2.19	28.4	
34HX2				..	626	2.20	27.6	
34HY				-	1067	2.20	26.7	
695-35V	m fr cn r sd			278.3 m	5609	2.17	28.0	
35HX				..	6342	2.17	28.2	
35HY				..	5283	2.19	26.9	
695-36V	f-m lam r·sd with			285.3 m	1309	2.21	26.6	

AREA 1

Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
695-36HY	f-m sd part cemented	Webheath B.H., Redditch, Worcs	SP00986693	285.3m	1607	2.22	26.0	
695-37V	vf-f con r sd lam partly cemented			292.3m	<1	2.33	19.4	
37HX				"	27	2.31	20.4	
37HY				"	72	2.28	22.1	
695-38V	con f cn r sd			292.9m	2120	2.19	27.5	
38HX				"	1294	2.21	26.8	
38HY				"	1788	2.18	28.0	
695-39V	f-m con r sd			299.9m	122	2.27	23.2	
39HX				"	144	2.26	23.9	
39HY				"	296	2.27	23.3	
739-1V	f-m fr r sd	Aston Expressway Site Investigation B.H., A48, Birmingham	SP	n/k	2032	2.22	25.7	
1HX				"	6177	2.20	26.2	
1HY				"	18383	2.19	26.9	
739-2V	vf-f mic lam r sd			n/k	3	2.31	20.7	

AREA 1 Formation: UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
739-2HX	vf-f lam mic r sd	Aston Expressway Site Investigation BH A48, Birmingham	SP 077875	n/k	24	2.31	20.9	
2HY				..	122	2.30	21.1	
739-3V	slt-vc fr lam r sd			n/k	24	2.27	22.7	
3HX				..	263	2.27	22.9	
3HY				..	477	2.36	17.6	
740-1V	vf-f fr lam r sd	Aston Expressway Site Investigation BH 24, Birmingham	SP 077875	n/k	-	2.19	27.3	
1HX				..	1995	2.18	28.8	
1HY				..	2364	2.21	26.8	
740-2V	vf-c lam fr r sd			n/k	-	2.20	27.1	
2HX				..	-	2.20	25.4	
2HY				..	-	2.17	25.7	
740-3V	vf-c lam fr r sd			n/k	-	2.17	28.4	
3H				..	-	2.15	24.8	
740-4V	vf-c lam fr r sd			n/k	375	2.17	26.5	

AREA 1 Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
740-4HY	vf-c lam fr r sd	Aston Expressway Site Investigation BH 24, Birmingham	SP 077875	n/k	2411	2.18	28.5	
740-5V	vf-m lam fr r sd			..	1645	2.20	26.9	
5HX				..	5454	-	-	
5HY				..	3415	2.13	26.7	
744-1V	vf-f fr lam r sd	Birmingham Tunnels Site Investigation BH 14	SP 07338658	c 21.3m	880	2.17	28.7	
1HX				..	810	2.17	28.4	
1HY	vf-c lam fr r sd			..	2363	2.19	27.5	
744-2V	wg f-m fr r sd			c 24.4m	1159	2.16	28.8	
2H				..	1977	2.17	28.3	
744-3V	wg f-m fr r sd			c 27.4m	1451	2.18	27.7	
3HX				..	2214	2.16	28.9	
3HY				..	1351	2.18	27.8	
744-4V	vf-f lam fr r sd			c 30.5m	583	2.20	26.4	
4H				..	1434	2.16	27.5	

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
743 - 1V	cn fr m br sd	Birmingham Tunnels Site Investigation BH 2	SP 06158637	c. 21.6m	6248	2.07	35.1	
1HX				"	8006	2.06	35.3	
1HY				"	7740	2.06	34.9	
743 - 2V	f-m r sd			c. 25.3m	1669	2.21	26.1	
2H				"	1274	2.21	25.8	
743 - 3V	fr cn m r sd			c. 29.0m	9317	2.16	28.7	
3HX				"	4706	2.16	28.8	
3HY				"	6860	2.14	29.3	
743 - 4V	fr cn m mic r sd			c. 31.7m	4427	2.19	30.9	
4HX				"	5648	2.16	29.1	
4HY				"	6180	2.14	29.6	

LOWER KEUPER SANDSTONE AREA 1

The Lower Keuper Sandstone in this area exhibits a wide range of lithology in contrast to adjacent districts, each of the rock types possessing characteristic physical properties, which together must result in rather complex hydrodynamic behaviour.

Not surprisingly, the least permeable units of the sequence are the mudstones and siltstones, which are found interbedded with sandstone in the higher parts of the succession in the eastern part of Area 1. These were, however, also encountered in the extreme south, where they were sampled in the Webheath BH (Samples 695). Permeability in the mudstones is effectively zero, whereas in the siltstones, it is commonly up to 20 md, rising to 50 md in the coarser beds (cf samples 325-1; 325-2; 466-3; 513; 695-1; 695-12; and 695-20). Porosity, on the other hand, is generally between 12 and 20 per cent, depending on the extent of cementation. These siltstones may be expected to extend over relatively wide areas, and in view of the fact that they commonly separate more permeable sandstone units, primary transmissivity (See p.212) especially in the upper part of the Keuper Sandstone is likely to be very reduced.

Fine grained sands are fairly widespread in the Keuper and these may be divided into three groups: i) clean sands with permeability of between 1000 and 2000 md and porosity of 30%, e.g. sample nos. 745-1 and 466-2.

ii) consolidated slightly silty sands (by far the most usual) with permeability 400-600 md and porosity of 27-30%, e.g. 68; 325-5; 330-4; 466-1; 512 and 695-13, and iii) well cemented fine sands in which permeability is less than 100 md, and porosity 20-25% e.g. 695-2; 695-7 and 695-22. The fine sands encountered in the Webheath borehole were found to be more cemented on the whole than those sampled elsewhere in this area at comparable depth.

The medium grained sands are generally clean, angular and well graded with permeability ranging from 2000 to 10000 md and porosity commonly about 30% (e.g. samples 27; 67; 69; 138; 325-8; 616; 695-6; 738-1; 745-4 etc.) The permeability value is sensitive to slight changes in grain size within the medium range. Many of the sandstones, however, range from fine to medium and these have been found to have marginally lower permeability of from 1500 to 5000 md, with porosity essentially the same (e.g. 25; 95; 325-7; and 330-2).

These highly permeable medium sands with their distinctive texture are the most significant rock types of the Keuper Sandstone sequence in the Midland area. They appear to be widespread in the centre of the area, and have been proved to be present beneath the Keuper Marl in the area between the Warwickshire and Leicestershire Coalfield, but they die out in the extreme east and south, where their presence in the Webheath borehole was found to be very subordinate.

Finally, we must consider the coarsest members of the sandstone squence which as a general rule lie at or near the base of the subdivision, close to the unconformable junction with the underlying Bunter. Samples of these beds have been tested both in the uncemented and cemented state, with very different results. As might be expected, the uncemented clean coarse sands are the most permeable members of the sequence, with values exceeding 10000 md (e.g. 325-10; 466-5; 466-8; 466-9; 695-16; and 738-2). Porosity in these beds is rather variable owing to the widespread presence of patchy cementation and it may range from 23 to 31% without significantly altering permeability. In the cemented state, permeability is obviously reduced but not to zero, even in beds which macroscopically appear to have very low to negligible porosity. Thus in samples 205; 695-10; 737-1 to 4 and 738-5, intergranular permeability ranges from less than 1 to about 250 md, and porosity shows a wide variation from 5 to 17% depending on the amount of cementation.

Density variation in the subdivision is closely related to the degree of cementation and also grain size distribution. General values showing quite wide variation are given below:

		$gms\ cc^{-1}$
siltstones		2.35 - 2.45
fine sands -	clean	2.16
	silty	2.18
	cemented	2.23
medium sands		2.15 - 2.18
coarse clean sands		2.10 - 2.25
cemented coarse sands		2.50

By way of a digression, the aquifer properties of the Lower Keuper Sandstone tend to reduce in value from the base upwards. There is abundant evidence from the several bore-hole sections examined that the coarsest and most permeable sands occur near the base and these become finer grained as the sequence is ascended, until, by gradation, the Keuper Marl is reached, which consists almost entirely of material of permeability less than 1 md. When consideration is being given to the behaviour of the overlying Keuper Marl as a confining bed, it should, therefore, be considered not as a single planar boundary, but as a zone of transition. Examination of the piezometric levels recorded in wells which partially penetrate to differing degrees the whole Keuper formation might reveal direct evidence of such a confining zone in the Keuper beds. The highest recorded levels would be expected in those wells which penetrated the greatest thickness of the confining zone, and only these would show values consistent over a wide area. The errors involved in calculating gradients based on data from partially penetrating wells would therefore be considerable.

AREA 1

Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
25 V	f-m dk rd fr sd	Rockhill Quarry, Bromsgrove, Worcs	SO94886980	o/c	1414	2.18	28.8	
H1-12				..	1600	2.33	28.2	
H2-12				..	1872	–	–	
H102				..	1417	–	–	
26V	vf-f con mic r sd			o/c	101	2.25	23.6	
H162				..	317	2.22	25.2	
H 252				..	177	2.25	24.4	
27 V1	cn wg m gy sd		SO 94916980	o/c	2717	2.15	30.1	
V2				..	2140	2.15	29.9	
H1-140				..	1538	2.19	27.9	
H2-140				..	1639	2.17	29.0	
H1-340				..	2372	2.17	28.6	
H2-340				..	1880	2.17	29.0	
H3-340				..	2539	2.16	29.4	
[illegible]	cn m wg	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	

AREA 1 Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
67H60	cn m wg fr br sd	Alrnalls, Lichfield	SK09741015	o/c	7868	2.15	29.6	
68 V1	f con mic dk r sd small vugs		SK09771014	o/c	603	2.18	28.3	
V2				..	245	2.19	27.7	
H90				..	793	2.18	28.3	
H1-180				..	941	2.20	27.5	
H2-180				..	632	2.17	29.0	
69 H55	cn m wg fr br sd		SK09741015	o/c	9733	2.14	30.0	
71 V	f con dk r sd	Wolgarston, Penkridge, Staffs	SJ94301387	o/c	1938	2.20	26.6	
H1-113				..	1898	2.21	26.5	
H2-113				..	425	2.24	24.6	
H203				..	554	2.22	25.7	
75 H5		Oulton Gorge, Stone, Staffs	SJ91573558	o/c	1713	2.17	29.6	To AREA 4
H95				..	2181	2.16	29.5	To AREA 4
95 V1	f-m cn con gy-gn [illegible]	Donington Park, Derbyshire	SK41962755	o/c	1207	2.17	28.6	
V2	[illegible]				[illegible]	[illegible]	[illegible]	

AREA 1

Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
95 H1-150	f-m con gn-gy sd cn	Donington Park, Derbyshire	SK 4196 2755	o/c	1411	2.18	28.3	
H2-150				"	1797	2.20	26.8	
H1-240				"	1257	2.17	28.8	
H2-240				"	1330	2.18	28.5	
138 V	cn m y fr sd	Altons No 1 BH, (NCB) Packington Leics	SK 3946 1523	24.1 m	761	2.18	28.4	
HX				"	2165	2.17	28.9	
HY				"	4616	2.17	29.4	
203 V1	f-vc pb dk r sd	NCB Swarestone Lodge B.H., Leics.	SK 3433 1015	59.3 m	250	2.32	22.8	
V2				"	151	2.32	22.8	
V3				"	158	2.34	21.8	
HX1				"	193	2.38	19.5	
HX2				"	188	2.38	19.5	
HY1				"	195	2.39	19.4	
HY2				"	198	2.39	19.1	
204 V1	f-vc pb			[illegible]	145	2.31	19.0	

AREA 1

Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
204 V2	f-vc pb dk r sd	NCB Sharestone Lodge B.H., Leics	SK34331015	c.60m	82	2.40	17.1	
HX1				..	458	2.36	20.1	
HX2				..	399	2.36	19.8	
HY1				..	616	2.34	20.8	
205 HX1	lam dk r cg			62.8m	78	2.53	13.9	
325-1V	br lam slt with gypsum vugs	Austrey House B.H., Atherstone, Warwicks	SK30270485	15.3m	<1	2.37	18.1	
1HX				..	5	2.40	18.0	
1HY				..	18	2.37	18.4	
325-2V	wc lam br slt with cement clots			27.2m	<1	2.40	13.7	
2HX				..	3	2.39	13.5	
2HY1				..	4	2.38	14.2	
2HY2				..	21	2.40	14.7	
325-3V	wc f gy lam sd			29.6m	<1	2.37	18.1	
3HX				..	<1	2.37	17.8	
3HY				..	<1	2.37	17.6	

AREA 1

Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
325-4V	vf-f br-r lam fr sd	Austrey House B.H., Atherstone, Warwicks	SK30270485	36.7m	1006	2.15	29.5	
4HX1				"	1852	2.11	31.6	
4HX2				"	2286	2.09	32.0	
4HY1				"	2147	2.10	31.7	
4HY2				"	2546	2.10	31.9	
325-5V1	vf-f con lam br-r sd			39.1m	262	2.17	28.5	
5V2				"	600	2.13	30.1	
5V3				"	559	2.15	28.4	
5HX				"	673	2.15	29.2	
5HY1				"	655	2.15	28.9	
5HY2				"	684	2.14	29.3	
325-6V1	f gy lam mic sd			52.8m	612	2.16	28.5	
6V2				"	1511	2.13	30.4	
6V3				"	1411	2.10	30.7	
6HX1				"	1299	2.15	29.6	

AREA 1

Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
325-6HX2	f gy lam mic sd	Austrey House B.H., Atherstone, Warwicks.	SK30270485	52.8m	1263	2.15	29.5	
6HY1				"	793	2.18	27.7	
6HY2				"	902	2.15	28.2	
325-7V1	f-m cn gy mic sd with patchy cementation			74.0m	2270	2.17	26.8	
7V2				"	1842	2.18	27.0	
7HX				"	2610	2.17	27.6	
7HY1				"	2817	2.17	27.6	
7HY2				"	2970	2.16	27.1	
325-8V1	m lam mic con cn gy sd			78.1m	1506	2.16	29.1	
8V2				"	2364	2.14	29.7	
8V3				"	2060	2.18	29.8	
8HX1				"	5972	2.08	29.4	
8HX2				"	5952	2.14	29.9	
8HY1				"	5283	2.14	30.3	
8HY2				"	5303	2.14	29.8	

AREA 1

Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
325-9V1	m con gn-gy sd	Austrey House B.H., Atherstone,	SK 30270485	88.7m	3322	2.13	30.7	
9V2				..	2959	2.12	30.7	
9HX				..	3356	2.15	30.8	
9HY1				..	3832	2.13	30.6	
9HY2				..	3437	2.12	30.8	
325-10V1	m-c wc gy sd			99.8m	49	2.41	14.5	
10V2	c fr gn-gy sd with patchy cementation			..	8619	2.16	29.1	
10HX1				..	7511	2.27	27.6	
10HX2				..	11619	2.20	26.6	
10HY				..	16278	2.21	27.2	
325-11V1	cn m gy mic sd			116.1m	4354	2.15	29.6	
11V2				..	4621	2.14	30.1	
11HX1				..	4250	2.14	30.4	
11HX2				..	4559	2.15	30.0	
11HY1				..	4660	2.14	30.2	

AREA 1 Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
325-11HY2	cn m gy mic sd	Austrey House B.H.,	SK30270485	116.1m	4506	2.14	30.3	
325-12V	f-m dk br mic fr sd	Atherstone, Warwicks		126.8m	3948	2.16	29.2	
12HX1				..	4049	2.16	29.4	
12HX2				..	5168	2.15	29.6	
12HY1				..	–	2.14	30.4	
12HY2				..	4884	2.15	29.5	
12HY3				..	4993	2.14	30.2	
325-13V1	fr m pk mic sd			135.9m	5171	2.20	26.9	
13V2				..	1178	2.18	27.8	
13HX1				..	3583	2.14	30.1	
13HX2				..	3539	–	–	
13HY1				..	4980	2.14	30.0	
13HY2				..	4898	2.13	30.3	
13CD				..	6377	2.19	27.3	

AREA 1

Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
330-1V1	lam f-m fr gy sd heavy minerals may include copper pyrite	Newton Regis B.H., Tamworth, Staffs	SK 2822 0728	22.8m	1860	2.18	27.8	
1V2				..	2393	2.18	27.9	
1HX1				..	2630	2.21	25.1	
1HX3				..	3148	2.18	28.3	
1HY1				..	2832	2.21	25.7	
1HY2				..	2652	2.20	27.0	
1HY3				..	2327	2.22	25.5	
330-2V1	f-m lam cr gy mic sd			24.4m	1343	2.14	30.3	
2V2				..	2776	2.07	29.6	
2V3				..	554	2.17	29.0	
2HX1				..	3136	2.12	31.2	
2HX2				..	4746	2.12	31.6	
2HX3				..	2183	2.17	28.9	
2HY1				..	4347	2.15	30.1	

AREA 1 Formation: LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
330-2HY3	f-m lam cn gy mic sd	Newton Regis B.H.,	SK 2822 0728	24.4m	3529	2.12	31.3	
330-3V1	f-m mic con dk br sd	Tamwork, Staffs		75.8m	2642	2.15	29.4	
3HX1				"	3600	2.15	29.8	
3HX2				"	2649	2.15	30.0	
3HY1				"	3421	2.16	29.8	
3HY2				"	3473	2.15	30.0	
330-4V	vf con mic r sd			87.9m	245	2.19	28.3	
4HX				"	422	2.19	28.5	
4HY				"	692	2.18	29.2	
466-1V1	f con gy gn sd	Appleby Parva B.H.; Leicestershire	SK 3067 0858	39.7m	454	2.17	29.3	
1V2				"	496	2.17	29.3	
1H				"	634 *	2.18 *	28.4 *	
1HX1				"	330	2.20	27.5	
1HX2				"	368	2.19	27.9	
1HY1				"	[illegible]	[illegible]	[illegible]	

AREA 1

Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
466-1HY2	f con gy gn sd	Appleby Parva B.H., Leicestershire	SK30670858	39.7m	735	2.16	29.6	
466-2V	f cn con gy-gn mic sd with cement clots			55.1m	1644	2.18	29.5	
2V1				"	2195	2.16	29.9	
2V2				"	1390	2.17	29.4	
2HX1				"	1505	2.16	29.9	
2HX2				"	2091	2.15	30.1	
2HY1				"	1510	2.17	29.3	
2HY2				"	1616	2.17	29.2	
2H				"	1854	2.18	28.9	
466-3V1	dk r gyp slt with vugs con			62.1m	<1	2.42	17.3	
3V2				"	<1	2.45	15.6	
3HX1				"	<1	2.43	16.6	
3HX2				"	<1	2.45	14.9	
3HY				"	<1	2.46	14.8	
	f gy con sd							

AREA 1 Formation: LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
466-4V2	f gy con sd cement clots heavy minerals may include copper pyrites	Appleby Parva BH, Leicestershire	SK 30670858	70.8m	1980	2.16	29.5	
4H				"	1248 *	2.18 *	28.7 *	
4HX1				"	1257	2.15	30.2	
4HX2				"	2124	2.17	29.6	
4HY1				"	1148	2.16	29.7	
4HY2				"	2104	2.16	29.5	
466-5V1	m-vc pb cn br-r sd patchy cementation			89.2m	6818	2.24	26.4	
5V2				"	7788	2.25	25.9	
5V				"	–	2.27	24.8	
5HX1				"	12074	2.30	23.8	
5HX2				"	13701	2.22	27.2	
5HY1				"	14451	2.21	27.7	
5HY2				"	8406	2.26	25.2	
5H				"	6344 *	2.24	26.3	
[illegible]	gn-gy con			[illegible]	[illegible]	[illegible]	[illegible]	

AREA 1 Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
466-6V2	gn-gy con mf cg matrix of patchy cemented m-c gy sd	Appleby Parva B.H., Leicestershire	SK30670858	107.7m	527	2.35	22.1	
6HX1				..	1440	2.3	21.4	
6HX2				..	1468	2.32	23.1	
6HY1				..	1072	2.37	21.3	
6HY2				..	1581	2.39	24.0	
466-7V1	f lam mic wg br-r sd			126.3m	236	2.18	29.0	
7V2				..	359	2.19	28.2	
7HX1				..	431	2.19	28.4	
7HX2				..	339	2.19	28.6	
7HY1				..	259	2.21	27.6	
7HY2				..	160	2.21	27.2	
466-8V1	m-c cn fr gy sd			132.9m	8454	2.12	31.1	
8V2				..	10112	2.11	31.7	
8HX				..	8807	2.14	30.5	
8H[illegible]					[illegible]	[illegible]	[illegible]	

AREA 1

Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
466-9V1	m-c pb cn fr gy sd	Appleby Parva B.H., Leicestershire	SK 30670858	137.1 m	10510	2.11	31.9	
9V2				..	10883	2.11	32.1	
9HX				..	11617	2.11	32.2	
9HY1				..	12215	2.11	32.1	
9HY2				..	10509	2.11	32.0	
466-10V1	f-c fr cs lam r sd			142.4m	1333	2.23	25.1	
10V2				..	676	2.23	25.5	
10HX1				..	4657	2.21	26.5	
10HX2				..	4087	2.22	25.7	
10HY1				..	6053	2.20	26.9	
10HY2				..	5704	2.22	26.2	
478 B	cn c pb sd patchy cementation	Sugarbrook No.1 B.H.	SO 96036815	253.6m	6598	2.27	23.2	
512 V	vf-f br con sd	Linton, Leics	SK 26641683	o/c	494	2.17	29.2	
H10				..	907	2.16	30.2	

AREA 1

Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
513 V	wc lam slt br mic mf	Newton Solney, Derbyshire	SK27982587	o/c	13	2:36	19.6	
HX				..	19	2.37	18.9	
HY				..	36	2.34	21.1	
613 V	m wg cn gy-br mt sd	Slitting Mill, Rugeley, Staffs.	SK02921753	o/c	3622	2.14	30.5	
H 11				..	4150	2.16	29.5	
H 281				..	4340	2.18	27.9	
614 V	m-vc fr r sd	Near Lichfield, Staffs	SK13380928	o/c	4945	2.13	30.8	
HX				..	4850	2.13	30.7	
HY				..	–	2.11	31.5	
616 V	cn m fr pk sd	A5 at Hints, Staffs	SK15780334	o/c	5685	2.12	31.7	
H 160				..	7123	2.12	31.8	
H 250				..	4706	2.15	30.1	
631 V1	m fr r sd	Tutnall, Bromsgrove	SO99067026	o/c	3854	2.12	31.2	
V2				..	4050 *	2.11 *	32.5 *	

AREA 1

Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
631 H 245	m fr r sd	Tutnall, Bromsgrove	SO99067026	o/c	2750	2.14	30.0	
633 V1	f-m lam fr mic r sd	Burcot, Bromsgrove	SO97617173	o/c	3028	2.12	31.6	
V2				..	1982 *	2.15 *	30.4 *	
H91				..	6341	2.07	34.9	
H181				..	10228	2.05	36.2	
695-1V	f-c lam slt br mic	Webheath B.H., Redditch, Worcs	SP00986693	40.5m	18	2.20	27.3	
-1HX				..	51	2.20	27.8	
1HY				..	19	2.20	27.7	
695-2V	f wc bf sd lam			48.2m	47	2.21	26.7	
2H				..	161	2.23	26.2	
695-3V	f wc wg bf lam mic sd			54.3m	104	2.17	29.9	
3HX				..	165	2.17	29.8	
3HY				..	221	2.16	29.9	
695-4V	f-m gn-gy wc sd with [illegible]			c.63.7m	<1	2.35	18.9	

AREA 1 Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
695-4HY	f-m gn-gy wc sd	Webheath B.H., Redditch, Worcs	SP 00986693	c. 63.7m	0.4	2.38	17.8	
695-5V	vf lam r sd mic mf			70.1m	<1	2.26	24.6	
5H				"	<1	2.28	24.1	
695-6V	cn wg m sd lt br with cement clots			76.2m	4933	2.07	34.5	
6HX				"	8467	2.07	34.6	
6HY				"	6685	2.08	33.9	
695-7V	wc vf-f r mic sd lam			83.8m	<1	2.23	26.2	
7HX				"	<1	2.25	25.2	
7HY				"	-	2.25	25.3	
695-8V	f-c fr gy sd mf			92.2m	840	2.18	28.4	
8HY				"	-	2.13	29.9	
695-9V	f-m con r sd			100.0m	370	2.16	29.4	
9HX				"	125	2.17	28.8	
9HY				"	405	2.16	29.2	

AREA I

Formation: LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
695-10H	g-y c wc pb sd	Webheath B.H., Redditch, Worcs	SP00986693	106.7m	13	2.49	10.9	
695-11V	f-m wc lam r sd			115.2m	32	2.20	27.1	
11HX				-	783	2.18	27.9	
11HY				-	245	2.23	25.7	
695-12V	vf-c wc slt gn-r mt			122.8m	<1	2.45	13.0	
12HX				-	<1	2.45	12.9	
12HY				-	<1	2.43	14.4	
695-13V	f con lam r sd			130.2m	172	2.18	28.1	
13HX				..	276	2.18	28.1	
13HY				..	315	2.18	28.3	
695-14V	f-m wc r sd			137.8m	359	2.22	25.8	
14HX				-	348	2.24	24.9	
14HY				-	282	2.26	23.5	
695-15V	f-m wc			c.144.8m	<1	2.28	23.5	

AREA 1

Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
695-15HY	f-m mic wc lam r sd	Webheath B.H.,	SP 00986693	c 144.8m	127	2.22	26.8	
695-16V	c-vc cn fr r sd	Redditch, Worcs		151.8m	11510	2.11	32.3	
16HX				-	2600	2.12	31.7	
16HY				-	15432	2.12	32.0	
695-17V	c-vc pb pk sd with partial cementation			153.0m	290	2.42	19.8	
17HX				-	1532	2.36	19.5	
17HY				-	2723	2.34	19.8	
695-18H	c-vc pb cg fr			159.4m	10094 *	2.24 *	25.2 *	
695-19	c-vc pb cg cm			160.6m	–	–	–	
695-20V	vf mic lam wc r sd			168.3m	2	2.34	20.7	
20H				..	3	2.32	22.3	
695-21				175.9m				
695-22V	f wc lam r sd			183.8m	6	2.24	25.1	
22HX				-	130	2.25	24.2	

AREA 1 Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
737- 1V	c-vc pb sd wc	Site Investigation BH No.1, Sutton Coldfield, Warwicks.		9.0m	74	2.39	17.0	
1HX				"	23	2.48	12.3	
1HY				"	71	2.44	14.5	
737- 2V	vf-f wc br sd			9.9m	6	2.45	13.7	
2HX				"	<1	2.54	9.1	
2HY				"	1	2.53	9.7	
737- 3V	f wg wc br sd			11.2m	5	2.48	11.6	
3HX				"	264	2.41	16.1	
3HY				.	250	2.42	15.9	
737- 4V	m wg wc br sd			12.9m	184	2.40	16.6	
4HX				"	166	2.43	14.6	
4HY				"	160	2.43	14.4	
738- 1V	cn m r sd mic	Site Investigation BH No.5, Sutton Coldfield Warwicks		8.2m	3094	2.18	27.9	
1HX				"	3046	2.18	28.2	

AREA 1

Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
738-2V	cn m-c fr mic pk sd	Site Investigation BH No.5, Sutton Coldfield, Warwicks		c.9.3m	13445	2.14	30.0	
2HX				"	14423	2.02	28.0	
2HY				"	13426	2.14	30.1	
738-3V	vf-f con mic r sd			c.10.8m	72	2.26	24.2	
3HX				"	157	2.27	23.8	
3HY				"	146	2.26	24.7	
738-4V	cn m fr lt br sd			c.12.2m	3564	2.16	29.7	
4HX				"	3509	2.17	29.3	
4HY				"	3629	2.17	29.7	
738-5V	wc m-vc pb sd			c.13.7m	<1	2.60	5.3	
5H				"	31	2.57	6.2	

AREA 1

Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
745-1V	f wg cn br mic sd	Birmingham Tunnels Site Investigation, BH 15	SP 0702 8622	11.0 m	859	2.15	30.2	
1HX				"	2552	2.14	30.9	
1HY				"	945	2.16	29.5	
745-2V	vf con mic br-r sd			14.3 m	13	2.28	23.7	
745-3V	cn f-m lt br sd			17.1 m	3131	2.20	27.9	
3HX				"	3167	2.19	28.6	
3HY				"	3062	2.21	27.6	
745-4V	cn wg m lt br sd			21.0 m	2016	2.24	26.0	
4HX				"	1447	2.31	22.4	
4HY	f-m partly cemented br sd			"	0.6	2.47	14.6	
745-5V	con vf lam mic sd			23.2 m	106	2.27	23.8	
5HX				"	2856	2.25	24.3	
5HY				"	80	2.27	23.5	
745-6V	cn f-m lt br sd			24.4 m	222	2.22	27.4	

AREA I Formation: LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
745-6HY	en f-m lt br sd	Birmingham Tunnels Site Investigation BH 15	SP 07028622	24.4m	3077	2.21	27.3	
741-1V	cn f-m br sd wg	Site Investigation BH 3, Coventry.	SP 335782	1.5m	4915	2.12	32.8	
1HX				..	6695	2.12	32.7	
1HY				..	6514	2.11	33.3	
741-2V	vf-m lam con r sd			c.4.4m	8	2.28	24.1	
2H				..	51	2.29	23.6	
741-3V	m wc br sd			c.7.6m	373	2.37	17.8	
3HX				..	459	2.34	19.4	
3HY				..	546	2.33	20.0	

LOWER MOTTLED SANDSTONE AREA 2

Only 2 samples were obtained of this subdivision in the Nottinghamshire area and therefore no firm conclusions can be drawn as to the probable range of aquifer property values. The geological evidence points to a silty and rather shaly nature with intergranular permeability probably significantly lower than in the overlying Bunter Pebble Beds, especially near the base, where the diachronous junction with Middle Permian Marl occurs. *

* This has recently been confirmed by tests on samples from the base of the formation at the IGS Research Site, at Styrrup, Notts.

AREA 2 Formation : LOWER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
112 V	f md fr r sd	Rushpool, Mansfield	SK 55526325	o/c	1563	–	–	
H1-215				"	1696	2.12	32.1	
H2-215				"	2128	2.12	30.8	
H 305				"	1450	2.13	31.5	
140 H1-8	f fr r sd	Hallams Grave, Mansfield.	SK 54956258	o/c	3315	2.10	33.2	
H98				"	3516	2.10	32.7	
H2-8				"	314	2.08	33.7	

BUNTER PEBBLE BEDS AREA 2

In the Nottinghamshire area, the Pebble Beds are characterised by only very slight lithological variation, principally associated with changes in grain size and bedding structure. Samples were examined from surface outcrops but the bulk of the material came from the Artificial Recharge Site of Water Resources Board at Edwinstowe, near Ollerton where a series of fully cored holes was drilled in 1969 (See Fig.20).

The outcrop samples were on the whole very unsatisfactory owing to the deeply weathered state of the formation which drilling has shown to exist down to depths of between 50 and 100 m. In this zone, the Pebble Beds consist to a great extent of scarcely consolidated coarse sand with thin pebbly lenticles. Recently, cores of very soft loose sand brought to the surface in drilling operations at Clipstone Forest apparently showed evidence of fracturing which may have been caused by permafrost conditions during the Pleistocene. The poor state of consolidation of the formation cannot, however, be wholly explained by glacial interference, since, in order for this to take place, high porosity and permeability must have pre-existed in the formation at the onset of glaciation.

Core material was extremely difficult to obtain down to about 20 m, and what little could be recovered was very friable and difficult to handle. There is, however, no doubt that the intergranular permeability of the shallow zones of the aquifer exceeds the maximum value which can be obtained on coherent cores. At a guess, it is probably about 40000-50000 md. (40-50 darcys), with a porosity of 35-40%.

Both at outcrop and at Edwinstowe, the lithological variation can be described in terms of several rock types, which have distinctive properties:

i) probably the commonest rock type is medium-coarse clean well graded sand, usually angular (cf the Lower Keuper Sandstone) and characterised by a permeability of 5000-10000 md, exceptionally reaching 15000 or 20000 md. Porosity is very high and short ranged between 30 and 32%. Shallow core samples and outcrop material gave slightly higher porosity values (33-36%). Density is low commonly ranging from 2.10 to 2.15 gms. cc^{-1}, decreasing to 2.05 to 2.10 gms cc^{-1} near the surface. Examples of this group: 121, 194, 195 (outcrop), 505-6 and 505- shallow), and 505-43, 505-53, 508-23, 508-37, 509-5, 509-14 and 509-55.

ii) Interbedded with group (i) and in a cross stratified relationship to it, are fine to medium less well graded laminated sands. Three types of these may be distinguished: a) friable fine-medium laminated with very similar properties to group (i), but perhaps a marginally lower porosity (examples are 508-56, 509-34, 509-44 and 509-49);

b) anisotropic laminated types, the anisotropy being commonly caused by thin (2 mm) bands of clean medium sand resulting in a high permeability in some horizontal plugs (eg samples 505-8, 505-22, 505-48, 505-75 and 509-27). In this category, permeability is liable to range very widely from as little as 1000 md or less, up to 10000 md. Porosity is also variable from 26 up to 34% and density shows an equivalent variation. Finally, the third type (c) comprises fine sands in which aquifer properties are severely reduced by compaction and by cementation. Permeability has values lying between 500 and 2000 md with porosity between 25 and 30% and density of approximately 2.20 - 2.25 gms. cc^{-1} (eg samples 175, 505-66, 508-24, 508-40 and 509-29).

iii) Coarse to very coarse pebbly sands with patchy yellow cementation giving a slightly indurated texture. These have properties similar to group (i) (eg 505-57, 508-20 and 508-27).

iv) Rare well cemented sands, with permeability of a few hundred millidarcys and porosity reduced to 20-21 per cent (eg 175, 176, 508-40 HY2 and 508-40 HX2, 509-25VI).

v) Finally, thin red siltstones and mudstones impersistent, lenticular and of local significance; in these beds intergranular permeability is typically less than 20 md, the precise value being closely dependent on particle size. Porosity is meaningless in view of the low permeability.

In contrast to other sections in the Pebble Beds, the Nottinghamshire sequence shows a distant lack of beds of massed shingle compared with, for example, Cannock Chase, and also a lack of induration and cementation, compared with eg Merseyside or the Severn Valley. Beyond doubt, it is the most permeable section of the British Permo-Trias together with its northerly extension into South Yorkshire (Area 6), although there the lower part of the succession shows signs of becoming finer grained, more consolidated with the total thickness of high permeability sand being rather reduced.

AREA 2 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
102 V	m-vc fr br-r sd	Bramcote, Notts	SK 50173877	o/c	–	2.26	33.8	
H1-14				..	4418	2.12	32.5	
H2-14				..	–	2.13	32.2	
108	m-c fr br sd	Foxcovert Plantation.	SK 58765053	o/c	–	2.10	33.0	
119 V1	f-m fr pk sd	Styrrup, Notts	SK 60479020	o/c	3663	2.08	34.8	
V2				..	3909	2.08	34.6	
H1-59				..	996	2.07	34.7	
H2-59				..	801	2.08	34.4	
H1-149				..	1168	2.08	34.6	
H2-149				..	3653	2.08	34.2	
120 V1	f-m fr pk sd			..	3327	2.09	34.1	
V2				..	3356	2.08	34.3	
H1-59				..	3048	2.09	33.8	
H2-59				..	3543	2.08	33.6	

AREA 2 Formation: BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
120 H2-149	f-m fr pk sd	Styrrup, Notts	SK60479020	o/c	3436	2.09	33.7	
121 V1	m cn wg gy-gn fr sd	Carr Hill, Everton, Notts	SK68859174	o/c	5135	2.06	35.5	
V2				..	5900	–	–	
H1-198				..	7556	2.05	35.9	
H2-198				..	7521	2.05	36.0	
H 288				..	11071	2.03	36.0	
122 H198	m cn wg gy-gn fr sd			..	11338	2.03	37.2	
H 288				..	10255	2.05	35.8	
123 V	m fr wg pk sd pb	Nornay, Blyth, Notts	SK62458792	o/c	5941	2.06	35.1	
H 119				..	–	2.04	35.3	
124 V1	m-vc fr pk sd cn			..	–	2.06	34.2	
V2				..	–	2.03	35.9	
H 99				..	9996	–	–	
144 V	m-c fr cn pk sd	Corunna Hill Plantation	SK58987214	o/c	–	2.11	31.8	

AREA 2

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
144 H 247	m-c fr cn pk sd	Corunna Hill Plantation, Notts	SK 58987214	o/c	4803	2.11	31.4	
145 H 245	m-c cn fr pk sd			..	5123	2.12	31.2	
146 V1	cn m fr r sd	Thoresby Park, Notts	SK 63567026	o/c	8528	–	–	
V2				..	7224	2.08	33.7	
H1-77				..	17178	2.07	33.7	
H2-77				..	5737	2.05	32.9	
H3-77				..	3772	–	–	
H1-167				..	16256	–	32.0	
H2-167				..	7459	2.06	34.0	
147 H 167	cn m fr pk sd			..	5976	–	28.7	
H 257				..	14075	2.05	33.9	
153 V	m-c cn lam r sd	Bilsthorpe, Notts	SK 64226209	o/c	8371	2.06	33.7	
H1-120				..	12181	2.07	33.1	
H2-120				..	12167	–	34.5	

AREA 2 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
153 H 210	m-c cn lam r sd	Bilsthorpe, Notts	SK 64226209	o/c	14999	2.06	34.1	
175 HX1	f con pk sd	Sutton B.H., Notts	SK 68148378	176.9 m	721	2.17	29.3	
HX2				"	646	2.17	29.4	
HX3				"	740	2.18	29.0	
HY				"	964	2.17	29.8	
176 V	f wc gn-gy sd			174.5 m	–	2.34	20.5	
HX1				"	354	2.32	21.7	
HX2				"	474	2.29	23.0	
HY				"	455	2.26	24.4	
177 V	c slt-vf sd lt br lam wc			164.1 m	–	2.28	23.9	
H1				"	17	2.26	24.5	
H2				"	19	2.27	24.4	
194 V	m cn fr r sd	Spital Hill, Harworth, Yorks	SK 61139307	o/c	–	2.08	32.7	
H1-199				"	8911	2.07	33.0	

AREA 2 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
195 V	m cn lam br-r sd fr	Spital Hill, Harworth, Yorks	SK 61139307	o/c	5875	2.10	32.9	
H199				..	21036	2.07	33.7	
H1-289				..	17498	2.07	34.3	
H2-289				..	–	2.08	33.4	
196 H	m-c cn lam r sd	Elkesley No.5 B.H.. Notts	SK 66397589	between 42.7 & 103.4 m	13702	2.09	32.5	
197 V1	f-m lam con pk sd			..	584	2.16	29.8	
V2				..	539	2.17	29.0	
HX1				..	1118	2.17	29.0	
HX2				..	1676	2.17	28.9	
HY1				..	1095	2.18	28.3	
HY2				..	1154	2.17	28.8	
505-3V	m-c fr pk sd	Water Resources Board No.5 B.H. Edwinstowe, Notts.	SK 63436814	16.0 m	–	–	33.0	
3HX				..	10501	2.07	34.2	
505-6V1	m-c cn fr pk sd			18.6 m	7277	2.04	35.6	
6V2				..	12055	2.05	35.0	

AREA 2

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
505 - 6HX	m-c cn fr pk sd	Water Resources Board, No 5 B.H. Edwinstowe, Notts	SK63436814	18.6 m	11806	2.06	35.1	
6HY				..	11702	2.03	33.0	
505 - 8V1	f-m lam pk sd			22.6 m	1082	2.14	30.3	
8V2				..	650	2.17	29.4	
8HX				..	2416	2.16	29.6	
8HY1				..	2332	2.16	30.1	
8HY2				..	8982	2.16	29.8	
505 - 12V	m-c cn fr pk sd			24.6 m	-	-	-	
12HX				..	9884	2.10	33.0	
12HY				..	7802	2.09	33.3	
505 - 15TT1	m wg fr y-br sd			26.5 m	7223	2.11	32.5	
15TT2				..	6336	2.12	32.2	
15CD				..	7845	2.10	32.8	
15CS				..	-	2.08	33.5	
505 - 16TT1	cn m-c			27.0 m	7768 *	2.12	[illegible]	

AREA 2 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
505-16TT2	cn m-c wg Y-br sd fr	Water Resources Board	SK 63436814	27.0 m	5956	2.10	33.2	
505-20V	f-m con r sd	No.5 B.H. Edwinstowe, Notts		29.4 m	2422	2.20	27.1	
20HX				..	552	2.22	26.2	
20HY				..	1013	2.21	26.6	
505-22V	f-c lam cn fr r sd			29.8 m	2301	2.16	28.1	
22HX				..	2333	2.19	27.8	
22HY				..	7962	2.08	34.0	
505-26V	f-m con pk sd			32.3 m	2883	2.19	27.9	
26HX				..	2999	2.22	26.5	
26HY				..	4211	2.15	30.2	
505-29TT1	m-c cn pk sd fr			36.9 m	8605	2.13	31.0	
29TT2				..	7729	2.13	31.4	
29CD				..	4760	2.13	31.3	
29CS				..	8165	2.12	31.7	
505-32[illegible]	m-c cn wg			39.[illegible]	5[illegible]	2.1[illegible]	31.[illegible]	

AREA 2

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
505-32V2	m-c cn wg pk fr sd	Water Resources Board, No.5 B.H.. Edwinstowe Notts.	SK63436814	39.6m	12584	2.08	34.2	
32HX				..	–	2.10	32.2	
32HY				..	6471	2.09	33.2	
505-37V	con f pk sd			41.8m	469	2.20	27.1	
37HX				..	1510	2.08	34.2	
37H				..	4976 *	2.14 *	31.0 *	
37CS				..	1776	2.16	29.3	
37CD				..	1575	2.18	28.0	
505-40TT	vf-c lam fr pk sd			45.0m	282	2.17	–	
40CD1	vf-m lam cs fr pk sd			..	3749	2.19	27.9	
40CD2				..	3794	2.21	26.9	
40CS				..	1586	2.22	27.1	
505-41HX1	m-c cn y-br fr sd			45.3m	7240	2.19	28.7	
41HX2				..	9084	2.17	29.4	
[illegible]					[illegible]	[illegible]	[illegible]	

AREA 2 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
505-41HY2	m-c cn y-br fr sd	Water Resources Board	SK63436814	45.3m	5975	2.24	25.9	
505-43TT1	cn m fr y-br sd cs	No.5 B.H., Edwinstowe, Notts		46.8m	10157	2.13	31.6	
43TT2				"	9919	2.13	31.5	
43H				"	9829 *	2.13 *	31.8 *	
43CS				"	8738	2.14	30.7	
43CD				"	9582	2.14	31.0	
505-44TT	cn m wg cs fr r sd			48.2m	7296	2.12	31.3	
44CD				"	10083	2.13	31.4	
44CS1				"	6028	2.15	30.3	
44CS2				"	6963	2.13	31.3	
505-47HX	f-c lam cn fr r sd			50.7m	7135	2.20	27.4	
47HY				"	7871	2.19	28.1	
505-48V1	f-m lam fr pk sd			51.8m	2117	2.17	29.0	
48V2				"	2074	2.16	28.8	
[illegible]					[illegible]	[illegible]	[illegible]	

AREA 2

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
505-48HX2	f-m lam fr pk sd	Water Resources Board, No. 5 B.H., Edwinstowe Notts	SK63436814	51.8m	5393	2.18	28.6	
48HY1				..	4043	2.17	28.8	
48HY2				..	6311	2.16	29.1	
505-49H	fr f-vc pk sd			53.8m	5704*	2.18*	28.1*	
49HX				..	3491	2.11	27.1	
49HY				..	7314	2.17	29.1	
505-51HX	pb cn m-c fr r sd			55.3m	6687	2.25	24.9	
51HY				..	—	2.21	26.6	
505-52V	wg fr m-c pk sd			56.4m	—	—	—	
52HX				..	7051	2.13	30.4	
52HY				..	6452	2.13	31.2	
505-53V	cn m-vc fr pk sd			57.7m	7590	2.12	30.5	
53HX				..	4319	2.13	30.1	
53HY				..	10093	2.13	31.1	

AREA 2

Formation: BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
505-54V	con f-m lam sd pk	Water Resources Board No.5 B.H. Edwinstowe, Notts	SK63436814	59.5 m	2111	2.19	28.2	
54HX1				..	1680 *	2.18 *	28.9 *	
54HX2				..	3204	2.19	28.0	
54HX3				..	3208	2.20	27.9	
54HY				..	2178	2.20	27.4	
505-56V	lam m-vc pb pk sd			60.0 m	610	2.23	25.1	
56HX				..	8474	2.24	25.7	
56HY				..	9225	2.24	25.0	
505-57V	m-vc pb pk sd patchy cementation			62.0 m	—	2.23	25.4	
57HX				..	11059	2.22	25.9	
57HY				..	10244	2.24	24.5	
505-60V	fr f-m r sd			63.3 m	5994	2.12	30.1	
60HX1				..	6215	2.12	30.9	
60HX2				..	1224 *	2.16	29.6	
[illegible]					[illegible]	[illegible]	[illegible]	

AREA 2 Formation · BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
505-61V	m-c cn fr pk sd	Water Resources Board, No.5 B.H. Edwinstowe, Notts	SK63436814	65.7m	8318	2.11	31.9	
61HX				"	6727	2.16	29.0	
61HY				"	5408	2.16	28.6	
505-62V	f-m con pk sd			67.2m	1722	2.19	27.8	
62HX				"	2004	2.19	28.1	
62HY				"	2207	2.19	27.7	
505-63V	f-m lam wc r sd			67.5m	1116	2.23	26.0	
63HX				"	835	2.23	26.2	
63HY				"	1158	2.23	25.9	
505-66V	f mic con pk sd			71.1m	520	2.23	26.4	
66HX1				"	447 *	2.23 *	25.9 *	
66HX2				"	345 *	–	–	
66HX3				"	626	2.23	26.1	
66HY				"	577	2.23	26.6	

AREA 2 Formation: BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
505-67V2	f-m lam con r sd	Water Resources Board	SK63436814	71.6m	247	2.24	25.7	
67 HX		No.5 B.H. Edwinstowe		..	550	2.25	24.6	
67 HY		Notts		..	513	2.24	25.1	
505-69TT1	f cs pk sd with small pebbles mic lam			72.2m	169	2.22	26.5	
69TT2				..	380	2.24	25.3	
69 CD				..	526	2.24	25.5	
69 CS				..	1595	2.23	26.0	
505-74V1	dk r mic slt			74.6m	2.4	2.48 *	12.7 *	
74 V2				..	107 *	2.31 *	22.2 *	
74 V3	wc f mic pk sd			..	11	2.31	21.9	
74 HX1	dk r mic slt			..	41	2.48 *	14.4 *	
74HX2	wc f mic pk sd			..	34	2.31	21.7	
74 HY1	dk r mic slt			..	7	2.48 *	12.4 *	
74HY2	wc f mic pk sd			..	45	2.30	21.9	
505-75V [illegible]	f-m lam [illegible]			74.8 [illegible]	[illegible]	[illegible]	[illegible]	

AREA 2

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
505-75HX	f-m lam con pk sd	Water Resources Board	SK63436814	74.8 m	536	2.21	26.9	
75HY		No. 5 B.H. Edwinstowe,		..	2748	2.21	27.0	
505-76V	c cn fr lt br sd	Notts.		75.7 m	3383	2.10	31.1	
76HX1				..	608 *	2.13 *	31.3 *	
76HX2				..	4673	2.12	31.3	
76HY				..	4257	2.12	31.2	
505-77V	cs lam f-m sd			76.6 m	4313	2.15	29.8	
77TT				..	3355	2.15	29.9	
77HX				..	2208	2.14	30.8	
77HY				..	2424	2.19	28.4	
77CS				..	3860	2.17	29.1	
77CD				..	6999	2.15	29.6	
508-1V	f-m lam mic r sd	Water Resources Board	SK63456808	8.4 m	90	2.20	26.9	
508-3TT	m con cs br-r pb sd	No. 8 B.H., Edwinstowe		9.4 m	1549 *	2.19 *	28.4 *	
[illegible]	wg cn fr mc	Notts		[illegible]	[illegible]	[illegible]	[illegible]	

AREA 2

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
508 - 5V2	wg cn fr lam r sd m-c	Water Resources Board, No.8 B.H, Edwinstowe, Notts	SK63456808	10.3m	2879	2.15	29.9	
5HX				..	12513	2.13	31.0	
5HY				..	8382	2.14	30.8	
508 - 7V1	wg fr br-y cn m-c sd			10.8m	7694	2.18	28.7	
7V2				..	11·232	2.17	29.4	
7HX				..	6195	–	–	
7HY				..	7120	2.16	30.0	
508 - 16V1	cn m wg fr br-y sd slight lamination			17.3m	4055 *	2.19	28.6	
16V2				..	–	2.12	30.9	
16V3				..	7103	2.16	29.7	
16H				..	6738	2.15	30.5	
508 - 17V	f-m lam con br-r sd			17.7m	1171 *	2.16	29.6	
508 - 18V	fr m-c pb pk sd			18.9m	16400 *	2.12	29.6.	
508 - 19V	wg cn m fr pk sd			19.4m	7168	–	–	
	m-vc pb							

AREA 2 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
508- 20HX	m-vc pb cn fr sd patchy white & yellow cement	Water Resources Board, No.8 B.H. Edwinstowe, Notts	SK63456808	20.0 m	4812	2.18	28.6	
20HY				..	11460	2.18	28.6	
508- 21V	fr m-c cn y-br sd			20.5 m	6912 *	2.15	30.8	
21HX				..	10468	2.13	31.0	
21HY				..	11455	2.12	31.5	
508- 23V1	fr m-c cn pk sd			21.2 m	7616 *	2.13	31.5	
23V2				..	6109	2.09	31.2	
23HX				..	8873	2.11	29.6	
23HY1				..	8043	2.12	31.3	
23HY2				..	7675	2.12	31.1	
508- 24V1	con f-m lam mic r sd			21.9 m	397	2.20	27.3	
24V2				..	362	2.20	26.8	
24HX1				..	2104	2.21	26.7	
24HX2				..	541	2.22	26.0	

AREA 2

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
508-24HY2	con f-m lam mic r sd	Water Resources Board	SK63456808	21.9 m	918	2.21	26.5	
508-27V	m-c cn sd patchy cement	No.8 B.H. Edwinstowe,		22.8 m	1368	2.33	21.3	
508-29A	m fr pb pk sd mf	Notts		24.0 m	–	1.87	24.8	
508-31V1	f-m con mic r sd ; a few pebbles			25.1 m	771	2.14	30.4	
31V2				..	620	2.15	30.0	
31HX1				..	927	2.18	28.5	
31HX2				..	913	2.17	29.1	
31HY1				..	1089	2.18	28.5	
31HY2				..	1136	2.17	29.1	
508-33HX	m-c lam fr pk sd cn			25.6 m	8016	2.12	31.5	
33HY				..	6295	2.13	31.1	
508-35V1	f-m lam fr mic pk sd			26.5 m	3405	2.17	29.1	
35V2				..	1944	2.18	28.7	
35V3				..	1498	2.15	30.2	
[illegible]					[illegible]	[illegible]	[illegible]	

AREA 2

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc⁻¹	Porosity per cent	Centrifuge Specific Yield per cent
508-35HX	f-m lam fr mic pk sd	Water Resources Board, No. 8 B.H. Edwinstowe Notts	SK63456808	26.5m	3943	2.14	30.6	
35HY				..	4673	2.14	30.7	
508-37V1	m-c cn fr pk sd			28.0m	7575	2.10	32.5	
37V2				..	6116	2.10	32.6	
37V3				..	6912	2.09	31.8	
37HX				..	9054	2.11	31.9	
37HY				..	9009	2.10	32.8	
508-38H	m pb fr br-y sd			28.4m	3443	2.19	27.8	
508-40V1	f con mic r sd			29.4m	191	2.23	26.0	
40V2				..	155	2.23	25.9	
40V3				..	222	2.20	27.2	
40HX1	c pb sd with patchy cementation			..	4143	2.23	26.2	
40HX2				..	–	2.33	21.4	
40HY1	f con mic r sd			..	318	2.23	25.7	
[illegible]	wc f mic				[illegible]	[illegible]	[illegible]	

AREA 2 Formation: BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
508-41TT1	cn wg cs fr pk sd	Water Resources Board No. 8 B.H. Edwinstowe Notts	SK63456808	29.5m	2581	2.12	31.9	
41TT2				"	5020	2.12	32.1	
41TT3				"	2762	2.11	32.1	
41CD1				"	5194	2.12	31.5	
41CD2				"	4156	2.13	31.2	
41CS1				"	—	2.09	32.4	
41CS2				"	3590	2.13	31.0	
508-42V	con br-y m sd			30.9m	3240 *	2.19	28.7	
508-44V1	con f-m lam r sd mic			31.5m	395	2.18	28.0	
44V2				"	392	2.18	28.2	
44HX1				"	794	2.18	28.0	
44HX2				"	800	2.19	27.4	
44HY1				"	765	2.19	27.4	
44HY2				"	1119	2.19	27.7	
[illegible]	con m lam			[illegible]	[illegible]	[illegible]	[illegible]	

AREA 2

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
508-48V	m-c lam con pk sd	Water Resources Board,	SK63456808	34.7m	184 *	2.19	28.0	
508-50V1	cn m-c fr pk sd	No.8 B.H. Edwinstowe		36.5m	4543	2.09	32.0	
50V2		Notts		"	3921	2.08	32.2	
50HX				"	4154	2.09	31.6	
50HY				"	5024	2.09	32.1	
508-51V	cn lam cs m fr pk sd			37.4m	3305	2.10	31.4	
51TT				"	759	2.12	30.5	
51HX1				"	5616	2.10	31.8	
51HX2				"	4864	2.10	31.4	
51CS1				"	5702	2.10	31.5	
51CS2				"	5930	2.10	31.3	
51CD1				"	7245	2.10	31.3	
51CD2				"	4842	2.11	30.9	
508-53V	m fr pk sd			38.9m	13 *	2.13	27.8	
[illegible]	m-c cn			[illegible]	[illegible]	[illegible]	[illegible]	

AREA 2

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield . per cent
508-55HX	m-c cn fr pk sd	Water Resources Board	SK63456808	39.7m	5092	2.10	31.1	
55HY		No.8 B.H. Edwinstowe,		"	2192	2.11	31.6	
508-56V1	f-m lam fr pk sd	Notts.		41.2m	1744	2.13	29.5	
56V2				"	1671	2.14	29.6	
56HX1				"	2609	2.13	30.1	
56HX2				"	2641	2.13	29.9	
56HY1				"	2087	2.13	28.3	
56HY2				"	1441	2.13	28.4	
509-2V1	m lam r slt	Water Resources Board	SK63476818	9.6m	–	2.19	28.0	
2V2		No.9 B.H. Edwinstowe,		"	<1	–	–	
509-3V1	m-c lam sd with patchy yellow cementation	Notts		11.4m	270 *	2.13	28.7	
3V2				"	1750	2.25	25.3	
3HX				"	5700	2.27	24.5	
509-4V1	fr lam f-m pk sd			11.7m	2318	2.18	28.9	
4HX					[illegible]			

AREA 2

Formation : BUNTÉR PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
509-4HY	fr lam f-m pk sd	Water Resources Board,	SK63476818	11.7m	–	2.21	14.3	
509-5V	cn m wg fr pk sd	No 9 B.H. Edwinstowe,		12.3m	9439	2.13	31.4	
5H		Notts		..	10092	2.12	31.7	
5CD				..	10312	2.13	31.5	
5CS				..	–	2.11	31.4	
509-8V	c pb con br-y sd			14.1m	5822 *	–	–	
509-11V	m-c fr pb lam pk sd			14.9m	2253 *	2.17	29.2	
509-12V1	dk r lam mdst			15.2m	17	–	–	
12V2				..	5.9	–	–	
12V3				..	12	–	–	
12V4	f-c lam cs fr pk sd			..	17148	2.17	28.6	
12HX				..	14057	2.17	28.6	
509-13V	m fr wg pk sd			15.6m	7077	2.13	31.3	
13TT				..	5228	2.13	31.2	
13CS1				..	7046	2.12	31.6	

AREA 2 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
509-13CS2	m fr wg pk sd	Water Resources Board No.9 B.H. Edwinstowe, Notts	SK63476818	15.6m	6924	2.13	31.3	
13CD1				..	8713	2.12	31.6	
13CD2				..	9540	2.14	30.7	
509-14V	m-c cn pb cs pk sd fr			17.7m	6539	2.13	31.3	
14TT				..	>23000	2.14	30.6	
14CS				..	10836	2.14	30.5	
14CD				..	21013	2.13	31.0	
14H				..	13737	2.15	30.3	
509-16V	m-c cn fr pk sd			18.8m	> 23000	2.15	29.0	
16HX				..	20480	2.14	31.0	
16HY				..	17808	2.15	28.7	
509-17V	cn pb br-y sd			19.2m	2859 *	2.25 *	24.8 *	
509-21V1	cn m lam fr pk sd			23.2m	3542 *			
21V2				..	7202	2.15	30.1	
[illegible]				..	[illegible]	[illegible]	[illegible]	

AREA 2

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
509-21HY	cn m lam fr pk sd	Water Resources Board,	SK63476818	23.2m	5132	2.12	31.5	
509-22V	cn m lam fr pk pb sd wg	No.9 B.H. Edwinstowe,		23.9m	15338	2.13	30.6	
22TT		Notts.		..	18951	2.12	31.5	
22CS				..	12868	2.13	30.9	
22CD				..	6303	2.12	31.9	
509-24V1	cn f-m fr lam pk sd			25.4m	6759	2.14	30.9	
24V2				..	8319	2.14	30.4	
24HX				..	7743	2.15	30.1	
24HY				..	12211	2.13	31.4	
509-25V1	m wc wg pk sd			28.8m	495	2.31	21.8	
25H	cn m lam pk fr sd			..	5600	2.17	29.0	
25HX				..	> 23000	–	–	
25HY				..	13403	2.15	30.2	
509-27TT1	f-m con lam r mic sd			30.4m	2435	2.18	28.5	
27H				..	10692	2.19	28.8	

AREA 2

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
509-27CD	f-m con cs pk sd	Water Resources Board,	SK 63476818	30.4m	16260	2.17	29.1	
27CS	f-m con cs sd	No.9 B.H. Edwinstowe,		"	5421	2.20	27.6	
509-29V	f-m lam con r sd	Notts		31.4m	510	2.21	27.5	
29HX1				"	638	2.20	27.6	
29HX2				"	770	2.21	27.0	
29HY1				"	832	2.20	27.4	
29HY2				"	1820	2.20	27.8	
29CD				"	898	2.20	27.4	
509-31V1	fr m-c pb pk sd lam			32.1m	1440 *	–	–	
31V2				"	2406	2.15	30.1	
31V3				"	10514	2.15	29.6	
31HX				"	10831	2.14	30.4	
31HY				"	18107	2.14	30.7	
509-34V1	f-m lam pk sd			33.3m	5655	2.18	28.8	

AREA 2

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
509 - 34HX1	f-m lam pk sd	Water Resources Board, No.9 B.H. Edwinstowe, Notts	SK 63476818	33.3m	5130	2.22	26.7	
34HX2				"	12636	2.16	29.6	
34HY1				"	5114	2.17	29.2	
34HY2				"	9442	2.19	28.5	
509-35V	m-c pb fr pk sd			34.5m	1475 *	2.18 *	28.9 *	
509-36V1	m-c fr lam pk sd			35.2m	2970	2.10	32.7 *	
36V2				"	2758	2.11	31.7 *	
36HX1				"	7268	2.09	33.1 *	
36HX2				"	5108	2.09	33.2 *	
36HY				"	4703	2.10	32.7 *	
509-38V	f-m lam cn pk sd, fr			36.2m	5232	2.17	28.7	
38HX				"	6000	2.16	29.5	
38HY				"	3551	2.18	28.4	
509-40V	f wc r sd			37.5m	97	2.22	27.2	
	f-m fr r							

AREA 2 Formation: BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
509-40HX2	f con r sd	Water Resources Board	SK63476818	37.5m	1171	2.24	26.3	
40HY	f-m r lam sd	B.H. No. 9. Edwinstowe		"	3816	2.17	29.5	
509-42V	con f-m lam pk sd	Notts		39.1m	2989 *	—	—	
509-44V1	f-m lam fr pk sd			40.2m	13059	2.15	29.9	
44V2				"	3286	2.15	30.2	
44HX				"	7765	2.13	31.6	
44HY				"	13106	2.13	31.4	
509-45H	con f-m lam pk sd			40.7m	846 *	2.17 *	29.7 *	
509-46V	f con mic lam r sd			41.5m	2044	2.22	27.2	
46HX				"	535	2.25	25.4	
46HY				"	639	2.24	25.9	
509-49V1	f-m lam r sd			42.4m	3095	2.17	29.0	
49V2				"	7423	2.16	29.4	
49V3				"	101 *	—	—	
[illegible]	cn m-c fr				[illegible]	[illegible]	[illegible]	

AREA 2 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
509-49 HY1	cn m-c fr r sd	Water Resources Board	SK63476818	42.4 m	16847	2.15	30.2	
509-51V	m-c cn fr pk sd	No.9 B.H. Edwinstowe,		43.4 m	3532	2.11	32.2 *	
51HX		Notts		"	3874	2.13	30.8 *	
51HY				"	3057	2.14	30.2 *	
509-52V	f-m lam cs pk sd			44.3 m	11629	2.17	29.2	
52TT	patches of cementation			"	8500	2.16	29.8	
52HX				"	10195	2.17	29.0	
52HY				"	8043	2.15	30.4	
52CS				"	17084	2.16	29.7 *	
52CD				"	11874	2.15	30.4	
509-53V	lam pb f-m fr pk sd			44.9 m	2157	2.18	28.9	
53HX				"	4475	2.18	28.3	
53HY				"	8289	2.17	29.0	
509-55V1	cn m wg r sd with			45.9 m	7971	2.12	32.0	

AREA 2 Formation BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
509-55HX1	cn m wg r sd fr with patchy cment	Water Resources Board, No.9. B.H. Edwinstowe, Notts	SK63476818	45.9 m	1181 *	2.27 *	24.1 *	
55HX2				"	5569	2.14	31.1	
55HY				"	10955	2.13	31.3	
509-56V1	m lam sd with patchy cment fr			47.3 m	11138	2.18	28.6	
56V2				"	8238	2.15	30.1	
56HX1				"	1188 *	2.19 *	27.9 *	
56HX2				"	18384	2.18	28.7	
56HX3				"	10458	2.18	28.4	
56HY1				"	6563	2.18	28.3	
56HY2				"	6269	2.18	28.8	

KEUPER WATERSTONES AREAS 2, 4 and 5

Owing to scarcity of exposure and a total lack of subsurface material, the evaluation of the properties of the Keuper Waterstones is restricted to the results of tests on only 8 samples from 6 localities. These were of brown siltstone and sandstone in which permeability was found to range from less than 1 md up to 800 md; porosity in the Nottinghamshire material was high at about 30 per cent, but this may be a result of weathering. Material from Cheshire and Shropshire showed a much lower porosity of between 4 and 24 per cent.

Bearing in mind the incidence of interbedded mudstone in this formation, it is considered that no firm conclusions can be drawn on such scanty data, but that it is likely that the sandy beds become progressively less permeable as the sequence is ascended and that, taken as a whole, the formation is hydrogeologically insignificant.

AREA 2 Formation: KEUPER WATERSTONES

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
106 V1	wg c slt-vf sd con mic lam	Edingley Hill, Edingley, Notts	SK66795561	o/c	264	2.15	30.2	
V2				"	176	2.16	29.4	
H1-81				"	444	2.15	29.9	
H2-81				"	548	2.15	30.4	
H171				"	584	2.14	30.7	
107 V1	wg c slt-vf sd con mic lam lt br			o/c	383	—	—	
V2				"	306	2.15	29.9	
H1-81				"	737	2.15	30.3	
H2-81				"	634	2.15	29.9	
H1-17				"	761	2.16	29.3	
H2-17				"	811	2.16	29.7	
151 V	wg c slt-vf sd con mic lam lt br	Kirton, Notts	SK69136941	o/c	102	2.19	28.4	
H71				"	152	2.18	28.9	
H161				"	160	2.19	28.3	

AREA 4

Formation : KEUPER WATERSTONES

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
53H85	wc f-m gn-gy sd	Marchamley Hill, Hodnet, Salop.	SJ59462900	o/c	696	2.38	15.7	
53H355	"			"	40	2.44	12.4	

AREA 5

Formation : KEUPER WATERSTONES

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
340 V	vf wc p sd	Quarry at Harthill, Cheshire	SJ49895537	o/c	<1	2.55	6.2	
H186				"	<1	2.58	4.4	
353 V	vf-f wc cav br sd	Newtown, Frodsham, Cheshire	SJ52837832	o/c	27	2.30	21.3	
H110				"	299	2.26	23.5	
H1-200				"	93	2.31	20.6	
H2-200				"	163	2.24	24.5	
354 V	vf-f wc wispy br sd	Railway cutting, Runcorn, Cheshire	SJ51018238	o/c	14	2.29	20.3	
H122				"	43	2.30	20.1	
H1-202				"	13	2.29	19.9	
H2-202				"	21	2.30	19.8	

Within the so-called type area of the Bunter, the Lower Mottled Sandstone, in spite of its striking variegated appearance in natural exposures (Plates 3A, 3B) has been found to have very uniform physical properties. Both surface and underground samples have been examined and no material difference in values was observed suggesting that the cementation which affects other parts of the Permo-Triassic sequence did not affect the formation to any great extent in this area.

The dominant lithology comprises rather poorly graded soft and friable red sandstones, ranging from very fine to medium. Coarse units tend to be thin and rare. Permeability ranges from 1000 to 10000 md, and is controlled mainly by the grain size distribution. Owing to the generally laminated structure of the beds, anisotropy is relatively common, eg samples 33, 44, 465-31, 640 and 644. Density is low ranging with rare exceptions from 2.08 to 2.18 gms cc^{-1}. Porosity is uniformly high from 28-33%.

It is remarkable that even at depths of between 360 and 420 m in the Bellington No. 4 BH (Fig.21), this sandstone was found to have a permeability of up to 6000 md and porosity of 28-29%, with very little sign of induration or cementation. Unfortunately, the very rapid thickness variation of this unit of the Bunter (mentioned in Chap.I and VI) greatly complicates the evaluation of its true significance as an aquifer, and its hydrogeological relationship to the more consolidated overlying Bunter Pebble Beds.

AREA 3

Formation : LOWER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
33 V1	f wg fr r sd	Wollaston, Stourbridge Worcs	SO 88228482	o/c	3416	2.10	32.6	
V2				..	3347	2.10	31.7	
H1-258				..	4054	2.10	32.7	
H2-258				..	4534	2.10	32.2	
H1-348				..	3931	2.09	32.5	
H2-348				..	4223	2.09	33.2	
35V	m wg ms fr r sd	Kinver Edge, Worcs	SO 83608352	o/c	–	2.08	32.7	
36 V1	f-m fr lt br sd	Catchems End, Bewdley, Worcs	SO 80337596	o/c	2086	2.14	33.4	
V2				..	3230	2.12	30.5	
H1-17				..	2423	2.11	31.8	
H2-17				..	5930	2.13	30.0	
H1-107	cemented veinlet			..	415	2.15	29.9	
H2-107				..	9584	2.15	29.5	
39 V	f-m fr r sd	Quatford, Bridgnorth	SO 73849028	o/c	5250	2.09	33.5	

AREA 3

Formation : LOWER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
39 H 300	f-m fr r sd	Quatford, Bridgnorth	SO73849028	o/c	6412	2.09	33.5	
43 V	m-c cn wg fr r sd	Sheriff Hales, Salop	SJ75981197	o/c	2640	–	–	
H3				..	2846	2.17	28.8	
H93				..	2898	–	–	
44 V	m-c cn wg fr r sd			o/c	7213	2.16	29.4	
H3				..	8917	2.16	29.5	
H93				..	13047	2.15	30.0	
232 HX1	m-c cn y fr sd showing dendritic manganese encrustation	Kinver Pumping Station Worcs	SO84848328	42.7m	9890	2.16	29.6	
HX2				..	14045	2.17	29.0	
HY1				..	9876	2.16	29.1	
HY2				..	10203	2.16	29.2	
HY3				..	8978	2.16	29.2	
HY4				..	10204	2.16	29.0	
HY5				..	10547	2.18	28.1	

AREA 3 Formation : LOWER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
465-28V	f-m lam fr r sd	Bellington No.4 B.H., Kidderminster.	SO87767689	366.0m	1701	2.28	24.5	
28HX				..	5183	2.18	28.	
28HY1				..	14575 [slight crack]	2.16	29.0	
28HY2				..	5644	2.15	29.9	
465-29V1	f-m fr fels r sd			381.3m	2106	2.14	29.9	
29V2				..	912 *	2.20 *	27.3 *	
29HX				..	2169	2.17	28.9	
465-30V	m-c r sd cement clots			396.5m	3666 *	2.22 *	27.2 *	
465-31V1	f-m fr lam r sd			411.8m	2804	2.17	28.6	
31V3				..	1222 *	2.20 *	27.3 *	
31HX				..	3586	2.17	28.7	
31HY				..	6270	2.18	28.2	
465-32V	f-c lam ms fr r sd			422.1m	—	—	—	
471-2A	f-m fels r sd	Cookley No.1 B.H., Worcs	SO84398062	164.6m	3833	2.13	31.2	
2B					[illegible]	[illegible]	[illegible]	

AREA 3

Formation : LOWER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
475 A	f wg cn fr r sd	Prestwood P.S. Stourbridge, Worcs	SO85928577	between 63.4 & 69.5 m	4251	2.10	32.8	
640 V	f-m fr fels r sd.	Enville, Worcs	SO82908615	o/c	3716	2.10	33.2	
H46				..	7860	2.09	33.3	
H316				..	9713	2.09	33.2	
643 V	f-m fr lam r sd	Road cutting at Dudmaston, Bridgnorth	SO74468937	o/c	1730	2.14	30.6	
H116				..	3038	2.14	30.9	
H206				..	2640	2.13	31.0	
644 V	f-m fr lam r sd		SO74318939	o/c	1387	2.11	32.6	
HX				..	3222	2.10	33.2	
HY				..	2819	2.10	32.9	
647 V	m-c wg ms fr r sd	Rindleford, Bridgnorth Salop	SO73339589	o/c	3656	2.16	29.4	
H43				..	5374	2.13	31.0	
H133				..	6068	2.13	31.1	
[illegible]	m-c dk	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	

AREA 3

Formation : LOWER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
649 H185	m-c dk r pb sd partly cemented	Quarry at Grindleforge, Ryton, Salop.	SJ75360338	o/c	1125	2.28	22.5	
H275				"	1013	2.31	21.3	
650 V	m-vc pb r sd fr		SJ75350341	o/c	2780	2.16	29.5	
H155				"	7670	2.15	30.0	
H245				"	3720	2.16	29.2	
651 V	m pk-gy fr sd white cement		SJ75320344	o/c	1298	2.17	27.5	
H86				"	2117	2.17	27.8	
H1-356				"	2214	2.17	27.9	
H2-356				"	-	2.20 *	26.6 *	
654 V1	vf cn r fr sd	Abbots Castle Hill, Seisdon, Salop	SO82279432	o/c	2199	2.11	32.3	
V2				"	1830 *	2.12 *	31.3 *	
HX				"	2014	2.11	32.5	
HY				"	2372	2.11	32.5	

The principal source of material from the formation in this area was the Bellington No 4 BH (sample Nos. 465-13 to 465-26, Fig.21). These samples were reinforced by numerous outcrop samples which gave values for aquifer properties of similar magnitude to horizons of the same lithology in the Bellington No 4 BH. The effect of weathering on plugs cut from the outcrop samples is therefore thought to be small.

The shingle facies of the Pebble Beds is present in the area in the cemented state except in the Shifnal area where the cementation is far less widespread. It has been established from measurements on samples 470, 471 and 646 that intergranular permeability is virtually nil in the cemented units (such as those shown in Plate 4A), and it is concluded that ground water movement through them can only take place by fissure flow. Storage is also likely to be minimal as porosity is reduced to between 5 and 9 per cent. As evidence of the degree of cementation, the saturated density of these beds was found to be between 2.53 and 2.60 gms cc^{-1}, which compares with about 2.15 gms cc^{-1} in the friable coarse sands which are the dominant lithology of the subdivision in this area.

The interbedded coarse sands possess a maximum intergranular permeability of about 9000 md and these deposits are therefore amongst the most permeable of the Permo-Triassic sandstones in the UK. They are also characteristically friable, even at considerable depth in boreholes (eg Sample 465-16 from 243.8 m depth and 465-18 from 274.3 m). Porosity in these coarse sands was found to be slightly less than the maximum and in spite of the high permeability seldom exceeds 27 per cent.

The effect of poor grading on permeability is well illustrated by sample 465-15 in which in spite of moderate porosity, intergranular permeability is remarkably reduced.

Not all the sandstones samples from this subdivision were coarse.Nos. 465-22, 627 and 639 are examples of the types of finer grained material also encountered in the sequence. In these intergranular permeability is much lower than in the coarser material and ranges up to only a few hundred millidarcys. Porosity in these units is moderate at about 24 per cent.

Many of the samples were found to show distinct permeability anisotropy, caused no doubt by marked laminated structure, eg sample Nos. 465-15, 465-16, 465-20 and 465-26.

AREA 3 Formation: BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
465-13V	vc pb fr r sd	Bellington No.4 B.H., Kidderminster	SO87767689	198.1m	2206	2.27	24.6	
13HX				..	9134	2.26	24.3	
465-14V	fr m-c pb sd			213.4m	8917	2.17	28.7	
14HX				..	4640	2.19	27.8	
14HY				..	–	2.20	27.4	
465-15V	f-c fr r sd			228.6m	255	2.24	25.4	
15HX				..	880	2.25	24.6	
15HY				..	1187	2.25	24.9	
465-16V	m-c cn fr pb r sd			243.8m	4009	2.19	27.5	
16HX				..	8490	2.18	28.0	
16HY				..	8458	2.18	28.5	
465-17V	m-c con r sd			259.1m	2442	2.23	17.8	
17HX				..	4157	2.19	27.6	
17HY				..	1304	2.21	26.5	
[illegible]	m-c dk r			[illegible]	[illegible]		[illegible]	

AREA 3

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
465 - 18V2	m-c dk r fr sd	Bellington No.4 B.H., Kidderminster.	SO87767689	274.3m	1449 *	2.26 *	24.8 *	
18HX1					11925	2.19	27.6	
18HX2					9056	2.21	26.5	
18HX3					3072 *	2.22 *	26.8 *	
18HY					1657	2.27	23.5	
465 - 19V	pk-gy wc f-m sd mic			274.9m	9	2.36	18.4	
19HX				..	104	2.36	18.3	
19HY				..	178	2.35	18.3	
19V2				..	32 *	2.38 *	17.4 *	
465 - 20V1	m-c pk gy fr sd, marked laminar cementation			285.0m	140	2.25	24.4	
20V2				..	278	2.23	24.9	
20HX				..	4877	2.25	24.3	
20HY				..	5199	2.25	24.3	
465 - 22V	f-m con r sd			304.8m	1233	2.24	25.9	
22HX				.	[illegible]	[illegible]	[illegible]	

AREA 3

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
465-22HY	f-m con r sd	Bellington No.4. B.H.	SO87767689	304.8m	1645	2.26	24.9	
465-23V	fr m-c r sd	Kidderminster		311.5m	2672	2.22	26.4	
23HX				"	3390	2.23	26.1	
23HY				"	1754	2.23	25.9	
465-24V				313.9m	94 *	2.45 *	16.8 *	
465-25H				320.0m	7470 †	2.38 *	20.4 *	
465-26V1	m-c pb r sd fr			335.3m	2968	2.28	24.8	
26V2				"	2028	2.27	24.8	
26HX				"	4383	2.16	29.0	
26HY				"	3701	2.27	24.8	
471-1A	wc pk cg	Cookley No.1 B.H.,	SO84398062	6.4m	<1	2.53	11.7	
1B				"	–	2.27	16.0	
627V	f-m con dk br sd	Cutting on B4194, Bewdley, Worcs	SO78887459	o/c	321	2.27	23.1	
H196				"	242	2.29	22.0	
H28[illegible]					[illegible]	[illegible]	[illegible]	

AREA 3

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
628 V	m-vc fr r sd	Cutting on B4194, Bewdley, Worcs	SO 78887459	o/c	6613	2.19	26.9	
H227				"	–	2.20	26.5	
H317				"	–	2.19	27.1	
629 V	m-c fr br-r sd	Cutting on B4190, High Habberley, Worcs	SO 80767695	o/c	8425	2.17	28.2	
H262				"	–	2.18	28.2	
H172				"	5945	2.17	28.6	
638 V	m-vc fr dk r sd	Kinver, Worcs	SO 84728297	o/c	–	2.16	28.9	
HX				"	4493	2.22	25.9	
HY				"	–	2.21	26.0	
639 V	wc vf-f lt r sd	Kinver, Worcs	SO 84758299	o/c	103	2.27	24.1	
H89				"	127	2.27	24.3	
H179				"	204	2.30	23.1	
645 V	m-c fr wc lt br sd	Cutting on A442, Rindleford, Bridgnorth	SO 73199574	o/c	154	2.45	11.9	
H260				"	–	2.40	13.5	
[illegible]					[illegible]	[illegible]	[illegible]	

AREA 3 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
646 V	wc gy cg	Cutting on A442,	SO73349591	o/c	<1	2.57	7.1	
H101		Rindleford, Bridgnorth		..	<1	2.55	8.1	
H191				..	<1	2.53	9.4	
652 V	m-c fr r	Brimstree Hill,	SJ75120579	o/c	4612	2.14	31.3	
H228	sd	Shifnal, Salop		..	5968	2.13	31.3	
H318				..	3743	2.17	29.1	
653 V1	fr c l	Abbots Castle Hill,	SO82269431	o/c	5934	2.15	29.9	
V2	r sd	Seisdon, Salop		..	7184 *	2.18 *	28.6 *	
HX				..	6893	2.14	30.4	
HY				..	12859	2.15	29.4	
470-1V	wc gy cg	Rindleford B.H.,	SO73709549	36.6m	<1	2.60	5.8	
1H		Bridgnorth.		..	–	2.55	7.7	
470-2V	wc gy cg			38.1m	<1	2.58	5.8	
2H				..	2	2.57	8.6	

In this area, a good section through most of this subdivision was examined in the Bellington No 4 BH (samples 465-0 to 465-12 Fig.21). The bulk of the sandstone has been found to have rather low intergranular permeability mainly between 100 and 1000 md owing to the generally muddy, indurated nature of the formation. There are, however, some units which consist of cleaner sand (samples 465-3 and 465-9) and in these, permeability ranges up to about 5000 md, the maximum for the Upper Mottled Sandstone.

Porosity tends to be rather reduced by the silt and mud content and the degree of induration; it is between 21 and 26% in these beds, rising to nearly 30% in the less cemented friable zones. Saturated density varies inversely with porosity and ranges from 2.14 to 2.30 gms cc^{-1}.

The few additional outcrop samples examined from this area provided rather low physical property values, in broad agreement with the data on the borehole cores.

AREA 3

Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
201 V	f-m fr r sd	Bellington No. 2 B.H., Kidderminster	SO877 768	61.0 m	478	2.24	24.6	
HX1				"	1204	2.24	24.7	
HX2				"	923	2.24	24.4	
465 - 0V	fr f r sd	Bellington No. 4 B.H., Kidderminster	SO87767689	14.9 m	2948	2.17	27.5	
0HX				"	4584	2.17	27.7	
0HY				"	2382	2.18	27.8	
465 - 1V	f cs lam r sd fr with patchy cementation			22.9 m	782	2.21	26.4	
1HX				"	18679 [slight crack]	2.29	21.4	
1HY				"	–	2.23	24.7	
465 - 2V1	f lam r sd partly wc cs			30.5 m	1	2.30	21.1	
2V2				"	316	2.27	23.2	
2HX				"	4	2.27	23.0	
2HY				"	292	2.28	21.9	
465 - 3V	fr f-m r sd			45.7 m	3047	2.19	27.4	

AREA 3 Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
465- 3HY1	fr f-m r sd	Bellington No.4 B.H. Kidderminster	SO 87767689	45.7m	5486	2.14	29.9	
3HY2				"	–	–	–	
465- 4V	fr f r sd			61.0m	439	2.18	27.5	
4HX				"	1237	2.18	27.9	
4HY				"	–	2.17	28.2	
465- 5Y1	f lam r sd patchy laminar cementation			76.2m	100	2.26	23.7	
5Y2				"	345 *	2.24 *	25.8 *	
5HX				"	254	2.30	21.7	
5HY				"	665	2.17	28.9	
465- 6V1	f r cs sd			91.7m	64	2.21	26.4	
6V2				"	154	2.22	26.2	
6HX				"	267	2.22	26.0	
6HY				"	277	2.22	26.2	
465- 7V	f-m fr r sd			106.7m	147	2.22	26.0	

AREA 3

Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
465-7HY	f-m fr r sd	Bellingtn No.4 B.H..	SO87767689	106.7m	104	2.24	24.8	
465-8V1	f-m con sd	Kidderminster		121.9m	9	2.20	27.1	
8V2				..	140 *	2.23 *	25.6 *	
8HX	f-m fr r sd			..	316	2.19	28.0	
8HY				..	466	2.16	29.4	
465-9V	f-m fr r sd			137.2m	4699	2.18	28.1	
9HX1				..	5220	2.16	29.3	
9HX2				..	4859	2.18	28.0	
9HY				..	7757	2.19	27.4	
465-10V	f con r sd			153.0m	212	2.17	29.1	
10HX				..	320	2.20	27.6	
10HY				..	424	2.21	26.8	
465-11V	f con r sd			167.6m	3	2.22	27.0	
11HX				..	30	2.24	25.4	
[illegible]					[illegible]	[illegible]	[illegible]	

AREA 3 Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
465-12V	f-m wc r sd	Bellington No.4 B.H., Kidderminster	SO87767689	182.9m	13	2.24	25.6	
12HX				"	53	2.25	25.0	
12HY				"	27	2.25	24.4	
472-2A	m wc gy-gn sd	Somerford No.2 B.H., Staffs	SJ89660931	256.9m	579	2.34	18.7	
2B				"	1618	2.32	19.7	
630V	md lam f sd	Churchill, Kidderminster, Worcs	SO87867933	o/c	29	2.19	27.3	
H149				"	111	2.19	27.4	
H239	f fr r sd			"	564	2.17	28.1	
655V1	con f-c lam r sd	Smestow Bridge Quarry Wombourn, Staffs	SO85329289	o/c	7	2.28	23.1	
V2				"	-	2.29 *	22.8 *	
HX				"	-	2.26	24.6	
HY				"	1275	2.24	25.7	
658V	fr f r sd	Wightwick, Wolverhampton.	SO87019839	o/c	465	2.19	27.2	
H209				"	-	2.18	26.6	

LOWER KEUPER SANDSTONE AREA 3

In Area 3, the general picture for the Lower Keuper Sandstone is one of fine to medium, mainly rather friable sandstones with permeability generally between 1000 and 4000 md and porosity ranging from 27 to 32%. There is a tendency for the sands to become finer to the south towards the surface junction with the overlying Keuper Marl and aquifer property values reduce in this direction.

It has to be admitted, however, that the distribution of samples is unsatisfactory owing to a complete lack of subsurface material. The samples from Shipley Hill, Claverley (Nos. 40 and 41) indicate how local carbonate cementation can reduce both the important aquifer properties to low values. It is significant that once again, the lowest values have been obtained from near the base of the formation (cf areas 4 and 5).

AREA 3 Formation: LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
24 V	f-m cn fr r sd	Newent, Gloucs.	SO72052625	o/c	1787	2.20	27.6	
H1-112				"	2429	2.19	27.7	
H2-112				"	2295	2.19	27.4	
H1-209				"	2278	2.20	27.2	
H2-209				"	2512	2.20	27.2	
32 V1	fr m r sd	Yieldingtree, Broom	SO 89637735	o/c	5585	—	—	
V2				"	4559	—	—	
H80				"	9000	2.10	32.2	
40 H 130	wc vf-f br sd	Shipley Hill, Salop	SO80349572	o/c	<1	2.53	8.0	
41 H 310	con vf r sd			"	62	2.24	25.0	
74 V	fr f-m r sd	Tong Castle, Tong, Salop	SJ79870653	o/c	2683	2.12	31.0	
H92				"	2493	2.13	30.6	
H182				"	3113	2.12	31.0	
472 A	wc m br sd	Somerford P.S. Staffs	SJ89660931	65.Pm	1413	2.27	22.4	
[illegible]	fr cn br	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	

AREA 3

Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
625 V2	fr cn br f sd	Ombersley, Worcs	SO83846262	o/c	2758 *	2.08 *	34.6 *	
H55				..	3721	2.08	34.8	
H145				..	4497	2.08	34.5	
626 V	f-m fr r sd	B4196, Astley Cross, Worcestershire	SO 80196822	o/c	3248	2.20	26.6	
H210				..	4873	2.19	27.0	
H300				..	6079	2.19	27.4	
636 V	vf-f mic con r sd	Mustow Green, Chaddesley Corbett, Worcs	SO 86967419	o/c	1012	2.16	30.0	
H130				..	721	2.17	29.5	
H220				..	1451	2.14	31.0	
637 V	f-m fr lam r sd			o/c	4592	2.10	32.7	
H117				..	5968	2.10	32.8	
H207				..	-	2.12	32.0	
648 V	br-r f-m con r sd	Badger Dingle, Badger, Salop	SO76739928	o/c	487	2.20	26.9	
H1-31				..	1124	2.19	27.2	

AREA 3

Formation : LOWER KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
648 H 301	br-r f-m con r sd	Badger Dingle, Salop	SO76739928	o/c	1013	2.20	26.8	
659 V	f-m fr lam fds gy-y sd	A41 at Oaken, Wolverhampton	SJ85000251	o/c	1576	2.21	26.4	
H 218				"	1168	2.20	26.7	
H 308				"	2164	2.20	26.7	

By comparison with the adjoining Area 3 in which a significant number of samples were examined, the Lower Mottled Sandstone in Shropshire and Cheshire shows much greater lithological variation. The consequent variation in aquifer properties has been studied using both surface and underground samples.

In the upper part of the formation, siltstones and very fine grained sandstones are common which as might be expected were found to have a very low intergranular permeability frequently below the lower limit of resolution of the equipment (1 md). Examples of these deposits are samples Nos. 747-5 and 763-10, 763-12 and 763-13. Slightly less cemented varieties (747-2 and 747-3) have a permeability rising to 20 md. Porosity in these beds was found to range between 10 and 15% exceptionally as low as 5%, with density relatively constant between 2.35 and 2.40 gms cc^{-1}.

At lower levels in the subdivision, on the evidence of the Shiffords Bridge, Rodway, Sheepbridge and Bolas Bridge (Fig.22) boreholes, it appears that much coarser and more permeable sandstones occur, a fair proportion of which are of the much described laminated 'millet seed' type. Except certain rather muddy types of these which gave only moderate values for aquifer properties (eg 461-4), the majority of the lower millet seed sands gave extremely high permeability figures, moderate porosity figures and intermediate density data. Permeability was found to be strongly anisotropic with respect to the vertical direction owing to the commonly laminated structure (eg samples 461-6, 597, 746-6 to 746-9). Even in cemented varieties, anisotropy was still found to occur (No.747-6). Samples Nos. 746-2, 746-3, 747-9 and 747-12 are typical examples of the millet seed sands, characterised by a highly sorted medium to coarse grain size and a high degree of rounding and polishing. Permeability ranges from 3000 to 10000 md and in a significant number of samples reaches 12-18000 md. In contrast, porosity rarely exceeds 30% and may be as low as 25% owing to the presence of patchy carbonate cementation. Density at about 2.20 gms cc^{-1} also is not as low as might be expected from the permeability figures.

In summary, therefore, the upper levels of the sub-division are predominantly silty in nature and of low intergranular permeability, and these are underlain by the classic, highly permeable millet seed sands. From examination of the complete cores at the Rodway, Sheepbridge and Bolas Bridge (Fig.22) sites, it is clear that these two subfacies interdigitate with one another and that no sharp junction exists between the two. The presence of the rather impermeable upper part of the sandstone in the Sheepbridge and Bolas Bridge boreholes partly explains the poor yield of these wells, compared with the Rodway site which commenced at a lower stratigraphic level and penetrated deeply into the much coarser lower sandstones.

AREA 4 Formation: LOWER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
48V	m wg r sd traversed by cemented veinlets	Knockin, Salop	SJ 32882228	o/c	<1	2.43	13.5	
48H1-108				..	86	2.36	17.6	
48H2-108				..	87	2.37	17.2	
48H1-198				..	17	—	—	
48H2-198				..	67	2.38	16.6	
461-4V	lam c slt & m sd very muddy appearance	Shiffords Bridge B.H Market Drayton	SJ 690 350	60.4m	1	2.30	22.4	
4HX				..	44	2.35	19.5	
4HY				..	287	2.37	18.3	
461-5V	cn fr m r sd ms			69.2m	12988	2.18	28.6	
5HX	cn fr f-m r sd			..	9446	2.19	27.8	
5HY				..	5251	2.19	28.0	
461-6V	vf-m lam r sd			72.5m	923	2.25	24.6	
6HX				..	2083	2.24	25.0	
6HY				..	2441	2.24	24.9	

AREA 4

Formation : LOWER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
461-7HX	vf-m wc r sd	Shiffords Bridge BH Market Drayton	SJ 690350	77.1m	241	2.32	20.3	
7HY				..	283	2.32	20.8	
596 V	f-c lam fr r sd	Road cutting on B5093, Preston Brockhurst Salop.	SJ54102529	o/c	–	2.15	28.7	
H104				..	7387	2.15	28.5	
H194				..	8680	2.17	27.8	
597 V	vf-m con dk r sd	Market Drayton, Salop.	SJ67573397	o/c	23	2.34	19.3	
H30				..	186	2.30	21.9	
H120				..	181	2.30	21.8	
599 V	f-m lam fr r sd ms	Childs Ercall, Salop.	SJ66632535	o/c	–	2.16	27.4	
H165				..	3919	2.18	27.1	
H256				..	–	2.17	25.3	
622 V1	fr m-c dk r sd patchy white cement	Llyndys, Salop	SJ 28602498	o/c	2883	2.18	28.2	
V2				..	1547*	2.21*	27.4*	
H130				..	2125	2.19	28.0	
H1[illegible]					[illegible]	2.1[illegible]	28.[illegible]	

AREA 4

Formation: LOWER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
660 V1	fr wg m ms sd patches of white cement	Cound Brook, Cound, Salop.	SJ55540508	o/c	7851	2.11	32.1	
V2				..	5559*	2.14*	30.8*	
H180				..	16158	2.12	31.4	
H270				..	7785	2.12	31.6	
746-1V	fr f-vc dk r sd ms	Rodway B.H., Wellington, Salop	SJ66231825	30.8m	–	2.22	25.5	
1HX				..	–	2.23	24.0	
1HY				..	–	2.24	23.9	
746-2V	wg f-m cn ms dk r sd			31.0m	6139	2.14	30.8	
2HX				..	6359	2.14	30.5	
2HY				..	6018	2.15	30.4	
746-3V	f-c lam fr dk r ms sd			45.4m	4968	2.21	26.1	
3HX				..	12052	2.23	25.1	
3HY				..	4363	2.23	24.9	
746-4V	vf-c lam dk r sd			c 54.9m	149	2.25	24.3	
4H[illegible]	f-c lam [illegible]			..	[illegible]	[illegible]	[illegible]	

AREA 4 Formation: LOWER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
746-4HY	f-c lam dk r ms sd	Rodway BH., Wellington, Salop	SJ66231825	c 54.9m	15638	2.21	26.3	
746-5V	c and vf lam fr ms sd dk r			64.0m	133	2.30	21.4	
5HX				..	-	2.26	21.9	
5HY				..	-	2.28	21.5	
746-6V	f-m wg dk r ms sd cn			74.7m	4773	2.24	25.1	
6HX				..	7664	2.22	26.3	
6HY				..	5979	2.22	26.2	
746-7V	cn wg f dk r ms sd			85.3m	2512	2.22	25.8	
7HX				..	6128	2.19	27.7	
7HY				..	3980	2.20	27.1	
746-8V	cn f-m dk r sd			97.5m	2705	2.19	27.5	
8HX				..	3727	-	-	
8HY				..	4101	2.19	27.0	
746-9V	cn f-m wg dk r			108.2m	7826	2.15	29.4	

AREA 4 Formation: LOWER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
746-9HY	cn f-m wg dk r ms sd	Rodway BH, Wellington, Salop	SJ 66231825	108.2 m	11144	2.15	30.1	
746-10V1	cn f con dk r sd cs			114.3 m	3204	2.18	28.5	
10V2				..				
10HX				..	3686	2.19	28.0	
10HY				..	3161	2.22	26.3	
746-11V1	wg con f dk r sd with cement clots			124.4 m	585	2.28	22.7	
11V2				..				
11HX				..	3514	2.28	22.5	
11HY				..	2290	2.29	22.2	
747-2V	vf-f lam dk r sd	Sheepbridge B.H., Wellington, Salop	SJ 67142067	26.5 m	16	2.33	18.5	
2HX				..	31	2.32	19.2	
2HY				..	5	2.34	18.2	
747-3V	lam dk r c slt-f sd con			35.4 m	<1	2.35	17.9	
3HX				..	18	2.37	17.0	

AREA 4

Formation : LOWER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
747-4V	vf-m lam fr-dk r sd	Sheepbridge BH, Wellington, Salop	SJ67142067	45.7m	174	2.26	23.3	
4HX				..	574	2.28	22.2	
4HY				..	2982	2.27	22.6	
747-5V	c-slt to m sd lam with cemented zones			54.9m	<1	2.39	15.9	
5HX				..	<1	2.42	14.8	
5HY				..	<1	2.39	16.3	
747-6V	wc m mic gy-r sd			64.0m	14	2.35	18.0	
6HX				..	164	2.34	18.8	
6HY				..	161	2.33	19.5	
747-7V	vf-m lam con-wc gy-r sd			64.9m	54	2.28	22.0	
7HX1				..	26	2.28	22.7	
7HX2				..	123	2.29	21.0	
7HY1				..	665	2.27	23.1	
7HY2				.	112	2.30	20.3	

AREA 4 Formation : LOWER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
747- 8HX	f-m lam wc r sd	Sheepbridge B.H. Wellington, Salop	SJ67142067	73.2m	283	2.35	18.1	
8HY				..	401	2.32	19.8	
747- 9V	f-c lam dk r fr ms sd cn			82.3m	4386	2.26	23.9	
9HX				..	10633	2.27	22.6	
9HY				..	5197	2.26	24.1	
747- 10V	wg m dk r ms sd cn			90.2m	8216	2.12	32.1	
10HX				..	6913	2.14	30.9	
10HY				..	6539	2.16	29.5	
747- 11V	cs f-m lam dk r sd			97.5m	4683	2.14	30.4	
11HX				..	6211	2.16	29.6	
11HY				..	6150	2.09	34.0	
747- 12V	cn m-c wg dk r ms sd			106.7m	15160	2.12	31.5	
12HX				..	13511	2.14	30.9	
12HY				..	10028	2.14	30.5	

AREA 4 Formation : LOWER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specif Yield per cent
747-13HX	cn m wg dkr ms sd	Sheepbridge BH, Wellington, Salop	SJ67142067	117.0m	13008	2.17	28.7	
13HY				..	15223	2.16	29.3	
747-14V	m-c cn fr dk r sd			122.8m	18746	2.14	29.8	
14HX				..	19840	2.14	30.8	
14HY				..	–	2.16	29.8	
763-9V	vf-f wc dk r sd	Bolas Bridge BH Wellington, Salop	SJ 64572027	102.1m	3	2.35	17.2	
9HX				..	18	2.34	17.5	
9HY				..	12	2.34	17.2	
763-10V	c slt-vf sd wc dk r mic			111.0m	2	2.34	11.8	
10HX				..	<1	2.37	9.3	
10HY				..	<1	2.34	10.0	
763-11V	vf-c lam md r sd			120.4m		2.31	19.6	
11HX				..		2.36	17.3	
11HY				..		2.31	20.1	
[illegible]	c slt-m sd [illegible]			[illegible]		[illegible]	[illegible]	

AREA 4

Formation : LOWER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
763-12H	c slt - m sd cemented zones	Bolas Bridge BH, Wellington, Salop	SJ64572027	127.4m	<1	2.42	13.3	
763-13V	dk r lam slt			128.0m	<1	2.42	5.5	
13H				..	<1	2.41	11.1	
763-14V	vf-f lam wc dk r sd			130.0m	0.6	2.39	16.8	
14HX				..	2	2.38	17.1	
14HY				..	2	2.39	16.7	
763-15V	f-c wc pb r sd			>130m	810	2.27	22.7	
15HX				..	2208	2.29	21.6	
15HY				..	766	2.30	21.6	
763-16V	f-c md lam dk r ms sd			>130m	92	2.31	20.9	
16HX				..	2069	2.32	20.6	
16HY				..	767	2.31	20.9	

In the mid-Cheshire and Shropshire area, the Bunter Pebble Beds, displaying a facies transitional between that present in Area 3 and that in Area 5, have been found to have rather variable physical properties.

The principal controlling factor is not so much grain size as degree of cementation. In comparison with Areas 1 and 3, this is far more widespread at this horizon, and many of the samples examined were similar in texture to those obtained in Merseyside and the Chester area.

Where the cementation is well developed, as for example in the coarse sandstone samples 461-1, 763-4, 763-5, and 763-8 (all from boreholes incidentally), permeability is found to be reduced to a few hundred millidarcys and porosity may be as low as 14%. In those sands where cementation has reduced porosity to a lesser extent, i.e. to about 21 or 22 per cent, permeability is much higher, being between 1500 and 2500 md (eg samples 55 and 601).

Some coarse clean subsurface sands were tested from the Shiffords Bridge BH (461-2 and 461-3) and these, with permeability up to 6000 md and porosity of up to 25% are physically identifiable with similar clean sands examined in Areas 1 and 3.

It is considered that in view of the far more widespread induration of this subdivision of the Trias in this area, the high aquifer property values obtained on certain friable outcrop samples such as 600 and 606 are probably over optimistic and are not representative of sub-surface conditions in the formation.

On the whole, therefore, both intergranular permeability and porosity are reduced in this area by cementation. Further data are required from West Shropshire where unfortunately very little material was forthcoming for the present study.

AREA 4 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
47V	m-c con r sd	Knockin, Salop	SJ 33002235	o/c	2819	2.25	23.4	
47H1-5				..	1498	2.27	21.9	
H2-5				..	3119	2.26	22.9	
H1-95				..	1953	2.26	22.9	
H2-95				..	1246	2.27	21.9	
55V	m-c con r sd	Shray Hill, Waters Upton, Salop.	SJ 65611918	o/c	1738	2.26	22.9	
H62				..	2453	—	—	
H152				..	1759	2.28	21.5	
77H250	m-c fr sd	Tittensor Common, Stone	SJ 87523748	o/c	2453	2.14	29.7	
461-1V	c pb wc pk cg	Shiffords Bridge BH Market Drayton Salop	SJ 690350	27.7m	145	2.41	15.2	
1HX				..	85	2.43	14.5	
1HY				..	236	2.40	15.9	
461-2V	m-vc pb r sd cn fr			43.6m	2802	2.26	23.8	
2HX				..	5874	2.23	25.2	
	m-vc cn							

AREA 4

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
593 V	m-c con cn dk br sd	River Roden at Lee Brockhurst, Salop.	SJ 54922674	o/c	4286	2.25	23.6	
H112				"	7220	2.24	24.4	
H202				"	5521	2.25	23.9	
598 V	m-c fr Y sd	Cutting on A 529 nr. Market Drayton	SJ 67843367	o/c	-	2.11	30.6	
H170				"	16292	2.11	30.0	
H260				"	-	2.11	31.0	
600 V	m-c cn fr r sd pb	Childs Ercall, Salop	SJ 66612553	o/c	16986	2.11	32.1	
H88				"	>23000	2.10	33.2	
H358				"	-	2.13	31.9	
601 V	m-c con cav br sd	Sambrook Hall, Sambrook, Salop	SJ 71482469	o/c	2928	2.25	23.9	
H62				"	2750	2.24	24.4	
H332				"	2460	2.26	23.5	
602 V	m-c fr r sd	Goldstone Common, Salop	SJ 70562947	o/c	-	2.12	30.2	
605 VI	m-c fr r sd	Maer Hills, Maer, Staffs.	SJ 77773903	o/c	5105	2.18	27.8	
[illegible]					[illegible]	[illegible]	[illegible]	

AREA 4 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
605 H 79	m-c fr r sd	Maer Hills, Maer, Staffs.	SJ77773903	o/c	5212	2.18	28.1	
H 169				"	7763	2.19	28.0	
606 H 35	m-c cn fr pk sd	Maer, Staffs	SJ78483962	o/c	12883	2.18	27.7	
H125		"		"	9606	2.18	28.0	
608 V	f-m fr gy sd	Quarry at Moddershall, Staffs	SJ92813668	o/c	1702	2.16	29.4	
H141				"	3666	2.15	30.0	
H 231				"	3608	2.16	29.3	
618 V	l lam ms sd dk r fr f-c	Tibberton, Salop	SJ68112041	o/c	3553	2.21	27.0	
H 38				"	11611	2.19	27.0	
H 128				"	8017	2.22	26.4	
620 V	f-m cn fr r sd	Ford, Shrewsbury, Salop.	SJ41851442	o/c	4945	2.17	28.2	
HX				"	-	2.17	27.6	
763-1V	vf-f lam sd	Bolas Bridge BH, Wellington, Salop	SJ64572027	38.1m	<1	2.29	19.6	
1HX				"	40 [incipient crack]	2.31	16.2	

AREA 4 Formation: BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
763-2V	m-c con gy sd	Bolas Bridge BH, Wellington, Salop	SJ 64572027	44.2m	104	2.20	26.0	
2HX				..	3399	2.20	25.9	
2HY				..	2590	2.22	24.3	
763-3V	f-c con cav r sd			54.0m	1882	2.19	26.0	
3HX				..	172	2.28	21.3	
3HY				..	411	2.27	21.6	
763-4V	m wc pk sd			63.1m	157	2.19	26.9	
4HX				..	354	2.28	21.0	
4HY				..	430	–	–	
763-5V	f-m wc r sd			67.4m	95	2.17	28.4	
5HX				..	241	2.30	20.4	
5HY				..	33	2.29	20.9	
763-6V	f-c lam pk sd			73.2m	1632	2.29	19.9	
6HX				..	1233	2.33	18.0	
[illegible]					[illegible]	[illegible]	[illegible]	

AREA 4 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
763-7V	f-m lam con r sd	Bolas Bridge BH, Wellington Salop	SJ64572027	83.8m	<1	2.38	15.4	
7HX				"	4	2.39	15.0	
7HY				"	64	2.35	16.6	
763-8V	wc pk gy pb cg			93.0m	23	2.34	17.6	
8HX				"	96	2.45	12.4	
8HY				"	22	2.39	15.0	

UPPER MOTTLED SANDSTONE AREA 4

In this area, these dominantly fine grained sandstones are found in both the cemented and the uncemented state. Samples 52 and 609 represent the cemented condition in which intergranular permeability is about 200 to 300 md and porosity lies at 24-26%. The uncemented sands tend to be brighter red in colour and markedly cleaner as a result of which permeability reaches several thousand millidarcys and porosity approaches 30% (samples 49, 72, 73 and 603).

Owing to the lack of samples from boreholes, one cannot speculate about the probable degree of cementation at depth. The present evidence suggests that it is rather patchy in its distribution.

AREA 4

Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
49 H 138	wg f r sd	Saudford Hall, Knockin, Salop	SJ 33992358	o/c	1568	2.21	25.9	
H 228				..	1915	2.21	26.2	
50 V	f-m fr r sd	Grinshill, Salop	SJ 51752383	o/c	1142	2.18	28.2	
H75				..	1147	2.18	28.3	
H165				..	1283	2.17	28.3	
52 V	con f br sd	Wixhill, Weston, Salop	SJ 55942854	o/c	269	2.21	26.5	
H1-120				..	309	2.24	24.4	
H2-120				..	288	2.24	24.8	
H1-210				..	391	2.23	24.8	
H2-210				..	391	2.24	24.5	
72 H 195	fr cn f sd	Tong Forge, Tong. Salop.	SJ 78370828	o/c	5409	2.15	29.1	
73 H 2	fr cn f sd			..	5446	2.14	29.3	
603 V	dk br fr cn f sd	Bishops Offley, Salop	SJ 78192983	o/c	2831	2.15	28.3	
H2				.	3882	2.15	29.3	

AREA 4

Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\,cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
603 H	dk br f sd	Bishops Offley, Salop	SJ78192983	o/c	2542	2.17	28.8	
607 V1	m-c cav fr pk sd	Railway cutting at Whitmore, Salop	SJ79714032	o/c	8468	2.12	31.4	
V2				..	5662	2.13	31.1	
H52				..	9191	2.13	31.0	
H142				..	7290	2.15	30.1	
609 V	mic wc f pk sd	Cutting on A.519, Forton, Salop.		o/c	15	2.38	17.0	
H72				..	31	2.37	17.5	
H162				..	42	2.37	17.8	
621 A	fr f r sd	Kinton, Salop	SJ36821948	o/c	2418	2.18	28.1	
B				..	2088	2.19	27.5	
C				..	1927	2.19	27.4	
661 V	fr cav f br sd	Clive, Salop.	SJ51372370	o/c	2445	2.16	29.1	
H1-45				..	2370	2.15	29.9	
H135				..	2151	2.13	31.4	

The aquifer property evaluation in this area was severly hampered by a total lack of subsurface material. The few outcrop samples examined were found to have quite variable properties, reflecting considerable lithological differences.

It appears that intergranular permeability and porosity may be reduced by cementation near the base of the subdivision (sample 610) where particularly hard, coarse sandstones may be present. Near the top, as at Marchamley Hill (sample 54) fine grain size may also restrict permeability, as the formation passes upwards into the mainly silty Waterstones facies. Occupying the middle part of the formation, are the much more permeable and commonly exposed cross-stratified friable yellow sands, in which porosity reaches 30% or more and intergranular permeability is as high as 2000 to 4000 md. It is emphasised, however, that the quantity of data available is small and that further work is required before a reliable estimate of the physical property variation can be given.

AREA 4

Formation : LOWER KEUPER SANDSTONE or KEUPER BUILDING STONES

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
45V	f-m cn fr cav gy-r sd	Nesscliff Hill, Nesscliff, Salop.	SJ 38992011	o/c	2608	2.18	27.6	
H 88				..	3791	2.15	29.1	
H178				..	4299	2.14	30.1	
51 V	f-c con br sd	Grinshill, Salop.	SJ 51792383	o/c	1783	2.21	25.6	
H1-120				..	1545	2.22	25.2	
H2-120				..	1285	2.23	24.6	
H 210				..	1262	2.22	24.8	
54 V1	vf-f cav con br sd	Marchamley Hill, Hodnet, Salop.	SJ 59512917	o/c	38	2.24	25.1	
V2				..	65	2.23	25.4	
H20				..	540	2.16	29.3	
H1-110				..	56	2.22	25.6	
H2-110				..	119	2.21	26.6	
75 H5	fr f-m y sd	Oulton Gorge, Stone, Staffs	SJ 91573558	o/c	1713	2.17	29.6	
H95				..	2181	2.16	29.5	
101V	fr f-m			o/c	[illegible]	[illegible]	[illegible]	

AREA 4

Formation : LOWER KEUPER SANDSTONE or KEUPER BUILDING STONES

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
101 H185	fr f-m y sd	Oulton Gorge, Stone.	SJ91573558	o/c	1805	2.16	29.4	
604 V	fr y-br f-m sd fels	Bishops Offley, Salop	SJ78202977	o/c	4064	2.13	31.2	
H42				..	2683	2.14	30.3	
H312				..	3178	2.14	30.7	
610 V	wc m pk-gy sd	A519 at Forton, Salop	SJ75932166	o/c	167	2.40	15.3	
H80				..	89	2.42	14.7	
H170				..	70	2.41	15.1	

LOWER MOTTLED SANDSTONE AREA 5

Throughout Area 5, the Lower Mottled Sandstone is very poorly exposed, and owing to the considerable depth at which it lies over much of south Lancashire and Cheshire, few boreholes penetrate it. Only 2 samples were examined both from natural outcrops at Burton and Stanlow. In both cases, the medium to coarse grained sandstones was found to have a moderate to high permeability and moderate porosity (see data sheets). The formation is markedly crossbedded, and further evidence from borehole cores is urgently required before the true extent of intergranular flow in the formation can be assessed. The evidence from other areas is encouraging.

AREA 5 Formation : LOWER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
348 V2	fr m mt r sd	Burton, Cheshire	SJ31237426	o/c	4517	2.21	25.8	
H1-54				"	2725	2.21	26.0	
H2-54				"	4174	2.20	26.4	
H1-144				"	5675	2.19	27.5	
H2-144				"	4947	2.19	27.2	
349 V1	fr m mt gy-r sd	Elton, Stanlow, Cheshire	SJ45767558	o/c	1800	2.22	25.2	
V2				"	1578	2.18	27.7	
H1-148				"	2954	2.18	27.7	
H2-148				"	1286	2.24	24.2	
H1-288				"	1844	2.23	24.5	

The rather indurated nature of the Pebble Beds and their general lack of pebbles in this area has already been mentioned (p25). The most common lithology, hard pale red cemented sandstones of medium grain size, is moderately permeable (up to about 3000 md) but porosity is reduced to between 20 and 25% by the cementation which is widespread at depths of only a few metres below surface. Many subsurface samples were taken in this area from the New Mersey Tunnel section and from cored boreholes in Liverpool and Birkenhead (see Fig.23). The presence of moderate permeability with rather reduced porosity indicates that the pore channels through these sandstones must be relatively wide, compared with those in more friable higher porosity sandstones of the same permeability.

Outcrop samples from the area were found to have much higher values for both porosity and permeability, a feature attributed to slightly coarser grain size and lack of cementation, caused partly by subaerial weathering. The samples from New Brighton and Hunts Cross, however, confirmed the rather low values obtained from the New Mersey Tunnel and Merseyside boreholes and these results point to a generally higher density (about 2.30 gms cc^{-1}) for the Pebble Beds in the Liverpool area than in the adjoining districts to the south (Area 4). Unfortunately borehole cores were not examined, except in the Merseyside area.

Occasional grey sandstones encountered in the New Tunnel, in boreholes and in surface outcrops were found to have a very low permeability without exception, an interesting case of colouration appearing to be correlated with distinct physical properties (cf samples Nos. 345, 359-10, 359-18 and 753-4).

Micro-laminations were found to cause severe permeability anisotropy in several samples (359-7, 359-11).

Finally, some sandy beds of very unusual texture were found in the eastern part of the New Tunnel drivage (359-21 to 359-23). These beds closely resemble parts of the Penrith Sandstone; they display a laminated structure, consisting of large millet seed grains embedded in a dominantly fine grained matrix. Their physical properties are similar to those determined on sample Nos. 549-2 to 549-4 from Stamp Hill Mine, Westmorland (see page 179).

AREA 5

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
336 V1	m-c pb r sd lam	Saighton, nr Chester	SJ44246193	o/c	1529	2.22	26.2	
V2				..	>23000	2.19	27.7	
V3				..	18237	2.22	26.2	
H1-120				..	16374	2.22	25.7	
H2-120				..	4668	2.22	25.8	
H3-120				..	7508	2.21	26.5	
H4-120				..	3131 *	2.21 *	27.0 *	
H1-180				..	7951	2.22	26.3	
H2-180				..	5533	2.21	27.1	
H3-180				..	4011	2.21	26.3	
337 V1	f cs lam r sd		SJ44246189	o/c	28	2.28	22.5	
V2				..	9	2.31	20.9	
H72				..	1365	2.28	22.3	
H162				..	10	2.33	18.8	

AREA 5 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
343 H0	m r sd	Farndon, Cheshire	SJ41505405	o/c	16313	2.21	26.3	
H90				"	4209	2.21	26.4	
344 V1	m r sd			o/c	2135	2.21	26.3	
V2				"	2176	2.20	26.8	
V3				"	2248	2.21	26.5	
H1-108				"	2786	2.21	26.1	
H2-108				"	3849	2.21	26.0	
H3-108				"	3382	2.21	26.1	
H1-198				"	3260	2.20	26.5	
H2-198				"	2847	2.22	26.6	
345 V	gy m con mic sd			o/c	14	2.27	22.2	
H				"	194	2.24	23.8	
347 V1	m-c con r sd	Burton Cliff Point, Wirral, Cheshire	SJ30157370	o/c	1249	2.25	23.1	
V2				"	798	2.26	22.8	
H1-163				"	4563	2.23	24.6	

AREA 5

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
347 H2-163	m-c con r sd	Burton Cliff Point, Wirral, Cheshire	SJ30157370	o/c	3203	2.25	23.7	
H1-253				..	2095	2.24	23.9	
H2-253				..	2025	2.25	22.8	
350 V1	m r sd	Dunham on the Hill, Cheshire	SJ47077270	o/c	3034	2.19	27.5	
V2				..	2951	2.19	27.5	
H1-25				..	4114	2.19	27.5	
H2-25				..	5408	2.18	28.0	
H3-25				..	5680	2.18	28.0	
H1-115				..	6174	2.19	27.9	
357 V1	con f-m r sd	Railway cutting at Hunts Cross, Lancs	SJ43088443	o/c	258	2.22	25.6	
V2				..	294	2.22	25.5	
H1-215				..	389	2.21	26.1	
H2-215				..	564	2.22	25.5	
H1-305				..	900	2.21	26.0	

AREA 5

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
358 V1	con m r sd	Railway cutting at Hunts Cross, Lancs	SJ 42928441	o/c	1335	2.22	25.4	
V2				"	1104	2.23	24.7	
H1-223				"	1052	2.24	24.6	
H2-223				"	404	2.24	24.3	
H1-313				"	335	2.24	24.4	
359-1V	mt cs wc gy-r f-m sd	New Mersey Tunnel, 1737 m from Liverpool Portal.	SJ 32529097	u/g	4	2.35	17.8	
1H1-235				"	74	2.33	18.7	
1H2-235				"	46	2.37	16.3	
1H1-325				"	224	2.35	18.5	
1H2-325				"	146	2.32	19.4	
359-2V1	wc cav r sd with mud flake	New Mersey Tunnel : 1643 m from Liverpool Portal	SJ 32619100	u/g	934	2.25	24.2	
2V2				"	781	2.23	25.5	
2H208				"	2548	2.20	26.0	
2H298				"	2439	2.21	25.8	

AREA 5 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
359-3H213	wc f-m lam r sd	New Mersey Tunnel : 1554m from L. Portal	SJ 32699103	u/g	490	2.28	21.9	
3H303				..	792	2.24	24.0	
359-4V	wc f-m lam r sd	New Mersey Tunnel : 1485 m from Liverpool Portal.	SJ 32759106	u/g	56	2.29	23.2	
4H230				..	738	2.23	25.4	
4H320				..	1006	2.22	26.3	
359-5V1	wc f pk sd showing microfaults	New Mersey Tunnel : 1340m from Liverpool Portal	SJ 32889111	u/g	1	2.44	13.2	
5V2				..	<1	2.48	11.4	
5H15				..	3	2.47	11.6	
5H105				..	1	2.43	13.5	
359-6V	wc f-m r sd	New Mersey Tunnel : 1247m from Liverpool Portal	SJ 32979114	u/g	234	2.33	19.7	
6H65				..	131	2.37	17.3	
6H1-155				..	457	2.33	19.3	
6H2-155				..	75	2.38	16.5	
359-7V	f lam r sd	New Mersey Tunnel	SJ 33069118	u/g	30	2.31	21.0	

AREA 5

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
359-7H1-110	f lam r sd	New Mersey Tunnel : 1158 m from L. Portal	SJ 33069118	u/g	266	2.28	23.2	
7H2-110				..	213	2.30	21.7	
359-8V1	con m r sd with mudstone pellet	New Mersey Tunnel : 1067 m from Liverpool Portal	SJ 33139120	u/g	850	2.30	21.2	
8V2				..	814	2.29	21.6	
8H70				..	486	2.31	21.3	
8H160				..	715	2.29	22.1	
359-9V1	wc f-m r sd mf	New Mersey Tunnel : 975 m from Liverpool Portal	SJ 33219124	u/g	67	2.33	19.6	
9V2				..	200	2.32	20.4	
9V3				..	11 *	2.33	19.9	
9H225				..	220	2.32	20.3	
9H315				..	214	2.32	20.8	
359-10V1	wc f gy sd	New Mersey Tunnel : 886 m from Liverpool Portal.	SJ 33299127	u/g	2	2.37	17.1	
10V2				..	<1	2.39	16.4	
10H1-70				..	3	2.39	16.1	

AREA 5

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
359-10H1-160	wc f-gy sd	New Mersey Tunnel: 886m from Liverpool Portal.	SJ33299127	u/g	2	2.39	16.1	
10H2-160				"	4	2.39	16.5	
359-11V1	wc f-m r sd lam	New Mersey Tunnel: 880 m from Liverpool Portal.	SJ33299127	u/g	113	2.31	20.9	
11V2				"	147	2.30	21.6	
11V3				"	40 *	2.32 *	20.9 *	
11H1-95				"	556	2.26	23.2	
11H2-95				"	266	2.30	21.6	
11H1-275				"	150	2.32	20.4	
11H2-275				"	473	2.28	22.3	
11H3-275				"	358	2.30	21.7	
359-12V1	wc m-c r sd	New Mersey Tunnel: 795m from Liverpool Portal	SJ33369131	u/g	396	2.28	22.3	
12V2				"	516	2.29	22.0	
12V3				"	–	–	–	
12H1-85				"	124	2.33	19.2	
[illegible]					[illegible]	[illegible]	[illegible]	

AREA 5

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
359-12H1-265	wc m-c r sd	New Mersey Tunnel : 795m from Liverpool Portal	SJ33369131	u/g	1473	2.26	23.5	
12H2-265				..	1073	2.27	23.0	
359-13V	m r sd	New Mersey Tunnel : 702m from Liverpool Portal	SJ33459135	u/g	1311	2.25	24.1	
13H50				..	1007	2.26	24.0	
13H140				..	1250	2.26	23.7	
359-14V	m con r sd	New Mersey Tunnel : 703m from Liverpool Portal	SJ33459135	u/g	1218	2.25	24.7	
14HX				..	1183	2.25	24.7	
14HY				..	1119	2.25	24.4	
359-15V	m con r sd	New Mersey Tunnel : 608m from Liverpool Portal	SJ33529138	u/g	1008	2.26	23.6	
15H34				..	1101	2.26	23.6	
15H124				..	1347	2.26	23.6	
359-16V	wc f-m sd r	New Mersey Tunnel : 522m from Liverpool Portal.	SJ33629140	u/g	291	2.31	20.2	
16HX				..	264	2.31	20.6	
16HY				..	275	2.32	19.8	

AREA 5

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
359-17H203	wc f-m r sd	New Mersey Tunnel : 424m from L. Portal	SJ 3371 9142	u/g	284	2.31	20.2	
17H293				..	297	2.31	20.4	
359-18 V1	wc bf f sd	New Mersey Tunnel : 335m from Liverpool Portal	SJ 3384 9145	u/g	<1	2.41	14.2	
18 V2				..	–	2.38	15.6	
18H 180				..	1	2.40	14.8	
18H270				..	0.4	2.40	14.8	
359-19V	con m-c cav cs r sd	New Mersey Tunnel : 335m from Liverpool Portal	SJ 3384 9145	u/g	508	2.21	26.5	
19HX				..	730	2.22	25.7	
19HY				..	627	2.22	25.7	
359-20V	cs gy slt mic lam	New Mersey Tunnel : 335m from Liverpool Portal	SJ 3384 9145	u/g	<1	2.36	17.8	
20 HX				..	<1	2.39	17.0	
20 HY				..	<1	2.40	16.2	
359-21V2	wc f-c r sd [ms in f sd]	New Mersey Tunnel : 245m from Liverpool Portal	SJ 3390 9145	u/g	<1	2.37	18.1	
21HX2				..	<1	2.28	22.6	

AREA 5 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
359-22 V2	wc lam cs r sd [ms in f sd]	New Mersey Tunnel : 213 m from Liverpool Portal	SJ 33939145	u/g	7*	2.26	24.3	
22 H				..	12	2.29	22.7	
22 H				..	15	2.30	21.6	
359-23 V2	wc f sd ms lam	New Mersey Tunnel : 213 m from Liverpool Portal	SJ 33939145	u/g	5	2.32	20.5	
23 H158				..	2	2.36	18.5	
23 H248				..	1	2.36	18.8	
366 V1	wc f-m lam r sd	New Brighton, Cheshire	SJ 30879459	o/c	124	2.30	20.7	
V2				..	29	2.31	19.7	
H1-274				..	322	2.30	21.0	
H2-274				..	510	2.28	21.8	
H1-359				..	262	2.30	20.6	
H2-359				..	342	2.29	21.2	
362 V	r f-m fr sd	Ruthin, Denbighshire	SJ 12885763	o/c	491	-	-	To Vale of Clwyd
372 V1	m r cs sd	Little Bolton, Eccles, L[illegible]	SJ 78579858	o/c	658 *	2.14*	29.9*	

AREA 5

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
372 V3	m r cs sd	Little Bolton, Eccles, Lancs	SJ76579858	o/c	773	2.14	29.9	
372 H1-7				..	2245	2.13	30.3	
H2-7				..	2230	2.12	30.8	
H1-97				..	2475	2.12	30.9	
H2-97				..	827	2.15	29.1	
373 V1	c pb r sd	Cutting at Haydock Park Station, Lancs.	SJ57439823	o/c	2736	2.31	29.8	
V2				..	1875	2.18	26.9	
H1-47				..	6061	2.16	28.9	
H2-47				..	3735	2.18	27.6	
H3-47				..	3378*	2.18*	28.0*	
H1-137				..	4301	2.17	28.2	
H2-137				..	6965	2.16	28.9	
H3-137				..	4451	2.17	28.3	
376V	f-m wc mic sd	Lowton B.H., East [illegible]	SJ63999745	n/k	0.5	2.33	19.6	

AREA 5 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
377 V1	m fr r sd	Railway cutting, Fallowfield Station, Manchester	SJ86089379	o/c	3780	2.15	28.9	
V2				..	2108	2.16	28.7	
H1-190				..	1685	2.15	29.2	
H2-190				..	1246	2.17	28.4	
H1-280				..	–	2.17	27.9	
H2-280				..	2467	2.17	28.5	
492 V1	m-c cav r sd	New Mersey Tunnel : 134m W of Wallasey Portal	SJ31929078	o/c	1919 *	2.21 *	27.0 *	
V2				..	4712	2.19	27.8	
H130				..	8646	2.19	27.9	
H 220				..	7238	2.18	28.2	
493 V1	wc bf-gy cs f sd	New Mersey Tunnel : 128m W of Wallasey Portal	SJ 31939078	o/c	–	2.37 *	15.8 *	
V2				..	1	2.40	15.1	
H 190				..	1	2.43	13.7	
H 280				..	3	2.40	15.5	
				o/c				

AREA 5 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
494HX1	wc f-m	New Mersey Tunnel :	SJ 31889077	o/c	–	–	–	
HX2	lam sd	168 m W of Wallasey		[loose block]	21	2.37	18.1	
HY	mic	Portal		"	63	2.34	20.1	
80 H	m-c fr pb sd	Cheddleton Heath, Leek,	SJ97905328	o/c	8905	2.14	30.8	
82 H		Staffs		"	6497	2.15	29.6	
592 V	lt br c ms	Merelake, Alsager.	SJ81195409	o/c	2321	2.54	16.6	
H102	sd with patchy			"	6681	2.26	25.8	
H12	cementation			"	6743	2.30	24.1	
664-1V	f-m con	Rushton No. 1 B.H.,	SJ93116303	54.9 m	171	2.27	23.8	
-1HX	r sd	Rushton Spencer,		"	545	2.27	23.9	
-1HY		Staffs		"	784	2.26	24.3	
664-2V	r pb cg			78.6 m	38	2.49	12.8	
2H	wc			"	197	2.52	11.8	
752-1V	wc m gy-br	British Rail, B.H. No. 2,	SJ32478884	25.9 m	58	2.31	20.7	
	sd	Liverpool			[illegible]	[illegible]	[illegible]	

AREA 5

Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
752-2V	wc f-m pk sd	British Rail B.H. No.2 Liverpool	SJ 32478884	26.8m	1	2.35	19.1	
2H				..	50	2.33	20.5	
752-3V	wc m r sd			27.7m	1066	2.24	24.8	
3H	wc gy-r mt lam sd			..	289	2.33	20.3	
752-4V	m-c cav r sd			28.7m	2680	2.21	26.9	
4H				..	3783	2.22	26.1	
753-1V	wc m r sd	British Rail B.H. No. 5 Liverpool.	SJ 34289038	32.9m	1054	2.22	25.8	
1H				..	904	2.24	25.0	
753-2V	wc m sd mf cav			33.8m	758	2.20	27.3	
2H				..	544	2.25	24.5	
753-3V	wc f lam sd			34.7m	302	2.24	25.1	
3H				..	282	2.25	24.6	
753-4V	wc f gy sd			35.7m	62	2.29	21.7	
4H				..	33	2.36	17.4	

AREA 5 Formation: BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
753-5H	wc m r sd	British Rail B.H.No.5	SJ34289038	36.6m	2233	2.21	26.7	
753-6V	wc f-m lam r sd	Liverpool		37.2m	–	2.23	25.8	
6H				..	809	2.25	24.2	
761-1V	con f-c lam sd	British Rail BH No17	SJ34289029	25.9m	3	2.28	22.4	
1H		Liverpool		..	–			
761-2V	fr m pk-gy sd			26.8m	–	2.27	21.8	
2H				..	–	2.16	29.1	
761-3V	wc m bf sd			27.7m	898	2.28	22.2	
3H				..	1495	2.26	23.4	
761-4V	wc m bf sd			28.7m	612	2.29	21.5	
4H				..	414	2.30	21.1	
761-5V	fr pk-y m sd			29.6m	2063	2.20	26.7	
5H				..	2056	2.21	26.3	
761-6V	wcf-m r sd			30.5m	217	2.29	21.9	

AREA 5 Formation : BUNTER PEBBLE BEDS

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
761-7V	wc f-m r sd	British Rail B.H 17 Liverpool	SJ34289029	31.4m	2417	2.26	23.1	
7H				"	3202	2.26	23.1	
761-8V	wc f r sd			32.3m	571	2.26	23.3	
8H				"	874	2.26	23.5	

Samples from the little-known Vale of Clwyd Triassic basin were obtained from 2 boreholes drilled by Water Resources Board near Denbigh and Ruthin. This work offered an opportunity of comparing the lithology and physical properties of the isolated Clwyd Triassic sandstone with similar sandstones in the Shropshire-Cheshire basin.

The core material was found to be distinctly homogeneous with coarse sands and pebble beds conspicuously lacking. The commonest rock type appeared to be fine to medium, laminated and rather indurated sandstone, much of it cross-stratified. The physical properties of this material were found to have relatively constant values; intergranular permeability is commonly between 100 and 400 md, porosity ranges from 20 to 25 per cent with centrifruge specific yield values ranging from 10-13 per cent. Density is moderate at about 2.25 gms. cc^{-1}. Typical examples of these sands are Nos. 748-2 to 748-6 and 749-3, 749-4 and 749-8.

Subordinate rock types interbedded with these sands comprise well cemented compacted fine sands such as 748-3V and 749-6 with permeability of less than 50 md, porosity of about 20% and centrifuge specific yield of only 4-5%. At the other end of the scale, the most permeable members of the sequence are either clean, well graded medium sands such as 749-5HX/HY and 749-7 (up to 4000 md) or those poorly graded laminated types in which the coarser laminae are composed of clean sands of the millet seed type, which, as expected, display a marked anisotropy (748-1, 748-9, 748-11). In these, although porosity does not rise beyond 24 per cent, permeability may reach 4000 md in the horizontal direction.

In general lithology and physical properties, the Clwyd sandstones closely resemble the Lower Mottled Sandstone of Shropshire (Area 4). Some rock types in particular show a striking similarity, eg: the anisotropic poorly graded sands, and the rather better graded medium types with patchy white cementation. The latter are especially found in the lower part of the formation around Oswestry (cf. samples 622 and 660 with 749-2, 749-5 and 749-8). Whether the close lithological similarity is evidence of chronological equivalence is, of course, more open to question.

AREA 5

Formation : BUNTER SANDSTONE (VALE OF CLWYD)

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
748-1V	wg lam f-m r sd	Water Resources Board B.H A1, Vale of Clwyd	SJ 1132 6191	33.8m	185	2.27	22.6	16.4
1HX				"	1337	2.25	24.1	
1HY				"	1305	2.25	23.9	
748-2V	f-m lam con r sd			38.2m	424	2.27	22.6	11.7
2HX				"	646	2.30	20.8	
2HY				"	417	2.30	21.1	
748-3V	f wc r sd			42.9m	<1	2.34	19.0	5.0
3HX	f-m lam con r sd			"	270	2.33	19.8	
3HY				"	414	2.33	19.4	
748-4V	f-m lam con r sd			47.4m	44	2.30	20.9	10.4
4HX2				"	239	2.30	20.9	
4HY				"	478	2.31	20.6	
748-5V	f-m lam con r sd			51.4m	141	2.30	21.0	11.1
5HX				"	531	2.30	21.0	

AREA 5

Formation : BUNTER SANDSTONE (VALE OF CLWYD)

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
748-6V	f-m con r sd	Water Resources Board B.H. A1, Vale of Clwyd.	SJ 11326191	56.9m	192	2.27	22.9	13.7
6HX				"	578	2.24	24.6	
6HY				"	390	2.27	22.9	
748-7V	wg f con r sd			61.0m	848	2.23	25.0	15.4
7HX1				"				
7HX2				"	454	2.26	23.6	
7HY				"	522	2.26	23.7	
748-8V	vf-c lam wc r sd			65.5m	<1	2.35	18.6	6.4
8HX				"	128	2.34	18.7	
8HY				"	357	2.34	18.9	
748-9V	vf-c lam con r sd cs			70.2m	253	2.26	23.7	12.7
9HX				"	2292	2.25	24.0	
9HY				"	1637	2.25	23.8	
748-10V2	vf-c lam gn-DK sd			73.9m	337	2.31	19.9	7.9

AREA 5

Formation : BUNTER SANDSTONE (VALE OF CLWYD)

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
748 - 10HY	vf-c lam gy-pk sd	Water Resources Board, B.H. A1, Vale of Clwyd	SJ11326191	73.9m	1936	2.31	20.3	
748 - 11V1	f-c lam r sd cs ms in coarse laminae			78.4m				
11V2				"	793	2.27	22.6	11.3
11HX1				"				
11HX2				"	2802	2.27	22.7	
11HY				"	1936	2.29	21.7	
749 - 1V	wc vf-c lam r sd cs	Water Resources Board B.H. B1, Vale of Clwyd	SJ06416536	23.9m	38	2.28	23.4	7.0
1HX				"	79	2.29	22.6	
1HY				"	131	2.28	22.8	
749 - 2V	fr f-m wg r sd patchy white cement			29.0m	3872	2.15	29.3	
2HX				"	2870	2.17	29.0	
2HY				"	3129	2.15	29.9	
749 - 3V	wc f-m wg r sd			33.7m	221	2.26	24.3	9.8
3HX2				"	213	2.26	24.4	

AREA 5

Formation : BUNTER SANDSTONE (VALE OF CLWYD)

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
749-4 V2	f-m con r sd patchy white cement	Water Resources Board B.H B1, Vale of Clwyd	SJ 06416536	37.9m	312	2.25	25.1	10.6
4HX				..	275	2.24	25.7	
4HY				..	181	2.22	26.8	
749-5V	f con r sd			42.5m	396	2.22	26.6	13.1
5HX	f-m cn r sd fr patchy white cement			..	4695	2.16	29.8	
5HY				..	1082	2.20	27.8	
749-6V2	wc f r sd			46.2m	3	2.31	21.7	4.0
6HX				..	8	2.30	22.2	
6HY				..	40	2.28	23.3	
749-7V	cn m wg r sd patchy white and yellow cement			52.2m	2014	2.16	29.8	16.7
7HX2				..	4407	2.15	30.7	
7HY				..	3124	2.17	29.7	
749-8V.	f-m lam con r sd			55.5m	122	2.23	26.3	11.8
8HX				..	362	2.24	25.2	
8HY				[illegible]	[illegible]	[illegible]	[illegible]	

AREA 5

Formation : BUNTER SANDSTONE (VALE OF CLWYD)

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
362V	rf-m fr sd	Ruthin, Denbighshire	SJ 12885763	o/c	491	-	-	

UPPER MOTTLED SANDSTONE AREA 5

The Upper Mottled Sandstone over this area is characterised by great lithological variation. This variation is emphasised by the physical property data and to a large extent the two parameters may be correlated.

Most of the outcrop samples were found to give values higher than borehole material, an effect commonly attributed to weathering processes. Even in these, however, the primary sedimentological feature of lamination characterised by very large differences in the grain size of adjacent laminae is very obvious and the cause of marked permeability anisotropy (eg. samples 341 and 342). In the outcrop samples, colour differences in the mottled parts of the sandstone bear no relation to differences in physical properties.

Some beds are muddy in appearance and these were found to have moderate porosity, fairly low saturated density and low permeability (samples 351 and 463-4). On the other hand, occasional clean sands of only fine to medium grain size gave particularly high values especially for permeabilit (samples 365, 370, 662-3, 756-4). These clean sands are als particularly well-graded.

A striking feature of the Upper Mottled Sandstone in this area is the presence of silicified veins which traverse the sandstone at high angles and are commonly associated with faults (see Plate 6B). From their disposition and general relations, they are likely to act as hydraulic barriers to ground water movement through the sandstone as a whole. It has been found that the intergranular permeability of these vein-rocks is very low (samples 371 and 379) and is probably minimal at right angles to the strike of the veins owing to the siliceous cementation having taken place along essentially vertical planes. Some of the borehole samples from Liverpool are from similar veins and here the values are even lower (see samples 760-1, 760-2 and 760-4). The saturated density of the veins is very high, approaching 2.43 gms cc^{-1} with porosity reduced to as low as 12.5 per cent.

The sandstone is found to show some variation in its properties with depth. Whereas at Partington, near Manchester (sample 463-3 and 4) it appears to have moderate to high intergranular permeability, moderate to high porosity and a generally friable nature, in the Ashton BHs, near Tarvin, Cheshire the sandstone is clearly more indurated, with porosity rather reduced and permeability distinctly lower. By contrast, the Liverpool BHs show a highly variable lithology with physical property values showing extreme range, the maximum values (up to 13000 md and 31% porosity) being obtained on the friable pink/yellow mottled sands (samples 756-4 and 756-5) and the minimum (less than 1md and 13% porosity) being obtained on cemented grey sandstones such as 760-1 and 760-2. Values from the more common laminated fine red sandstones are intermediate in magnitude.

AREA 5

Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
334 H	f fr r sd	Tilston, Cheshire	SJ46615072	o/c	-	2.17	18.9	
335 V	f fr r sd		SJ46595073	o/c	4710	2.12	19.1	
341 V1	f fr lam r sd some coarse laminae	Harthill, Cheshire	SJ50175517	o/c	1679	2.24	24.6	
V2				..	1352	2.24	24.5	
V3				..	1663	2.24	24.6	
H1-175				..	2840	2.24	24.2	
H2-175				..	4195	2.23	25.0	
H2-265				..	4621	2.25	23.9	
V4				..	1393	-	-	
342-V1	fr lam gy sd f-m			o/c	2323	2.22	25.6	
V2				..	2566	2.22	25.6	
V3				..	2766	2.22	25.5	
H1				..	4596	2.22	25.6	
H2				..	4581	2.21	25.8	

AREA 5

Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
355 V1	m wg fr r sd cn	Railway cutting at Runcorn, Cheshire	SJ50998242	o/c	8824	2.12	31.3	
V2				"	10336	2.11	31.7	
V3				"	9408	2.11	31.8	
H1-42				"	9579	2.11	31.9	
H2-42				"	8910	2.12	31.3	
H132				"	8622	2.12	31.5	
356 V1	fr bf m sd with small segregations of ? copper pyrites	"	SJ50978244	o/c	7755	2.10	32.9	
V2				"	7397	2.11	32.1	
H1-84				"	4887	2.12	31.4	
H2-84				"	7152	2.11	32.0	
H1-174				"	6658	2.11	31.8	
H2-174				"	7793	2.10	32.6	
H3-174				"	7664	2.10	32.7	

AREA 5 Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
351 V1	f lam fr r sd	Helsby Hill, Helsby, Cheshire	SJ49037563	o/c	270	2.19	26.6	
V2				"	252	2.19	26.9	
H1-189				"	2063	2.19	26.7	
H2-189				"	1970	2.19	26.1	
H1-259				"	737	2.20	26.5	
H1-279				"	1623	2.20	26.2	
365 V1	fr f-m r sd cn	Dingle Tunnel, Dingle, Liverpool	SJ36408714	o/c	5178	2.20	26.3	
V2				"	4972	2.20	26.1	
H1-12				"	5103	2.21	26.3	
H2-12				"	5282	2.22	26.0	
H1-282				"	7212	2.21	26.4	
H2-282				"	6742	2.20	26.6	
370 V1	fr f-m r cn sd	Thurstaston Hill, Wirral, Cheshire	SJ24568462	o/c	5032	2.19	27.0	
V2				"	4716	2.18	27.8	
H1-135				[illegible]	[illegible]	[illegible]	[illegible]	

AREA 5

Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
370 H235	fr f-m r cn sd	Thurstaston Hill, Wirral, Cheshire	SJ 24568462	o/c	4297	2.19	27.2	
H 120				"	5210	2.18	27.7	
371 V1	m gy-r sd with siliceous veinlets		SJ 24578462	o/c	39	2.27	22.2	
V2				"	169	2.28	21.7	
H1-16				"	0.6	2.36	17.0	
H2-16				"	5.7	2.32	19.5	
379 V	gy wc m sd [siliceous vein rock]	Dickens Farm Quarry, Alderley Edge, Cheshire	SJ 86107831	o/c	88	2.70	18.4	
H1-260				"	2	2.43	12.5	
H2-260				"	137	2.36	16.0	
H3-260				"	15	2.32	18.8	
380 V2	fr cs r sd f-m		SJ 86097835	o/c	4249	2.18	26.9	
CS1-250				"	3207	2.17	27.3	
CS2-250				"	3485	2.17	27.7	
CS1-340				"	3320	2.17	27.7	

AREA 5 **Formation:** UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
380-H1-340	fr cs f-m r sd	Dickens Farm Quarry, Alderley Edge, Cheshire	SJ86097835	o/c	5069	2.17	27.1	
H2-340				..	4363	2.19	26.5	
463-3V	fr f-m r sd	Partington B.H., Manchester.	SJ 729 912	45.7m	7419	2.15	29.2	
3HX				..	19238	2.13	29.0	
3HY				..	3919	2.12	30.5	
463-4V	f r sd			70.9m	10.	2.22	24.4	
4HX				..	1922	2.19	26.9	
4HY				..	265	2.24	23.7	
495 V1	f bf mt sd	Scotland Road Cut, Liverpool Portal, New Mersey Tunnel.	SJ34689152	o/c	–	–	–	
V2				..	3453 *	2.12 *	32.2 *	
V3				..	6503	–	–	
H80				..	6313	2.12	31.9	
H170				..	8944	2.12	31.2	
496 V1	f-c lam cs fr mt		SJ34699155	o/c	–	–	–	
..								

AREA 5 Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
496 H180	f-c lam cs fr mt sd	Scotland Road Cut, Liverpool Portal, New Mersey Tunnel	SJ34699155	o/c	1265	–	–	
H270				"	1921	2.14	30.4	
497 V1	f-c lam cs y sd fr		SJ34699152	o/c	1350*	2.18*	28.6*	
V2				"	2241	2.17	28.9	
H1-250				"	–	2.17	27.5	
H2-250				"	2534	–	–	
H340				"	6547	2.16	29.5	
662-1V	p mic slt	Ashton No.1 B.H., Tarvin Cheshire	SJ50376876	46.3m	–	2.46	6.2	
662-2V	f-m con pk sd			59.4m	249	2.23	25.6	
2H				"	2360	2.21	26.7	
662-3V	m dk r sd with spotty cementation			107.9m	5417	2.30	22.9	
3HX				"	2964	2.36	20.0	
3HY				"	4376	2.34	20.9	
662-4V	f-vc lam con r sd			198.1m	177	2.35	20.1	

AREA 5

Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
663-1H	p mic slt	Ashton No.3 B.H., Tarvin, Cheshire	SJ50506903	63.1m	<1	2.49	12.3	
663-2V	f-m con r sd			93.0m	945	2.26	23.5	
2H				"	-	2.25	23.9	
663-3V	f-m con r sd			114.9m	17	2.32	20.8	
3H				"	361	2.30	22.2	
663-4V	f-m con r sd			122.8m	416	2.30	22.3	
4HX				"	322	2.31	22.0	
4HY				"	386	2.31	21.5	
663-5V	f-m con r sd			129.8m	1084	2.26	25.2	
5HX				"	1616	2.27	24.3	
5HY				"	2040	2.26	24.8	
663-6V	m con r sd patchy cementation			134.1m	2367	2.22	26.9	
6HX				"	2429	2.22	27.1	
6HY				"	4809	2.21	27.6	

AREA 5

Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
754-1H	f-m fr r sd	British Rail B.H No 6, Liverpool	SJ 34349049	29.9m	1192	2.21	26.3	
754-2V	f-m fr r sd			30.5m	4812	2.19	27.2	
2H				..	5124	2.19	27.3	
754-3V	bf f-m wc sd			31.4m	15	2.25	23.3	
3H	mt f-m con sd			..	381	2.22	25.9	
754-4V	f wc mt sd			32.3m	1	2.26	23.2	
4H	lam f-m mt sd			..	38	2.28	22.6	
754-5V	f-md mt con sd r-gy			33.2m	16	2.25	24.0	
5H				..	198	2.25	24.2	
754-6V	f mt con sd r-gy			34.1m	2	2.24	24.8	
6H				..	65	2.24	24.5	
754-7V	f-m lam mt con sd			35.1m	4	2.22	25.5	
7H				..	–	2.23	25.3	
755-1V	f cs lam mt sd	British Rail B.H. No. 8, Liverpool	SJ34539096	32.0m	7	2.16	28.6	
[illegible]					125	2.18	28.2	

AREA 5

Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
755-2V	f-m r sd	British Rail B.H. No.8 Liverpool.	SJ34539096	32.9m	1883	2.22	26.0	
2H				..	567	2.17	28.7	
755-3V	f con r sd			33.8m	475	2.18	28.5	
3H				..	132	2.21	26.8	
755-4V	f-m lam con sd			35.2m	17	2.18	28.2	
4H				..	50	2.20	26.8	
756-1V	r-y mt lam f sd	British Rail B.H. No.9, Liverpool.	SJ34709088	21.6m	1	2.31	20.3	
1H				..	1	2.33	19.1	
756-2V	fr pk-y mt f sd			22.8m	175	2.16	27.9	
2H				..	-	2.17	27.9	
756-3V	f-m cs con $ sd			23.5m	2	2.22	25.7	
3H				..	-	2.21	26.2	
756-4V	cn f-m mt sd			24.4m	13690	2.13	31.2	
4H				..	12204	2.13	31.2	

AREA 5

Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
756-5H	fr pk-y f sd	British Rail B.H.No.9	SJ34709088	25.3m	1660	2.18	27.8	
756-6V	fr f-m pk mt sd	Liverpool		26.2m	308	2.20	26.9	
6H				"	1143	2.19	27.3	
759-1V	gy-o f sd lam cav	British Rail B.H.No 14	SJ34709022	18.0m	33	2.20	26.7	
1H		Liverpool		"	17	2.23	24.9	
759-2V	lt y lam f sd			19.2m	40	2.21	26.1	
2H				"	145	2.21	26.0	
759-3V	fr lam f-m mt sd			20.0m	–	2.13	29.1	
3H				"	–	2.14	28.2	
760-1V	wc wh f sd	British Rail B.H.No.15	SJ34519025	17.7m	<1	2.42	13.4	
1H		Liverpool		"	0.4	2.40	14.7	
760-2V	wc wh f sd			18.7m	<1	2.39	15.3	
2H				"	7	2.42	13.6	
760-3V	f con r sd microfault			19.5m	1	2.22	26.4	
[illegible]	f lam con				[illegible]	[illegible]	[illegible]	

AREA 5

Formation : UPPER MOTTLED SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
760- 4V	Y-pk mt vein-rock	British Rail B.H.No.15	SJ34519025	19.5m	15	2.31	20.6	
4H	f-m r sd veined	Liverpool		..	156	2.28	22.1	
762- 1V	mt lam f sd	British Rail B.H.No. 24	SJ34699017	18.7m	-	-	-	
1H	f-m lam r sd	Liverpool		..	37	2.24	25.0	
762- 2V	f-m lam con sd			19.7m	25	2.21	26.0	
2H				..	-	2.21	26.2	
762- 3V	f pk sd			20.6m	-	2.19	27.4	
3H				..	92	2.17	26.9	
762- 4V	f-m pk sd			21.5m	215	2.19	27.1	
4H				..	1018	2.18	27.8	
762- 5V	f-m con pk sd			22.4m	6	2.20	26.8	
5H				..	377	2.20	27.0	

Of the Keuper Conglomerate, a local development restricted to this area, only two samples were examined. The results (samples 338 and 382) indicate clearly that intergranular permeability and porosity in this unit is very reduced by siliceous cementation, and it is concluded that movement of water through it must take place by fissure flow.

On the other hand, the overlying mainly buff, yellow or pink Keuper Sandstone is characterised by a highly distinctive petrophysical nature. In spite of widespread cementation, which imparts to the sandstone a moderate degree of strength, the beds are extremely permeable ranging from 1000 up to 15000 md. Porosity, however, is not particularly high at 20-25 per cent. The sandstone is one of the best examples in this country of a coarse clean sand in which cementation has to a large extent only occurred at the contact points of the individual grains. As the sands are, on the whole, relatively well graded, this has led to the presence of well defined pore channels of quite large dimensions; but the cementation has also had the effect of significantly reducing porosity while at the same time, greatly, strengthening the formation. The petrophysics of these sandstones contrast strongly with less well graded uncemented Triassic sands, for instance, the Bunter formation in Nottinghamshire in which permeability has much the same magnitude, but porosity is slightly higher owing to the absence of cementation.

A few of the samples from this area were markedly fine and coarse laminated in much the same manner as some beds from the Upper Mottled Sandstone subdivision. The texture is responsible for great anisotropy, eg samples 757-1 and 758-2. These rock types are, however, rather uncommon, and the bulk of the clean medium sands of the Keuper are isotropic.

Owing to the superior strength of the sandstone, jointing is more widespread and less random in occurrence than in the other sandstones of the Permo-Trias sequence in the area. This factor, coupled with the magnitude of the intergranular permeability, should result in high transmissivity.

AREA 5

Formation : KEUPER SANDSTONE & KEUPER CONGLOMERATE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
332 V1	m-c cn fr lt br sd	Overton Scar, Kidnall Cheshire	SJ 47304926	o/c	2851	2.26	23.0	
V2				..	2215	2.27	22.4	
H64				..	2043	2.27	22.1	
H154				..	2588	2.26	22.7	
333 V				o/c	1865	2.29	21.3	
H1-52				..	3658	2.27	22.3	
H2-52				..	2704	2.28	21.7	
H142				..	3358	2.28	21.7	
339 V1	m pk lam fels sd con cs	Peckforton Hill, Ches	SJ 52675580	o/c	211	2.28	23.4	
V2				..	715	2.29	22.7	
V3				..	245	2.31	21.8	
H1-290				..	380	2.30	23.5	
H2-290				..	2668	2.24	25.4	
H1-20				..	550	2.29	23.0	

AREA 5

Formation : KEUPER SANDSTONE & KEUPER CONGLOMERATE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
352 V1	br wg m sd cm-fr	Helsby Hill, Helsby, Cheshire	SJ49117541	o/c	1605	2.23	24.7	
V2				..	2659	2.23	24.8	
H1-95				..	2138	2.25	23.7	
H1-185				..	2297	2.24	24.5	
H2-185				..	2310	2.24	24.1	
463-1V	f lam con r sd	Partington B.H., Manchester (N.W.G.B)		5.8–6.7m	6	2.28	21.3	
1HX				..	299	2.22	25.2	
1HY				..	101	2.27	22.3	
463-2V	m cn fels pk-gy sd			24.4–25.9m	1840	2.29	21.3	
2HX				..	4994	2.23	24.8	
2HY				..	3905	2.23	24.4	
367 V1	l bf con sd m-c cn fels	New Mersey Tunnel Approach, Poulton, Wallasey	SJ30359119	o/c	2679	2.22	25.5	
V2				..	2758	2.23	24.8	
HX1				..	2690	2.22	25.1	

AREA S   Formation : KEUPER SANDSTONE & KEUPER CONGLOMERATE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
367 HX3	l bf con sd m-c cn fels	New Mersey Tunnel Approach, Poulton, Wallasey.	SJ 30359119	o/c	3397	2.23	24.8	
H41				"	2233	2.22	25.5	
H42				"	2502	2.22	25.2	
H43				"	2442	2.22	25.2	
368 V	bf m-c wc fels sd		SJ 30089125	o/c	299	2.30	20.2	
H 90				"	589	2.30	20.4	
H 180				"	860	2.30	20.7	
369 V	m-c wc cn bf sd			o/c	3299	2.29	21.1	
H0				"	3732	2.28	21.3	
374 V	bf m wg con fels sd	Scarth Hill, Ormskirk Lancs	SD 42960661	o/c	3423	2.26	23.2	
H 244				"	2353	2.25	23.5	
H1-334				"	4315	2.26	23.3	
H2-334				"	-	2.26	23.3	
381 V	f-c l cn lam bf sd	Brynlow Hill, Alderley Edge, Cheshire	SJ 855772	o/c	4603	2.33	22.1	

AREA 5

Formation: KEUPER SANDSTONE & KEUPER CONGLOMERATE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
381 H1-110	f-c cn lam bf sd	Brynlow Hill, Ches.	SJ855772	o/c	4526	2.36	20.8	
382 H1-30S	m-c pb con br sd	Alderley Edge, Cheshire	SJ861776	o/c	4601	2.26	22.8	
H2-30S				..	3483	2.27	23.4	
498 V1	cn c wg fr-con pk-gy sd	Central Station, Liverpool	SJ35168999	o/c	6799 *	2.20 *	27.2 *	
V2				..	16248	2.17	28.7	
H30				..	5988	2.20	27.0	
H120				..	4877	2.20	27.1	
499 V1				o/c	1413 *	2.24 *	24.3 *	
V2	f-m con pk sd			..	2294	2.22	27.4	
H30	m-c cn r sd			..	6740	2.19	27.4	
H120				..	5313	2.20	26.9	
757-1V	m-c lam cn wc Y fels sd	British Rail BH 10, Liverpool	SJ34919072	20.1m	8624	2.21	26.5	
1H				..	>23000	2.18	28.5	
757-2V	f-c lam cn con			21.0m	2754	2.23	25.2	

AREA 5

Formation : KEUPER SANDSTONE & KEUPER CONGLOMERATE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
757-3V	vf-c lam pk-y wc sd	British Rail BH 10 Liverpool	SJ34919072	21.9 m	13	2.25	24.2	
3H				"	45	2.26	23.5	
757-4V	vf-c lam wh wc sd			22.9 m	<1	2.31	20.9	
4H				"	28	2.27	22.9	
757-5V	f-c lam pk sd			23.8 m	802	2.29	20.0	
5H	vf-f lam wc pk sd			"	206	2.24	24.8	
757-6V	f-c lam fels pk-gy sd			24.7 m	871	2.22	26.1	
6H				"	5649	2.19	27.8	
758-1V	f-m fr y sd fels	British Rail BH 12, Liverpool.	SJ 35199046	28.0 m	1888	2.17	29.0	
1H				"	3325	2.11	32.3	
758-2V	f-c lam fels y sd			29.9 m	878	2.23	25.3	
2H				"	3634	2.25	24.2	
758-3V	fr cn wg m o sd			31.7 m	7811	2.15	30.2	
3H				"	12162	2.14	30.7	

BUNTER SANDSTONE (Undivided) AREA 6

Within the undivided Bunter Sandstone of this area, extending from Doncaster in the south to the coast at West Hartlepool in the north, there is a general tendency for the sandstone units to become finer in a northward direction and this is demonstrated well by the core analysis data presented on the accompanying data sheets. South of York, the sandstones are on the whole medium to coarse grained, friable in nature, ranging in colour from pale grey to brownish red. Many of the core samples from boreholes in the Doncaster-York area (see Fig.24) have a high intergranular permeability approaching the maximum reported for sandstones. The results from the Hatfield Woodhouse, Highfield Lane and Finningley B.Hs (Nos. 485-7) show very high values approaching or exceeding 10000 md. There is, however, a marked tendency for these values to reduce at depth, as the sandstones become more fine grained at lower levels in the Bunter Sandstone. However, samples of the sandstone from deep boreholes drilled in the east of the area (Nos. 155, 166 and 178) suggest that the sandstone has a significant intergranular permeability (up to 2000 md) even at depths of 300 m below surface. As a general rule, the fine sandstones have a permeability of 2-300 md, medium sands range up to 2-3000 md and coarse sandstones up to 10-15000 md

The presence of mudflakes, eg. in sample 155-3 reduces k values in coarse sandstones, but on the whole it is the grain size which is the controlling factor. There is no evidence to suggest that the grey or greenish grey sandstones differ in their physical properties from the red members of the sequence.

To the north of York, the sandstones become noticeably more indurated and the coarse units die out. The bulk of the material consists of fine grained red or grey sandstones with permeability seldom exceeding 1000 md. Some units are well cemented, with permeability reducing to zero. Lack of borehole material has resulted in a picture which may not truly represent conditions at depth, where calcareous cementation is expected to be more widespread.

As will be seen from the data sheets, south of York the sandstone is characterised everywhere by moderate to high porosity owing to the general lack of cementation and the friable nature of the formation. High porosity is particularly noticeable in the shallower borehole samples. Fine, medium and coarse samples show porosity as high as 30-34%, with values of saturated density as low as 2.04 gms cc^{-1}, even at depths of about 300 m. In most of the deep boreholes, however, porosity is reduced to 22-25% with the saturated bulk density rising to 2.28 gms cc^{-1}. In the lowest levels of the formation near the junction with the underlying Middle Permian Marl, fine grained basal sandstones show a reduced porosity as low as 22.9% and increased saturated density reaching 2.29 gms cc^{-1}.

North of York, the physical property data suggests that the fine grained sandstones found close to the Permian junction in the south expand at the expense of the upper coarser units. The dominantly brownish red sandstones of the Vale of York and Teesside have a saturated density which exceptionally reaches 2.51 gms cc^{-1} (No.538) with porosity as low as 9.6%. As a general rule, porosity is about 27% and saturated density about 2.18 gms cc^{-1}.

AREA 6 Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
155-1H	m sd gy v	Westwoodside B.H.,	SE 74310027	63.4m	265	2.15	30.7	
155-2HX	m sd gy v	Haxey, Yorks		65.3m	293	2.15	30.5	
2HY	c sd lam			..	-	2.12	32.2	
155-3V	c gy sd fr with mud flakes			73.2m	372	2.23	27.3	
3HX1				..	749	2.24	26.6	
3HX2				..	469	2.22	27.4	
3HY1				..	260	2.32	23.7	
3HY2				..	703	2.26	26.3	
155-4V	m gn-gy mic sd			75.6m	1358	2.10	33.2	
4H				..	2115	2.11	32.7	
155-5H1	fr m gy mic sd			92.4m	1974	2.12	32.4	
5H2				..	2021	2.10	33.6	
155-6H	m gy sd			115.9m	1748	2.11	32.9	
155-7HX	m-c gy sd fr			128.7m	7689	2.08	34.6	

AREA 6 Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
155-8V	lt gn-r mic slt or f sd	Westwoodside B.H., Haxey, Yorks	SE74310027	133.8m	-	2.25	24.3	
8HX				..	15	2.28	22.4	
155-9V	c pk sd with thin mud flakes			133.8m	1193	2.13	31.4	
9HX1				..	4794	2.12	32.6	
9HX2				..	7490	2.11	33.5	
9HY1				..	4899	2.11	33.3	
9HY2				..	5115	2.10	34.0	
166-1HX	f lt br sd	Crowle B.H., Yorks	SE77731199	105.4m	2651	2.10	33.7	
1HY1				..	2703	2.08	34.0	
1HY2				..	2703	2.08	33.5	
166-2V1	f lt br sd			114.8m	484	2.12	31.0	
2V2				..	439	2.13	30.8	
2HX				..	1063	2.13	30.8	
2HY1				..	1116	2.13	30.8	

AREA 6

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
166-3HX	vf lt br sd mic	Crowle B.H., Yorks	SE 77731199	124.8m	30	2.23	25.0	
3HY1				..	36	2.23	25.4	
3HY2				..	37	2.25	23.6	
166-4HX	f lt br mic sd.			140.3m	172	2.18	28.2	
4HY				..	204	2.18	27.8	
166-5H1	f lt br mic sd.			145.5m	276	2.18	27.9	
5H2-1				..	227	2.18	28.1	
5H2-2				..	217	2.18	28.3	
166-6HX	m-c lt br fr sd			197.6m	7706	2.11	32.9	
6HY				..	9042	2.09	34.1	
166-7HX	f-m lt br sd			205.0m	1530	2.14	30.8	
7HY				..	1644	2.12	31.5	
166-8H1	m con pk sd lam			297.4m	1026	2.21	27.3	
8H2				..	1602	2.20	27.9	

AREA 6

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
170H1	m-c fr sd	Hatfield No.2 B.H., Doncaster	SE67250673	91.5m	2423	2.13	30.9	
H2				"	1205	2.11	32.4	
178-1V	f lt r sd with cement clots	Bank End B.H., Haxey, Yorks	SK70639972	307.4m	242	2.19	27.7	
1HX1				"	451	2.19	27.8	
1HX2				"	521	2.19	28.2	
1HY1				"	429	2.20	27.3	
1HY2				"	409	2.21	26.9	
178-2V1	f-m lt r sd			310.5m	910	2.20	27.5	
2V2				"	1320	2.18	28.7	
2HX				"	1669	2.17	29.5	
2HY1				"	1864	2.15	30.4	
2HY2				"	1735	2.16	29.9	
178-3V1	con f r sd with cement clots			313.5m	87	2.21	26.7	
3V2				"	97	2.21	26.9	
[illegible]					[illegible]	[illegible]	[illegible]	

AREA 6

Formation : BVNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
178-3H1-2	con f r sd	Bank End B.H.,	SK70639972	313.5m	94	2.24	25.2	
178-4H1-1	vf lam gy	Haxey, Yorks		314.3m	70	2.27	23.2	
4H1-2	sd			..	87	2.26	24.1	
182-1V1	vf con	Whitemoor B.H.,	SE66743584	244m	18	2.29	22.9	
1V2	sd br-r	Selby, Yorks		..	18	2.29	23.1	
1HX1				..	266	2.28	23.5	
1HX2				..	98	2.28	23.7	
1HX3				..	91	2.28	23.7	
1HY1				..	–	2.29	23.2	
182-2V1	con r slt			294.6m	32	2.27	25.5	
2V2				..	35	2.26	25.7	
2HX				..	66	2.28	25.0	
2HY				..	76	2.28	24.8	
184-1HX	m fr gy	Poppleton Road B.H.,	SE57675302	18.2m	2838	2.14	31.0	
[illegible]	sd	York			[illegible]	[illegible]	[illegible]	

AREA 6 Formation: BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
184-2HX1	m lt br sd	Poppleton Road B.H., York.	SE57675302	93.9m	1682	2.15	30.6	
2HX2				"	1347	2.16	30.1	
2HY				"	1578	2.17	28.6	
186-1HX	con f sd	Northallerton B.H., N.R. Yorks	SE36279347	112.9m	480	2.25	24.1	
186-2HX1	wc f r sd with mud flakes			119.0m	292	2.27	23.4	
2HX2				"	226	2.29	22.7	
188V	con f r sd	Sappers Corner B.H., Greatham, Co. Durham	NZ49052836	20.7m	2	–	–	
HX				"	266	2.24	25.5	
483V	f-m r sd fr	Armthorpe No.1 B.H., Doncaster	SE63040591	not deeper than 90m	174	2.19	27.1	
HX					1236	2.20	26.3	
HY				"	1373	2.21	25.8	
484-1V	m fr r sd	Lings Plantation No.3 B.H. Hatfield, Yorks	SE65240810	34.8m	–	2.04	34.1	
484-2V	f-m lt br sd			65.5m	1158	2.19	27.1	
2HX				"	2037	2.15	29.2	

AREA 6

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
484-4V	f-m lam lt r sd	Lings Plantation No.3 B.H. Hatfield.	SE 65240810	114.3 m	135	2.22	25.3	
4HX				"	305	2.22	25.4	
4HY				"	369	2.22	25.2	
485-1V	fr m r sd	Hatfield Woodhouse B.H. Doncaster	SE 685 097	c.33.5 m	2112	2.20	27.1	
1HX				"	2669	2.21	26.4	
1HY				"	3081	2.22	26.2	
485-2V	c lt br sd			c.36.6 m	1508	2.17	28.9	
2HX				"	6410	—	—	
2HY				"	5014	2.15	29.7	
485-3V	c fr lt br sd			c.45.7 m	7560	2.11	31.4	
3HX				"	11571	2.12	32.0	
485-5V	m-c lam fr sd			91.1 m	1016	2.15	30.4	
5HX				"	10456	2.12	31.5	
5HY				"	3844	2.14	30.9	
485-[illegible]	f-m fr sd			105.[illegible]	[illegible]	2.15	[illegible]	

AREA 6

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
485-6HX	f-m fr lt br sd	Hatfield Woodhouse B.H. Doncaster.	SE685097	105.2m	2757	–	–	
6HY				..	4757	2.14	30.9	
485-7V1	fr m lt br sd			114.3m	2343	2.14	30.4	
7V2				..	2341	2.15	29.8	
7HX				..	6354	2.13	30.3	
7HY				..	3895	2.14	30.3	
485-9V	f-m lt br sd			152.4m	1007	2.18	29.3	
9HX				..	1371	2.17	29.2	
9HY				..	1410	2.16	29.7	
485-10V	f pk sd with cement clots			231.7m	740	2.14	31.0	
10HX				..	2963	2.16	30.3	
10HY				..	1047	2.16	29.9	
485-5H				91.1m	6108 *	2.13 *	31.7 *	
486-1V	fr m-c lt br sd	Highfield Lane B.H., Doncaster	SK65989536	30.5m	6843	2.07	34.3	
1HX					[illegible]	[illegible]	[illegible]	

AREA 6 Formation: BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
486-1HY	fr m-c sd	Highfield Lane B.H., Doncaster	SK65989536	30.5m	16155	2.07	34.8	
486-2V	fr c lt br sd			c. 81m	10353	2.10	32.5	
2HX				"	10303	-	-	
2HY				"	10491	-	-	
486-3V	fr m-c sd				3819	2.17	29.2	
486-4V	f lt br sd			91.4m	729	2.17	28.8	
4HX				"	1038	2.17	28.3	
4HY				"	1412	2.17	28.6	
486-6V	c lt br sd			c.122 m.	5220	2.11	32.3	
6HX				"	7683	2.10	32.4	
6HY				"	8621	2.11	32.3	
486-7V	f-m lt br sd			137.2m	933	2.18	28.6	
~~7HX~~				"	—	—	—	—
486-8V	fr m lt br sd			c 168m	1787	2.15	30.6	

AREA 6

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
486-8HY	m lt br sd	Highfield Lane B.H., Doncaster	SK 65989536	c 168 m	3673	2.16	30.5	
486-9V	f lt br sd			c.159 m	364	2.16	29.7	
9HX				"	588	2.17	29.2	
9HY				"	1073	2.20	27.7	
486-10V	fr f-m lt br sd			152.4 m	1759	2.12	31.5	
10HX				"	2077	2.12	31.9	
10HY				"	2122	2.12	31.5	
487-1V1	fr c lt br sd	Finningley No.3 B.H., Doncaster	SE 67640006	Near surface	5177	2.13	30.7	
1V2				"	3451	2.13	30.7	
1HX				"	4487	2.14	30.4	
1HY1				"	4425	2.16	29.5	
1HY2	c bf fr sd			"	11905	2.08	33.6	
487-3HX	f-c lam sd			c. 183 m	2486	2.15	29.6	
487-4V	fr c lt br sd			"	8693	2.10	31.7	
[illegible]					[illegible]			

AREA 6

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
488-1V	fr c bf sd	Littleworth B.H., Doncaster, Yorks	SK63709829	c.30.5m	10555	2.07	34.4	
1HX				..	14935	2.06	34.9	
1HY				..	16740	2.06	35.1	
488-2V	fr c bf sd			..	7586	2.08	32.9	
2HX				..	7044	2.11	32.0	
2HY				..	9027	2.10	32.0	
488-4V1	fr c bf sd			between 73.2 & 167.6m	5614	2.13	31.4	
4V2				..	6827	2.11	31.8	
488-5V	f lt br sd			..	343	2.15	29.8	
5HX1				..	350*	2.19*	28.6*	
5HX2				..	632	2.17	29.2	
5HY				..	938	2.16	29.3	
488-6V	f lt br sd			..	1196	2.12	31.6	
6HX				..	1189	2.13	31.6	

AREA 6 Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
488- 7V	f lt br sd	Littleworth B.H, Doncaster, Yorks	SK63709829	between 73 & 167.6m	181	2.19	28.5	
7HX1				..	–	–	–	
7HX2				..	284	2.19	28.4	
488- 8V	f lt br sd with cement clots			..	324	2.19	28.3	
8HX				..	349	2.16	29.7	
8HY				..	322	2.17	29.3	
501- 1V1	c pb lt br sd	Boston Park Farm B.H., Doncaster	SE 677 045	39.6m	9581	2.21	26.8	
1V2				..	1365	2.25	24.8	
1HX				..	2294	2.22	26.1	
1HY				..	3794	2.20	27.0	
501- 4V1	c lt br sd			97.8m	1218	2.20	27.2	
4V2				..	1032 *	2.23 *	25.5 *	
4HX				..	3116	2.21	26.1	
4HY				..	5384	2.17	28.4	
501- 5V				113.2[illegible]	[illegible] *	2.1[illegible] *	[illegible] *	

AREA 6

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
501 - 6V	f-m lt br sd.	Boston Park Farm B.H. Doncaster	SE 677 045	132.0m	226	2.16	28.8	
6HX				..	54	2.15	29.6	
6HY				..	1043	2.14	30.1	
501 - 7HX	f-c lam sd			144.5m	8626	2.17	23.6	
501 - 8V	fr f-m lam sd.			154.5m	591	2.17	28.0	
8HX				..	2203	2.17	27.8	
8HY				..	-	2.16	28.5	
501 - 9V	fr f-m sd			177.7m	1861	2.12	30.4	
501 - 11V1	f lt br sd with cement clots			204.2m	494	2.14	31.0	
11V2				..	299*	2.15*	31.6*	
11HX				..	463	2.16	31.1	
501 - 12V	lt gn-r f sd			207.0m	29	2.26	23.3	
12HX				..	93	2.27	22.7	
12HY				..	26	2.28	22.3	

AREA 6 Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
501- 13HX	dk r f sd	Boston Park Farm B.H., Doncaster	SE 677045	209.7m	18	2.24	25.7	
13HY				..	25	2.24	25.4	
501- 14V	gn-gy f-m sd with cement clsts			221.3m	224	2.20	26.8	
14HX				..	313	2.19	27.0	
14HY				..	356	2.19	27.2	
501- 15V	f r sd with cement clsts			225.9m	73	2.21	26.9	
15HX				..	166	2.20	27.3	
15HY				..	141	2.20	27.4	
519 V1	m br-r sd fr	South Yard, Doncaster Station, Yorks	SE 5714 0239	o/c	3051	2.08	33.8	
H90				..	4093	2.09	33.6	
H180				..	4054	2.09	33.9	
520 V	fr c lt br sd	Cutting on Doncaster–Gainsborough Railway	SE 6212 0024	o/c	–	2.01	35.3	
523 V	fr dk br m sd	Hambleton Haugh, Selby, Yorks	SE 5546 2986	o/c	–	2.07	34.4	

AREA 6

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
523 H 153	fr dk br m sd	Hambleton Haugh, Yorks	SE 55462986	o/c	8115	2.09	33.7	
524 V	fr dk br m sd	Brayton Barff, Yorks	SE 58563044	o/c	-	2.07	34.2	
525 V	fr m·r sd	Bilbrough, Yorks	SE 53224591	o/c	9734	2.04	36.2	
HX				..	10975	2.04	36.3	
HY				..	8388	2.05	36.3	
526 V	f-m r sd	Cutting on York – Knaresborough Railway at Cattal, Yorks	SE 45395587	o/c	451	2.15	30.5	
H121				..	1787	2.14	31.1	
H211				..	696	2.13	30.6	
527 V	f-m r sd			o/c	1958	2.08	34.4	
H156				..	3833	2.07	35.5	
H 246				..	2701	2.08	34.9	
528 V	f-m r sd		SE 45385587	o/c	680	2.15	31.0	
H94				..	1341	2.14	31.3	
H184				..	1246	2.15	30.5	

AREA 6 Formation: BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
529 V2	f-m r sd	Chapel Hill, Aldborough, Yorks.	SE 40436607	o/c	1069	2.16	30.2	
H1-26				"	1025	2.16	30.1	
H2-26				"	1387	2.17	29.6	
H116				"	1716	2.16	30.2	
530 V	m bf sd	Quarry beside A61 Ripon, Yorks	SE 32107240	o/c	585	2.16	30.2	
HX				"	829	2.16	29.9	
HY				"	1029	2.16	29.6	
531 V	~~m~~ f r sd con			o/c	15	2.28	22.8	
H169				"	34	2.28	23.1	
H259				"	32	2.29	22.6	
532 V	f con r sd	River Swale at Catton, Yorks	SE 36807779	o/c	14	2.32	20.3	
H140				"	32	2.32	20.6	
H230				"	75	2.32	20.6	
533 V	f-m cs r sd			o/c	1071	2.15	29.2	
[illegible]						[illegible]	[illegible]	

AREA 6 Formation: BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density $g\,cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
533 H116	f-m cs r sd	River Swale at Catton, Yorks	SE 36807779	o/c	1315	2.16	29.2	
534 V	f con r sd	River Tees at Croft, N.R. Yorks.	NZ 29040998	o/c	269	2.17	28.7	
H1-30				..	493	2.15	29.4	
H2-30				..	291	2.17	28.5	
H120				..	294	2.16	28.7	
535 V	f pk cs sd			o/c	102	2.18	27.7	
H 231				..	524	2.16	29.2	
H 321				..	301	2.17	28.4	
536 V	gy wc f sd	River Tees at Over Dinsdale, Yorks	NZ 35191101	o/c	37	2.37	17.6	
H 64				..	29	2.39	16.4	
H154				..	26	2.35	18.6	
537 V	wc pk mic slt		NZ 35201099	o/c	12	2.34	19.4	
HX				..	44	2.38	17.0	
HY				..	99	2.34	19.3	

AREA 6 Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
538 V	wc pk f sd	River Leven, nr. Middleton-on-Leven, N.R. Yorks.	NZ 4586 0958	o/c	6	2.45	13.0	
H 35				..	29	2.42	14.9	
H 125				..	13	2.51	9.6	
539 V	gn-gy f sd	Quarry at Ingleby Barwick, N.R. Yorks	NZ 4354 1534	o/c	50	2.21	26.2	
H 34				..	99	2.20	26.6	
H124				..	96	2.20	26.5	
540 V	gn-gy cav f sd cs			o/c	41	2.22	26.0	
HX				..	54	2.23	24.6	
HY	m gn-gy sd			..	521	2.20	27.0	
541 V	f pk cs sd	Little Scar, Seaton Carew, Co. Durham	NZ 5265 3036	o/c	261	2.21	26.1	
H 231				..	484	2.21	25.9	
H 321				..	632	2.20	26.5	
542 V	wc gn-gy f-m sd		NZ 5262 3045	o/c	14	2.31	20.8	
HX				..	259	2.32	20.4	
[illegible]						[illegible]	[illegible]	

To the north of Barrow-in-Furness, the northward continuation of the Bunter Sandstone of Lancashire is referred to as St.Bees Sandstone. This formation has been found to be characterised by low to very low permeability, and low to moderate porosity. In general the properties are much lower in value than the Bunter farther south in Area 7, although the overall range is quite similar, especially for porosity and density.

The most permeable sandstones are medium grained with patchy cementation which may result in a slightly cavernous appearance under the microscope. In these, permeability may range up to several hundred millidarcies with porosity about 22-25 per cent (e.g. 751-3 and 751-23). The majority of the sandstones, however, are more uniformly cemented, frequently laminated and generally fine grained. In these, typical values are from 30 md down to 0.3 md permeability, and from 12 to 20 per cent porosity. Permeability anisotropy is noticeably high in these sands (750-5, 751-15), but owing to the low magnitude of the permeability is probably of very little practical significance. Finally, at the low end of the scale are very fine grained well-cemented sandstones with permeability as low as 10^{-3} md and porosity ranging as low as 4 per cent (751-41 and 751-43).

In summary, the St.Bees in this area displays a spectrum of gradational lithological types, and the physical property values vary accordingly.

AREA 7

Formation : ST BEES SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
395 V1	vf-f wc fels pk sd	Townend Quarry, Ponsonby, Cumberland	NY 0549 0610	o/c	30	2.26	23.2	
V2				..	43 *	2.26 *	23.4 *	
H196				..	38	2.26	23.0	
H286				..	33	2.26	23.1	
396 V	vf lam wc r sd	Prirling, Calder Bridge, Cumberland	NY 0560 0688	o/c	0.8	2.34	18.3	
H62				..	20	2.32	17.8	
H152				..	6	2.35	19.2	
397 V1	wc vf fels lam pk sd	Grange Quarry, Egremont, Cumberland	NY 0308 1022	o/c	<1	2.41	15.0	
V2				..	<1	2.41	14.9	
H126				..	2	2.41	14.5	
H216				..	2	2.42	14.4	
398 V1	slt-f sd r wc lam	South Head, St Bees, Cumberland	NX 952 118	o/c	<1	2.44	6.3	
V2				..	<1 *	2.46 *	10.4 *	
H-17				..	<1	2.44	10.4	

AREA 7

Formation : ST BEES SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
398 H 287	r wc slt	South Head, St Bees	NX952 118	o/c	<1	2.46	3.7	
750-1V	f-m we lam br sd	Low Prior Scales B.H., Calder Bridge, Cumbs (WRB B.H. 1B)	NY0579 0725	12.9 m	0.25	2.36	19.3	
1H				"	2.9	2.36	17.6	
750-2V	m we lam br sd mdst flakes			15.3 m	1.8	2.32	20.7	2.3
2H				"	11	2.34	20.2	
750-3V	f we lam br sd cs			16.0 m	0.20	2.63	11.6	0.48
3H				"	1.3	2.67	11.8	
750-4V	f-m we br sd			16.7 m	1.1	2.43	14.0	
4H				"	39	2.29	22.0	
750-5V	f-m we br mic sd			17.5 m	4.2	2.33	19.2	
5H				"	16	2.33	19.0	
750-6V	f we br lam fels sd cs			18.4 m	0.36	2.46	13.0	
6H				"	1.4	2.46	13.7	
750-7V	m lam wc br sd cs			19.5 m	4.5	2.31	21.1	

AREA 7 Formation : ST. BEES SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
750-8V	m cav lam br sd cs patchy cement	Low Prior Scales B.H., Calder Bridge, Cumbs (WRB B.H. 1B)	NY05790725	23.2m	41	2.28	22.4	
8H				..	41	2.29	21.0	
750-9V	f-m wc br sd			27.3m	7.2	2.34	18.5	
9H				..	4.6	2.35	17.8	
750-10V	f wc lam br sd cs			30.6m	0.04	2.51	8.6	
10H				..	0.02	2.46	9.6	
750-11V	m wc br sd whcement			33.9m	6.6	2.38	15.2	
11H				..	8.6	2.38	15.8	
750-12V	m wc br sd v dk br staining			36.1m	2.0	2.32	19.9	
12H				..	2.1	2.56	21.0	
750-13V	m br lam sd cav with patchy cement cs			36.7m	3.1	2.34	17.5	4.8
13H				..	46	2.31	20.1	
750-14V	m lam br sd patchy cement			39.8m	23	2.31	20.2	10.1
14H				..	18	2.34	18.5	
[illegible]	f-m wc br			[illegible]	[illegible]	[illegible]	[illegible]	

AREA 7 Formation : ST BEES SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
750-15H	f-m we br sd small lam	Low Prior Scales B.H., Calder Bridge, Cumbs. (WRB B.H. 1B)	NY05790725	41.6m	5.0	2.35	17.4	
750-16V	f-m we br lam sd cs			44.9m	0.30	2.48	13.4	
16H				..	0.29	2.40	15.3	
750-17V	f-m we br lam cav sd small mdst flake			46.0m	0.48	2.39	16.1	
17H				..	1.1	2.39	15.0	
750-18V	f lam we br sd cs dk br horizontal staining in band			47.2m	0.10	2.50	9.1	
18H				..	0.08	2.46	11.4	
750-19V	f lam we br sd cs dk br staining in horizontal bands			48.0m	0.64	2.41	15.2	
19H				..	0.32	2.43	14.3	
750-20V	f we lt br lam sd			51.6m	0.29	2.48	11.0	
20H				..	0.45	2.49	10.1	
750-21V	vf-f we lam sd lt br			53.0m	0.24	2.45	12.3	
21H				..	0.20	2.50	9.0	
750-22V	f we br sd small calcite vein			57.4m	0.09	2.46	12.6	

AREA 7

Formation : ST. BEES SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
750-23V	g^{n}_{b} p wc	Low Prior Scales B.H. Calder Bridge, Cumb. (WRB B.H. 1B)	NY05790725	59.8m	0.48	2.58	7.6	
23H				..	0.58	2.60	7.2	
751-1V	f-m lam br sd	Robertgate Bridge B.H., Beckermet, Cumb. (WRB B.H. 2B)	NY04610746	13.3m	23	2.30	21.4	
1H				..	29	2.29	22.0	
751-2V	vf-f fels br sd			13.7m	0.06	2.32	13.9	
2H				..	0.05	2.45	13.4	
751-3V	m br mic sd patchy cement.			15.9m	162	2.29	21.5	12.9
3H				..	160	2.29	21.6	
751-4V	m br sd wh patchy cement			17.1m	78	2.34	18.4	
4H				..	94	2.32	19.6	
751-5V	f-m br sd			18.0m	0.49	2.34	19.0	
5H				..	54	2.31	20.4	
751-6V	f wc fels br sd small patches [illegible]			21.3m	0.06	2.43	13.3	
[illegible]					[illegible]	[illegible]	[illegible]	

AREA 7 Formation : ST. BEES SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
751-7V	f-m we lam br sd patches of ? fermg minerals	Robertgate Bridge B.H., Beckermet, Cumb (WRB B.H. 2B)	NY04610746	22.8m	0.52	2.33	19.6	
7H				..	0.18	2.40	15.8	
751-8V	m fels br sd			23.1m	18	2.27	23.0	13.5
8H				..	197	2.26	23.8	
751-9V	m fels br sd patchy cement mdst flake			24.2m	7.5	2.24	24.4	
9H				..	204	2.24	24.6	
751-10V	vf we mic br sd			24.9m	0.10	2.41	15.2	
10H				..	0.10	2.45	13.2	
751-11V	f we br sd			27.1m	1.6	2.31	21.0	
11H				..	8.5	2.29	22.3	
751-12V	f-m br sd			29.6m	0.60	2.34	19.2	
12H				..	0.68	2.35	18.7	
751-13V	f-m mic br sd cs			31.2m	0.08	2.43	14.0	0.41
13H				..	0.04	2.42	14.5	
	f-m mic							

AREA 7 Formation : ST. BEES SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
751-14H	f-m mic br sd	Robertgate Bridge B.H., Beckermet, Cumb (WRB BH 2B)	NY04610746	31.9m	29	2.26	24.2	
751-15V	m mic br cs sd wh cement			33.6m	0.99	2.44	13.4	
15H				"	12	2.41	14.6	
751-16V	f-m felds br sd wh cement mdst flake			34.1m	2.0	2.42	13.9	
16H				"	4.3	2.41	14.5	
751-17V	m fels br sd cs wh cement			34.7m	4.1	2.64	13.3	
17H				"	8.8	2.46	12.6	
751-18V	vf-f wc mic br sd			35.3m	0.02	2.46	12.3	
18H				"	0.02	2.46	11.6	
751-19V	f-m fels br sd small mdst flake "			36.9m	15	2.36	17.9	
19H				"	23	2.41	14.9	
751-20V	f-m wc br fels sd			38.1m	0.42	2.38	16.7	
20H				"	4.7	2.40	15.0	
751-21V	m wc br sd wh cement			39.0m	1.2	2.46	12.0	

AREA 7

Formation : ST. BEES SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
751-22V	f-m mic br sd cav patchy cement	Robertgate Bridge B.H., Beckermet, Cumb (WRB B.H. 2B)	NY 04610746	39.6m	1.6	2.33	19.0	
22H				"	1194	2.21	26.0	
751-23V	m mic fels br sd patch cement			42.6m	330	2.26	22.9	
23H				"	296	2.26	23.8	
751-24V	f wc lam br sd patches of ?ferrug minerals			43.0m	$< 10^{-3}$	2.45	13.2	0.12
24H				"	0.42	2.43	14.1	
751-25V	m br sd			44.5m	31	2.33	19.1	9.5
25H				"	83	2.33	19.1	
751-26V	m mic br sd			45.5m	7.7	2.35	18.5	
26H				"	6.9	2.39	15.7	
751-27V	m br mic sd small mdst flakes			47.9m	33	2.30	21.1	
27H				"	62	2.32	20.3	
751-28V	f-m mic br sd lam			51.9m	2.5	2.41	14.8	
28H				"	14	2.40	15.1	

AREA 7 Formation : ST. BEES SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
751-29H	f-m we br sd wh cement	Robertgate Bridge B.H., Beckermet, Cumb. (WRB BH 2B)	NY04610746	52.7m	27	2.40	14.7	
751-30V	f-m we br fels sd			53.3m	103	2.30	20.7	
30H				..	203	2.31	20.5	
751-31V	f-m we fels br sd small mdst flakes			55.2m	0.03	2.47	8.6	
31H				..	0.04	2.47	8.9	
751-32V	f mic lam br sd			57.0m	0.15	2.41	14.8	
32H				..	0.83	2.38	16.7	
751-33V	f mic lam brsd band of dk br ? ferrug minerals			57.9m	0.09	2.48	11.1	
33H				..	0.06	2.47	11.4	
751-34V	m br sd fels small cav due to patchy cement			59.3m	147	2.25	24.0	
34H				..	319	2.24	24.4	
751-35V	m mic br sd patchy wh cement			62.2m	37	2.29	21.2	
35H				..	263	2.29	21.1	
751-36V	f-m we mic fels br sd small mdst			63.8m	19	2.31	20.2	

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Formation : ST. BEES SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
751- 37V	f-m we br mic sd	Robertgate Bridge B.H., Beckermet, Cumb. (WRB B.H. 28)	NY 0461 0746	65.9m	5.6	2.40	15.7	
37H				"	8.5	2.39	15.3	
751- 38V	f we mic br sd			68.6m	0.96	2.41	15.0	
38H				"	2.0	2.42	14.1	
751- 39V	vf-f we fels cs br sd			69.4m	$< 10^{-3}$	2.44	10.8	
39H				"	$< 10^{-3}$	2.41	10.9	
751- 40V	f-m we fels br sd wh cement small mdst flake			71.7m	26	2.39	15.4	7.5
40H				"	39	2.39	15.2	
751- 41V	vf-f we mic br sd wh cement			72.8m	$< 10^{-3}$	2.51	5.3	0.19
41H				"	0.07	2.53	4.2	
751- 42V	m br sd with f bands dk br. m cn patch on H sample			74.0m	25	2.28	23.3	
42H				"	1464	2.21	27.2	
751- 43V	f we br banded sd ? Fe Mg minerals patches of wh cement			75.7m	$< 10^{-3}$	2.51	7.2	0.02
43H				"	0.007	2.47	8.3	
751- 44V	f-m we (wh) br sd small [illegible]			78.2 [illegible]	10	2.45	12.4	

AREA 7

Formation : ST. BEES SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
751- 44H	f-m wc(wh) br fels sd	Robertgate Bridge B.H., Beckermet, Cumb. (WRB B.H. 2B)	NY04610746	78.3m	47	2.40	15.2	
751- 45V	dk br mic slt - vf sd			79.0m	$<10^{-3}$	2.54	9.6	0.40
45H				..	2.6	2.55	9.1	
751- 46V	f-m wc(wh) br sd small mdst flake			80.4m	2.3	2.46	12.0	
46H				..	14	2.47	11.5	
751- 47V	f-m wc mic sd			82.9m	0.19	2.44	12.6	4.7
47H				..	0.91	2.45	13.0	
751- 48V	f wc br banded sd			84.6m	0.19	2.45	13.2	
48H				..	0.94	2.44	13.2	
751- 49V	f-m wc(wh) fels sd			87.9m	7.7	2.40	15.1	7.2
49H				..	92	2.39	16.0	
751- 50V	f cs wc br sd			91.2m	$<10^{-3}$	2.52	5.6	
50H				-	0.04	2.46	5.2	

Over most of this area, the Bunter beds are covered with variable thicknesses of glacial drift. For this reason, only three of the samples examined were from outcrops, one from Roach Bridge near Preston and the others from a disused quarry at Ormsgill, near Barrow-in-Furness; all the remaining samples came from borehole cores.

In marked contrast to other sections of the Permo-Trias, particularly those in Nottinghamshire and the central Midlands, the formation in this area has a generally low intergranular permeability and low porosity. The sandstones are almost entirely consolidated or well cemented, and the friable types encountered further south are practically completely lacking even close to the sub-drift surface.

Much of the material is fine grained, occasionally becoming very fine grained, and permeability in these beds ranges from 10 to 100 md with porosity lying between 15 and 20 per cent. Where the grain size grades upwards into medium, then permeability is found to increase marginally to 300 or 400 md, and porosity may rise slightly to 24 per cent. Lamination is common in the finer grained sandstones where it leads to marked permeability anisotropy, with values in the horizontal direction up to 4 or 5 times the vertical values (e.g. samples 394, 462-7, 491-1, 491-4, 577 and 582-2).

Both coarser and very fine-grained rock types occur in the formation to a limited extent. The coarser sandstones, ranging up to medium or coarse sand may be fairly clean, moderately well graded and less cemented, eg. samples 462-3, 577 and 579. In these, permeability reaches 2-300 md, and porosity rises to 28%, with saturated density decreasing from about 2.35 gms cc^{-1} (in fine-sands well cemented) to 2.20 gms cc^{-1}.

Occupying the other end of the scale, are the very fine grained sands and coarse silts which occur more and more frequently in the sequence as the formation is traced northwards. As might be expected, these units are characterised by minimal permeability, porosity as low as 10 per cent, and saturated density as high as 2.51 gms cc^{-1}.

AREA 7

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
383 - 1V1	f-m lam wc sd	Haighton B.H., Preston, Lancs	SD57163469	134.1m	–	2.35	17.2	
1V2				"	3	2.36	17.1	
1HX				"	84	2.41	16.6	
1HY				"	53	2.38	16.6	
383 - 2V1	f-m lam wc br-r sd			128.0m	73	2.32	20.3	
2V2				"	14	2.31	20.3	
2V3				"	24	2.31	20.5	
2HX				"	–	2.31	20.7	
2HY				"	119	2.32	20.0	
383 - 3V1	f-m wc r sd			125.0m	11	2.41	15.9	
3V2				"	44	2.32	20.0	
3V3				"	16	2.35	17.6	
3HX1	m-c con sd			"	481	2.28	21.8	
3HX2				"	614	2.27	22.9	

AREA 7

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
383 - 3HY	f-m wc lam sd	Haighton B.H. Preston	SD57163469	125.0m	213	2.31	20.5	
383 - 4V1	f-m wc lam r sd	Lancs		n/k	9	2.35	18.6	
4HX1				..	27	2.37	17.2	
4HX2				..	27	2.37	17.6	
4HY1				..	31	2.36	18.1	
4HY2				..	19	2.38	16.7	
383 - 5V1	pk lam c slt			n/k	<1	2.42	14.4	
5V2				..	<1	2.42	14.3	
5HX1				..	<1	2.42	13.9	
5HX2				..	<1	2.45	12.0	
5HY1				..	<1	2.44	13.2	
384 V	f-m lam con r sd	Roach Bridge, Preston, Lancs	SD59572887	o/c	282	2.23	24.7	
HX				..	387	2.23	24.1	
HY1				..	269	2.25	23.7	

AREA 7

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
393Y1	vf cs lam pk sd wc	Ormsgill, Barrow-in-Furness, Lancs	SD19997183	o/c	<1	2.33	19.2	
V2				..	<1	2.33	19.0	
H135				..	1	2.32	19.3	
H1-225				..	3	2.33	19.1	
H2-225				..	0.5	2.33	19.1	
394 V	vf-f cs lam sd			o/c	3	2.29	21.4	
H225				..	41	2.28	21.8	
H315				..	148	2.28	22.0	
462- 1V	f-m con r sd	Fylde Water Board, BH R2, Stubbins Lane, Garstang	SD50904290	22.9m	235	2.24	24.1	
1HX1				..	187	2.23	24.2	
1HX2				..	129 *	2.26 *	24.0 *	
1HY				..	128	2.26	22.9	
462- 2V1	f-m con r sd			45.7m	120	2.23	24.2	
2V2				..	202	2.24	23.8	

AREA 7 Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
462- 2HX2	f-m con r sd	Fylde Water Board, BH R2, Stubbins Lane, Garstang.	SD 50904290	45.7m	284	2.24	23.7	
2HY1				..	286	2.24	23.6	
2HY2				..	321	2.23	24.1	
462- 3V1	m con r sd l cn			61.0m	1841	2.18	27.6	
3V2				..	1753	2.18	28.0	
3HX1				..	2585	2.16	28.8	
3HX2				..	2600	2.17	28.3	
3HY1				..	2774	2.17	28.2	
3HY2				..	2352	2.18	27.7	
462- 4V1	f-m wc mf sd			73.8m	51	2.35	17.9	
4V2				..	61	2.35	17.6	
4HX				..	116	2.35	17.9	
4HY				..	68	2.35	18.1	
462- 5V1	o-gy mt lam slt			74.7m	<1	2.46	11.0	
5V2				[illegible]	[illegible]	[illegible]	[illegible]	

AREA 7

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
462- 5HX1	o-gy mt lam slt	Fylde Water Board, BH R2, Stubbins Lane, Garstang	SD50904290	74.7m	<1	2.45	10.8	
5HX2				"	<1	2.45	11.3	
5HY1				"	<1	2.51	11.5	
5HY2				"	<1	2.47	11.1	
462- 6V1	r slt mf mic			85.3m	<1	2.42	13.8	
6HX				"	7 [hair line crack]	2.43	13.1	
6HY				"	<1	2.47	12.4	
462- 7V1	wc lam f sd			115.2m	8	2.36	18.8	
7V2				"	9	2.37	18.8	
7HX1				"	27	2.36	18.9	
7HX2				"	26	2.36	19.0	
7HY1				"	27	2.36	18.7	
7HY2				"	28	2.36	18.6	
462- 8V1	gy-r mt slt mf mic	"		118.9m	<1	2.42	16.2	

AREA 7 Formation: BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
491-1V	m-c wc pk sd	Fylde Water Board, BH T36, Gubberford Bridge, Garstang.	SD 494 473	49.1 m	39	2.45	12.6	
1HX				"	391	–	–	
1HY1				"	419			
1HY2				"	430	2.46	12.2	
491-2V	m-c wc pk sd			70.7 m	301	2.48	10.9	
2HX				"	316	2.49	10.2	
2HY				"	129	2.50	9.5	
491-3V	f-m cs wc r sd			99.7 m	1	2.35	18.2	
3HX				"	1	2.40	15.8	
3HY				"	40	2.36	18.1	
491-4V1	f-m dk r mt cs sd			106.7 m	3	2.34	19.9	
4V2				"	3	2.33	20.1	
4HX				"	48	2.33	20.1	
4HY1	"			"	53	2.33	20.2	

AREA 7

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
491-5V	f-m wc lam r sd mf	Fylde Water Board, BH T36, Grubbaford Bridge, Garstang	SD 494473	125.0m	38	2.39	16.5	
5HX1				..	127	2.40	16.0	
5HX2				..	226	2.38	16.7	
5HY1				..	199	2.39	16.5	
5HY2				..	141	2.41	15.5	
491-6V	vf-f wc lam r sd			143.3m	1	2.39	5.4	
6HX				..	<1	2.39	5.5	
6HY				..	0.4	2.45	7.0	
491-7V	f wc mic cs sd			151.8m	2	2.39	16.8	
7HX				..	2	2.39	17.1	
7HY				..	<1	2.39	17.2	
572-1V	f-m wc lam r sd	Fylde Water Board, B.H. T6	SD 47613684	between 71.6 & 74.7m	–	2.36	19.8	
1H				..	22	2.36	19.6	
572-2V	f-m wc r sd			between 74.7 & 77.7m	13	2.37	19.7	

AREA 7

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
573-2H	f wc r sd	Fylde Water Board, BH T2	SD 519349	between 63.4 & 64.9m	9	2.34	20.4	
573-3H	m wc br sd			between 81.7 & 83.2m	1073	2.25	24.6	
574-1V	f-m lam fr cs r sd	Fylde Water Board, BH T22	SD 47974312	n/k	1051	2.23	25.5	
1H				"	1285	2.24	24.8	
574-2V	f-m lam fr r sd			24.4m	–	2.22	25.4	
2HX				"	1630	2.23	24.8	
2HY				"	–	2.21	23.0	
575 V1	f-m wc lam r sd	Fylde Water Board, BH T28	SD 46594389	32.0m	6	2.37	18.9	
HX				"	37	2.36	19.1	
HY				"	72	2.38	18.3	
576V	f-m wc r sd	Fylde Water Board, BH T8	SD 48164687	>27.4m	204	2.30	21.7	
				"				
577V	m wc cn cav r sd	Fylde Water Board, BH T5	SD 47164065	n/k	200	2.28	21.8	
HX				"	1740	2.29	21.8	

AREA 7

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
578-1V	wc f r sd	Fylde Water Board, BH T30.	SD 45245132	29.0 m	10	2.46	16.4	
1HX				"	64	2.48	16.3	
1HY				"	16	2.47	16.3	
578-2V	lam con c slt			32.0 m	–	2.40	17.8	
2HX				"	–	2.42	15.0	
2HY				"	–	2.43	15.5	
578-3V1	m wc pk gy sd			38.10 m	20	2.32	21.0	
3V2				"	63 *	2.25 *	24.7 *	
3HX				"	133	2.33	21.0	
3HY				"	114	2.32	21.4	
578-4V	vf–c lam r sd			41.10 m	4	2.35	17.6	
4HX				"	104	2.35	18.0	
4HY				"	1	2.38	16.4	
578-5V	vf–f wc r sd			44.2 m	13	2.26	24.1	

AREA 7

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
578-5HY	vf-f wc sd	Fylde Water Board BH T30	SD 45245132	44.2m	25	2.26	24.1	
579-V	f-m cn con r sd	Fylde Water Board BH L1	SD 49794104	between 83.8m & 86.9m	2388	2.19	27.3	
580-1V	m con r sd l	Fylde Water Board, BH T35	SD 49794104	between 91 & 122m	1120	2.18	27.8	
1H				..	1094	2.21	27.0	
580-2V	f-m wc r sd			between 122 & 126.5m	448	2.27	23.2	
2H				..	–	2.27	22.7	
580-3V	f-m con r sd			between 146 & 149m	184	2.23	25.8	
3HX				..	256	2.23	25.9	
3HY				..	187	2.24	25.7	
581-1V	f-m con r sd	Fylde Water Board, BH K2	SD 50044009	10.4m	369	2.42	28.5	
1HX				..	1027 [slight crack]	2.22	26.3	
1HY				..	433	2.23	25.8	
582-1V	m wc r sd	Fylde Water Board, BH. T39.	SD 50524185	12.5m	147	2.26	23.8	
1HX				..	334	2.27	23.2	

AREA 7

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
582-2V	f-m lam wc r sd	Fylde Water Board, BH T39	SD50524185	15.5m	25	2.27	23.8	
2HX				..	600	2.28	23.6	
2HY				..	1021	2.28	23.4	
582-3V	wc f r sd			21.6m	333	2.17	29.1	
3HX				..	593	2.24	24.9	
3HY				..	496	2.24	25.0	
582-4V	wc f-m r sd partly clean			24.7m	1108	2.22	25.8	
4HX				..	1212	2.24	25.1	
4HY				..	1387	2.23	25.2	
582-5V	partly wc m r sd			27.7m	1008	2.22	26.2	
5HX				..	1316	2.25	24.2	
5HY				..	1234	2.25	24.6	
582-6V	wc f-m r sd			n/k	15	2.29	22.1	
6HX				..	113	2.29	21.8	

AREA 7 Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
583-1V	f-m wc r sd	Fylde Water Board, BH T38	SD48814316	n/k	34	2.33	20.5	
1HX				..	63	2.31	21.4	
1HY				..	115	2.28	23.3	
583-2V1	f-m r sd with patchy cementation			n/k	162	2.27	23.7	
2V2				..	193 *	2.28 *	24.1 *	
2HX				..	157	2.28	23.3	
2HY				..	370	2.26	24.2	
665-1V	con vf r sd	Fylde Water Board BH T52	SD45724583	24.7m	10	2.30	21.1	
1HX				..	18	2.29	21.8	
1HY				..	19	2.30	21.4	
665-2V	con vf r sd lam mf			33.5m	0.4	2.40	16.5	
2HX1				..	57	2.29	21.6	
2HX2				..	36	2.40	15.9	
2HY				..	3.6	2.39	16.1	
[illegible]	vf mic lam			[illegible]			[illegible]	

AREA 7

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
665-4V	vf lam mic r sd con	Fylde Water Board, BH T52	SD45724583	37.5m	26	2.31	20.8	
4HX				"	25	2.31	20.6	
4HY				"	34	2.33	19.8	

In view of the generally rather soft, medium grained nature of the Penrith Sandstone and its obvious potential as an intergranular flow aquifer, sampling over the outcrop was carried out at rather more frequent intervals, especially in the Penrith-Brough district . The author is grateful to Mr. A.J. Wadge, IGS Leeds Office, for suggesting localities, the samples from which would adequately cover the complete range of lithology in the formation. Surface data was reinforced by data from drill-cores at three sites, and by underground samples from the Stamp Hill Mine of British Gypsum Limited.

As has already been pointed out, the Penrith Sandstone is subject to a good deal of local facies variation; accordingly, the correlation of lithology with aquifer properties will be considered on the basis of a traverse along the strike of the beds from SE to NW.

Taking first the brockram formation in the extreme south-east of the outcrop, any brief examination of it in the field (Plate 7A) will rapidly convince the observer that intergranular flow through the deposit must be effectively zero, so extensive is the cementation. The same judgement must apply to certain cemented interbedded sandstones which are found between two units of brockram in the same area.

As the sandstone is traced towards the northwest however, the thickening arenaceous units between the brockrams (see Plates 7B, 8A, 8B and 9B) have been found generally to have a very high intergranular permeability in the area between Appleby and Penrith. Friable 'millet-seed' sands are very prevalent; typical samples from sections along the River Eamont (545), the River Eden (553-555), near Cliburn (559-561, 562 and 566), near Great Ormside (568) and the Hilton Beck (585 and 586) indicate that where they are virtually uncemented, the millet seed sands have a permeability exceeding 10000 md, sometimes even exceeding the upper limit of resolution of the equipment (23000 md). Porosity in these extraordinary deposits is also high at about 30%, but not extreme. Density, as might be expected, is low, ranging generally from 2.06 to 2.16 gms cc^{-1}. These sands are the coarsest, cleanest and most well graded encountered in the Permo-Trias during the course of this investigation.

Unfortunately as far as the value of the formation as an aquifer is concerned, certain factors reduce the overall permeability. Principal amongst these is local cementation (dealt with below) but other more subtle factors are also prevalent. Particularly in this context one might mention anisotropy caused by alternation of coarse sands with less well graded fine to very fine sand. Experimental data on samples 436-3, 559, 567, 588-1, 588-7 and 588-10 suggest that lamination can cause reduction in microscopic vertical permeability to about 0.1 or 0.05 of the horizontal values. Add to this the problem of these laminae being inclined at angles of up to 30° to the horizontal because of large scale current or dune bedding and the result is a very complex system of ground water flow at the microscopic level.

Within the sequences of coarse clean millet seed sands, there are intervals of much less well graded fine to medium material, also dune bedded, which have been found to possess characteristically intermediate aquifer property values. Samples 441, 544, 546, 553, 560 and 584 fall into this category with permeability generally ranging from 500 to 2000 md, porosity ranging from 25 to 30 per cent and density varying between 2.15 and 2.25 gms cc^{-1}. In this type of material, permeability is apparently reduced by sorting factors alone and cementation is not responsible. As these sands are interbedded with the highly permeable millet seed types, they are in a position to reduce still further an already low vertical formation permeability.

Next, we must consider the properties of the formation in the cemented state, and here we are dealing essentially with the upper half of the Penrith Sandstone over rather localized areas. In brief, samples were taken on the scarplands to the south east and north east of Penrith (Nos. 432, 435, 437, 439, 543, 556-558), from an underground section in Stamp Hill Mine (549-1 to 4), from the top of the formation in the Hilton Beck IGS Borehole, and from quite high in the stream section of Hilton Beck (441). With one or two exceptions, the cementation has affected medium to coarse millet seed sands probably preferentially in view of their very high permeability in the uncemented state. Commonly it takes the form of secondary quartz intergrowth, easily visible even under binocular examination at low magnification (X40). It is, however, of a different type in the Stamp Hill Mine section where the sediments appear muddy and indurated. In the cores from Hilton Beck IGS Borehole, the cementation is of gypsum or anhydrite or both.

The cemented samples show gradational aquifer property values as the pore space becomes progressively reduced. Thus in sample 588-12 incipient quartz intergrowth is visible and porosity is already reduced to 27% from the 30% found in the uncemented millet seed sands. Permeability at this stage is, however, hardly decreased. In samples 435 and 558, the pore space has been further decreased to about 15% with permeability already down to a few hundred millidarcys, whereas density has increased to 2.35 to 2.40 gms cc^{-1}. Further reduction in the values is found until a minimum figure of only 5 to 8 per cent porosity is reached, as for example in sample 556 from the vein shown in Plate 9A. Here permeability is less than 1 md and density reaches 2.51 gms cc^{-1}. In the Hilton Beck Borehole where gypsiferous cementation occurs, the equivalent values are 11-15% porosity, minimum permeability of less than 1 md and density of 2.45 gms cc^{-1}.

In some of the sands cemented to an intermediate degree, the anisotropy of the original millet seed sand may be preserved (eg sample 558).

What is surprising is that in much of the cemented facies, microscopic permeability though very low is definitely present, a reflection of the relatively large dimensions of the pore channels in the original sandstone. It seems quite clear, however, that ground water movement in the cemented zones must take place primarily by fissure flow, and that a complex transition zone occurs in the area over which the cemented rock passes laterally into unaltered material. Quasivertical sheets of cemented sandstone of the type pictured in Plate 9A may perhaps be common in these transitional zones. The effect of such sheets in reducing horizontal permeability must be considerable (cf the rather similar veins found in the Upper Mottled Sandstone Plate 6B).

In the Stamp Hill Mine section, very low values of intergranular permeability were obtained on four samples (549-1 to 4) from a tunnel which intersects an upfaulted block of the sandstone. This material is probably quite high in the succession. The majority of the rock exposed in the tunnel shows irregular inclined jointing and the roof is coated by a stalactitic growth of gypsum. The intergranular permeability figures suggest that this could have been produced by microscopic flow, followed by evaporation caused by mine ventilation.

The low permeability data from this locality, caused some concern that the outcrop samples, which were showing quite an optimistic aquifer property picture, did not truly represent subsurface conditions. Further test data, however, obtained on cores from the IGS boreholes at Lounthwaite and Blackmosspool confirmed that at depths of up to at least 50 m and possibly 100 m, the Penrith Sandstone can be expected to be relatively friable and permeable away from areas of known cementation. Thus in the Blackmosspool BH (Fig.26), the dominant fine to medium grained red sandstones have a permeability of 1000 to 4000 md, porosity of 25 to 30% and density of about 2.20 gms cc^{-1}. Near the bottom of the hole, the millet seed sands make their appearance (sample 588-12) in the uncemented state, with a permeability of more than 23000 md.

In the vicinity of Carlisle, only few samples were obtained, those from the surface outcrop at Scalesceugh, Gatesgill and Highbridge being inadequate. Data from these sites, however, suggested that the sandstone in this area has only moderate intergranular permeability ranging as low as 100 md up to several thousand. Porosity is also reduced by cementation to 18-26% and density is moderate at 2.20 to 2.30 gms cc^{-1}. Whether these data are indicative of subsurface conditions is not known. It is very unfortunate that the Nord Vue boreholes of Eden Valley Water Board were not fully cored as these would have provided very interesting data.* There is, however, an urgent need for a cored borehole to the base of the Penrith Sandstone near Carlisle.

The only samples examined from the northern side of the Carlisle Basis were those from the presumed outcrop in the banks of the River Esk, at Dead Neuk Pool, Canonbie. Here, friable well graded pink coloured sandstones which cannot on lithological and structural grounds be other than Penrith Sandstone were found to have a moderately high intergranular permeability (up to 3000 md) with moderate porosity and low density (samples 547-548). Further information is also required of the extent of these very promising sandstones which at Canonbie are only 10 m thick.

* However, the drilling by the I.G.S., of 3 cored boreholes in the Penrith Sandstone to depths of up to 180 m at Cliburn near Penrith is now in progress.

AREA 8 Formation : PENRITH SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
408 V1	f-m wc pk sd	River Petteril at Scalescaugh Hall, Cumberland	NY44764954	o/c	30	2.32	18.8	
V2				"	41	2.30	19.7	
H1-74				"	106	2.29	20.7	
H2-74				"	22	2.31	19.1	
H1-164				"	22	2.32	18.5	
H2-164				"	36	2.32	18.7	
423 V1	wc wg m pk sd lam	Hall Hill, Gatesgill, Cumberland.	NY 38584592	o/c	527	2.30	20.4	
V2				"	829	2.29	21.0	
H1-75				"	4280	2.31	20.3	
H2-75				"	1579	2.31	20.0	
H1-165				"	233	2.30	20.6	
H2-165				"	1363	2.30	20.8	
424 V1	f-c lam con br-o sd	Highbridge, Gatesgill, Cumberland.	NY 3912 4440	o/c	1770	2.21	26.4	
V2				"	658	2.23	25.2	

AREA 8

Formation : PENRITH SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
424 H2-141	f-c lam con br-o sd	Highbridge, Gatesgill, Cumberland.	NY 39124440	o/c	1973	2.22	26.2	
H1-231				..	3242	2.21	26.6	
H2-231				..	3294	2.22	26.3	
427 V1	f-c lam fr r sd cs laminae partly cemented	Townhead, Ousby, Cumberland	NY 63613410	o/c	2269	2.18	28.4	
V2				..	4478	2.18	28.6	
HX1				..	1461	2.16	29.8	
HX2				..	1235	2.16	29.4	
HY1				..	2188	2.18	28.4	
HY2				..	2286			
430 V1	fr wg m dk r ms sd	Near Gamblesby, Cumberland	NY 62293890	o/c	4521	2.20	26.8	
V2				..	4960	2.19	27.5	
H1-130				..	5551	2.19	27.6	
H2-130				..	6083	2.19	28.1	
H1-40				..	4807	2.20	27.2	

AREA 8 Formation : PENRITH SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
432 V1	c wc ms sd	River Eden, Eden Lacy, Cumberland.	NY5622 3799	o/c	25	2.44	12.0	
V2				..	–	2.55	9.5	
H1-193				..	201	2.48	9.5	
H2-193				..	389	2.44	12.0	
H1-283				..	385	2.42	13.1	
H2-283				..	931	2.40	14.5	
435 V1	m-c wc r sd much secondary quartz intergrowth	Maidenhill Quarry, Penrith, Cumberland	NY5240 3321	o/c	353	2.37	17.0	
V2				..	284	2.35	17.8	
H1-13				..	481	2.37	17.1	
H2-13				..	403	2.36	17.2	
H1-103				..	444	2.37	16.8	
H2-103				..	455	2.37	16.9	
436-1V	vf-vc lam fr r sd	Nord Vue B.H., High Hesket, Penrith.	NY4941 4425	between 22.6 & 24.1m	–	2.26	23.2	
1H				..	3371	2.29	22.1	
[illegible]	wg c ms				[illegible]	[illegible]	[illegible]	

AREA 8 Formation : PENRITH SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
436-2V2	wg c ms sd fr	Nord Vue B.H., High Hesket, Penrith.	NY49414425	between 22.6 & 24.1m	18386	2.13	31.1	
2H1				..	17568	2.13	31.2	
2H2				..	17299	2.13	31.2	
436-3V	wg c lam ms sd fr			..	1991	2.24	25.2	
3H				..	17957	2.19	27.9	
437-V1	m-c wc pk sd extensive quartz intergrowth	Wan Fell, Penrith	NY53423522	o/c	82	2.43	13.0	
V2				..	38	2.44	12.7	
H1-250				..	54	2.43	12.7	
H2-250				..	65	2.42	13.3	
H1-160				..	69	2.42	13.6	
H2-160				..	70	2.41	14.3	
438 V	f-c fr cn fels r sd	Cowraik Quarry, Penrith, Cumberland.	NY54083103	o/c	2746	2.14	30.1	
H1-113				..	4524	2.13	30.6	
H2-113				..	3611	2.14	30.1	

AREA 8 Formation : PENRITH SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
439 V1	m-c wc pk sd secondary quartz intergrowth	Udford, Penrith, Cumbs.	NY 57113030	o/c	220	2.42	13.5	
V2				..	288	2.43	12.9	
H1-98				..	351	2.43	12.9	
H2-98				..	277	2.44	12.1	
H1-188				..	370	2.43	12.6	
H2-188				..	295	2.44	12.3	
441 V1	f-m wc pk-gy sd	Hilton Beck, Appleby, Westmorland.	NY 71872047	o/c	76	2.27	22.6	
V2					131	2.28	21.9	
H1-240	f-c fr br sd				2907	2.22	25.8	
H2-240					1528	2.27	22.9	
H1-150					1665	2.24	24.7	
H2-150					2616	2.23	25.6	
543 V	c wc ms sd	Woodside, Temple Sowerby, Westmorland	NY 5825 2937	o/c	8	2.48	9.5	
H34				..	1	2.49	8.8	

AREA 8 Formation : PENRITH SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
544 V	f-m lam fr r sd	River Eamont at Honeypot, Penrith	NY 55813014	o/c	797	2.18	27.6	
HX				..	1475	2.17	28.5	
HY				..	1790	2.17	27.7	
545 V1	c wg pk fr ms sd		NY 55823011	o/c	> 23000	2.08	33.6	
V2				..	–	2.06	34.8	
H1-32				..	> 23000	2.06	34.6	
H2-32				..	> 23000	2.06	35.1	
H122				..	> 23000	2.06	35.0	
546 V1	f-m con lam fels r sd	Beacon Hill, Penrith	NY 52883112	o/c	255	2.21	26.2	
V2				..	–	2.24	24.7	
H				..	–	2.24	24.5	
H28				..	778	2.21	26.3	
H118				..	501	2.21	26.0	
547 V	fr wg r m cn sd	River Esk, Canonbie, Dumfriesshire	NY 39247623	o/c	950	2.16	28.9	
H1-18				..	[illegible]	2.15	[illegible]	

AREA 8

Formation : PENRITH SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
547 H2-18	fr wg cn m r sd	River Esk, Canonbie, Dumfriesshire	NY39247623	o/c	2928	2.15	29.6	
H108				..	2845	2.17	28.6	
548 V	f-m fr r sd fels			o/c	1567	2.17	27.7	
H8				..	2653	2.18	28.0	
H98				..	-	2.16	18.4	
549-1V	wc f-c gy-r sd	Stamp Hill Mine, Kirby Thore, Westmorland	NY66392567	47.9m	53	2.35	18.5	
1HX				..	920	2.35	18.5	
1HY				..	280	2.31	20.4	
549-2V	vf-c md ms sd gy-r		NY66302567	63.7m	9	2.38	17.0	
2H239				..	3	2.41	16.4	
2H329				..	2	2.48	12.6	
549-3V	vf-c md lam sd wc dk r		NY66222567	77.1m	<1	2.45	13.3	
3H90				..	4	2.44	13.7	
3H180				..	6	2.46	12.7	
549-4V	vf lam wc r sd		NY66182567	84.7m	2	2.34	19.4	

AREA 8

Formation : PENRITH SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
549 - 4HX	vf lam wc r sd	Stamp Hill Mine, Kirby Thore, West.	NY 66182567	84.7m	1	2.39	16.9	
4HY				..	-	2.34	19.4	
551	vf-vc lam dkr sd	Near Brampton, Westmrld	NY 68512324	o/c	8	2.28	23.2	
553 V	f-m cn cs dk r fr sd	River Eden at Oglebird Scar, Westmorland.	NY 60272737	o/c	1389	2.14	30.2	
H198				..	1296	2.15	29.4	
H1-288				..	1764	2.14	30.2	
H2-288				..	2058 *	2.18 *	28.0 *	
554 VI	c wg cn r sd		NY 60242734	o/c	10367	2.16	28.8	
H90				..	> 23000	2.15	29.6	
H180				..	> 23000	2.15	29.7	
555 V	f-c cn fr r sd		NY 60222732	o/c	4018	2.11	32.0	
HX				..	7562	2.10	32.3	
HY				..	-	2.11	31.2	
556 V	gy wc m-c sd	Eden Bridge, Temple Sowerby, Westmorland	NY 60322812	o/c	<1	2.52	5.6	
H				..	<1	2.50	8.1	

AREA 8

Formation : PENRITH SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
557V	wo pk c sd	Quarry in Whinfell	NY59002717	o/c	5	2.43	12.5	
H1-58	c wc pk sd secondary quartz intergrowth	Forest, Cliburn,		..	1217	2.39	15.0	
H148		Westmorland		..	1007	2.41	14.3	
558 V	c wc lt br sd secondary quartz intergrowth	Salterwood Quarry,	NY58302643	o/c	40	2.40	14.6	
H1-236		Cliburn, Westmorland		..	463	2.37	16.4	
H2-236				..	491 *	2.43 *	13.6 *	
H1-326				..	632	2.38	16.1	
H2-326				..	427 *	2.41 *	14.0 *	
559 V	f-c lam fels dk r ms sd	Commonholm Scar,	NY57622482	o/c	3486	2.24	25.0	
H133		Cliburn, Westmorland		..	9963	2.21	26.3	
H223				..	6979	2.21	26.4	
560 V	f-m con fels dk r sd	Trough Gill, Cliburn,	NY58842427	o/c	253	2.20	27.9	
HX		Westmorland.		..	1006	2.19	28.2	
HY				..	452	2.21	26.9	
H128				..	368	2.21	27.3	

AREA 8

Formation. PENRITH SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
560 H 218	f-m con fels dk r sd	Trough Gill, Cliburn.	NY 58842427	o/c	532	2.20	27.8	
561 V	wg f-m cn r sd cs some silty laminae	River Lyvennet, near Cliburn, Westmorland	NY 60002473	o/c	628	2.16	29.7	
H 29				"	12164	2.12	32.0	
H 119				"	9010	2.12	31.8	
562 V	wg m-c cn r sd fr		NY 60012466	o/c	2439	2.19	27.8	
HX				"	7519	2.16	29.5	
HY				"	8543	2.15	30.5	
563 V	wc m-c pk sd	River Eden at Eden Grove, Westmorland.	NY 64572342	o/c	307	2.37	16.5	
H90				"	54	2.36	17.3	
H180				"	6	2.43	13.3	
564 V	m-c fr veined dk r sd fels			o/c	-	2.17	28.7	
HX				"	-	2.15	30.1	
HY				"	-	2.21	26.5	
565 V1	f-m fr fels dk r lam sd	Near Morland, Westmorland.	NY 61092313	o/c	-	2.21	25.9	
V2				"	1140*	2.25*	24.6*	

AREA 8 Formation : PENRITH SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
565H98	f-m fr fels dk r lam sd	Near Morland, Westmorland.	NY 61092313	o/c	3060	2.23	25.9	
H188				"	2854	2.23	25.8	
566 V	f-c lam fr fels cn dk r sd	Crossrigg Hall, Bolton, Westmorland	NY 60532411	o/c	303	2.22	26.6	
HX				"	> 23000	2.14	30.8	
HY				"	15036	2.16	29.9	
567 V	m-c lam fr r sd cn	Bongate, Appleby, Westmorland	NY 68612034	o/c	1662	—	—	
H 113				"	6819	2.31	20.6	
H 203				"	5078	2.33	18.9	
568 V	wg m cn fr r sd	Helm Beck, Great Ormside, Westmorland	NY 70511604	o/c	9231	2.11	32.3	
H116				"	8192	2.11	31.9	
H206				"	10891	2.12	31.6	
571 V	wc c cav ms sd	Haybergill, Warcop, Westmorland.	NY 75071656	o/c	33	2.49	11.3	
H 67				"	29	2.50	10.5	
H157				"	1672	2.47	13.2	
584 V	f-m fels dk r sd	Hilton Beck, Appleby	NY 71892051	o/c	1286	2.16	30.5	

AREA 8

Formation: PENRITH SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
584 H193	f-m fels dk r sd	Hilton Beck, Hilton, Westmorland.	NY71892051	o/c	742	2.24	25.7	
H103				..	568	2.24	25.7	
585 V	m-c cn fr dk r sd		NY70782000	o/c	7611	2.17	29.1	
HX				..	13813	2.16	30.0	
HY				..	6775	2.15	30.2	
586 V	m-c cn fr ms sd		NY70761991	o/c	16293	2.12	31.8	
H265				..	-	2.12	30.1	
588-1V	f-m lam cn r sd cs ms	IGS Blackmosspool, B.H., Cumberland.	NY48244816	8.1m	329	2.22	26.7	
1H				..	2441	2.22	26.6	
588-2V	f-m fr r sd			9.8m	2192	2.14	31.3	
2HX				..	3172	2.15	30.6	
2HY				..	4027	2.13	31.6	
588-3V	f lam con r sd			12.4m	17	2.23	25.7	
3H				..	130	2.25	24.4	
588-4V	cav vf-vc con r sd			13.6m	81	2.25	25.6	

AREA 8 Formation : PENRITH SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
588-4HX	cav vf-vc con r sd	IGS Blackmoss pool B.H. Cumberland.	NY48244816	13.6 m	304	2.25	25.9	
4HY				..	280	2.22	27.1	
588-5V	vf-c lam fr r sd			15.0 m	1257	2.22	26.0	
5HX				..	–	2.23	23.3	
5HY1				..	–	2.23	22.7	
5HY2				..	–	2.27	23.3	
588-6V	f-m con dk r sd			28.0 m	1175	2.20	27.9	
6HX				..	1725	2.20	27.9	
6HY				..	1799	2.20	27.6	
588-7V	m-c cs cn lam r sd			30.0 m	414	2.21	27.0	
7HX				..	2408	2.25	25.3	
7HY				..	1685	2.24	25.0	
588-8V	m-c fr cn wg ms sd			32.1 m	12071	2.13	31.4	
8HX				..	17068	2.13	31.4	
8HY				..	>23000	2.12	31.5	

AREA 8

Formation : PENRITH SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
588- 9V	c-cn fr ms cs r sd	IGS Blackwosopool B.H., Cumberland.	NY48244816	35.8m	14076	2.14	30.5	
9HX				..	–	2.14	30.9	
9HY				..	–	2.14	30.7	
588- 10V	f-m cs lam r sd con			40.9m	130	2.20	27.4	
10HX				..	1805	2.20	27.2	
10HY				..	1724	2.21	26.9	
10TT				..	111	2.21	26.8	
10CD				..	1070	2.20	27.5	
10CS				..	1170	2.20	27.3	
588- 11V	con f-m cs lam r sd			42.5m	1122	2.17	28.9	
11HX				..	4319	2.17	28.7	
11HY				..	4941	2.17	28.6	
588-12V	c-vc wg en r sd fr incipient quartz			43.7m	–	2.23	25.3	
12HX				..	>23000	2.21	26.2	
12HY				..	>23000	2.19	27.6	

AREA 8

Formation : PENRITH SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
589-1V	wc m-c wh sd gypsum cement	IGS Hilton Beck B.H. Appleby, Westmorland	NY72852056	226.1m	<1	2.44	13.7	
1HX				"	<1	2.48	11.7	
1HY				"	<1	2.46	12.5	
589-2V	wc m-c pk sd			228.2m	<1	2.43	15.2	
2HX				"	<1	2.45	13.9	
2HY				"	–	2.46	13.2	
589-3V	wc f-m pk-gy sd lam			231.6m	1	2.43	14.7	
3HX				"	4	2.44	14.3	
3HY				"	6	2.44	14.3	
590-1HX	f-c lam fr ms sd	IGS Lounthwaite B.H., Cumberland	NY65353092	114.7m	1250	2.20	27.2	
1HY				"	1848	2.18	28.5	
590-2V	f-c md lam r sd			116.2m	453	2.22	26.0	
2HX				"	1165	2.23	25.3	
2HY				"	668	2.20	27.0	
590-3V	f-vc md r sd			118.0m	136	2.23	25.2	

AREA 8

Formation : PENRITH SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
590 - 3HX	f-vc md r sd	IGS Lounthwaite B.H., Cumberland.	NY65353092	118.0m	29	2.23	24.8	
3HY				"	165	2.23	25.2	

Within the Carlisle Basin and Eden Valley, a striking lithological contrast is seen between the older Penrith Sandstone and the overlying St. Bees Sandstone. This lithological contrast is paralleled by an equally marked difference in the aquifer properties of the two formations.

Whereas the Penrith Sandstone is characterised by a very variable degree of cementation and wide range in grain size, the St. Bees formation shows virtual uniformity of grain size and degree of consolidation over the whole outcrop from Appleby in the south, to Maryport and Canonbie in the west and north. Whether this formation is significantly different at depth is at present unknown, and to resolve this problem, there is an urgent need for a deep cored borehole in the Carlisle - Gretna area.

Owing to the rather uniform lithology, it is easy to generalise about the aquifer properties of the formation, bearing in mind however that all of the present study was based on outcrop material only (in contrast to West Cumberland, see section on St. Bees Sandstone in Area 7). Intergranular permeability is commonly between 200 and 600 md, and even in some of the laminated types, most of the sandstone is isotropic (eg samples 409, 422, 429, 431 and 550). Porosity is everywhere moderate to high, commonly having a range of 24-27 per cent; density is intermediate in value, generally about 2.20 gms cc^{-1}.

In most of the samples, grain size ranges from very fine to fine, but a few much better graded fine types were encountered which have a relatively "clean" appearance. In these (eg samples 406, 429 and 434), permeability increases to a maximum of 2000 md; porosity is also much higher, at 30-35 per cent and density is reduced to about 2.10 gms cc^{-1}.

No cemented sandstone was encountered amongst the samples examined.

The evidence suggests that the St. Bees Sandstone in this area generally has a higher intergranular permeability than either the Bunter - St. Bees Sandstone of Area 7 or the stratigraphically equivalent Bunter Sandstone in Northern Ireland. A cored borehole into the sandstone in Area 8 is however, clearly required in order to verify this hypothesis.

AREA 8

Formation : ST BEES SANDSTONE .

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
401 V	wg wc f pk sd	Quarry at Maryport, Cumberland	NY04163784	o/c	224	2.27	22.3	
H 53				..	418	2.26	23.0	
H143				..	601	2.25	23.9	
402 V1	wg wc cav f cs sd	Aspatria, Cumberland	NY14104257	o/c	33	2.31	20.0	
H151				..	110	2.28	21.8	
H 241				..	37	2.32	19.3	
V2				..	21 *	2.31 *	20.8 *	
406 V1	wg fels lam f pk sd	Great Orby, Cumb.	NY47645461	o/c	937	2.19	26.9	
V2				..	643	2.20	26.6	
H 86				..	574	2.21	26.1	
H2-86				..	749	2.18	27.5	
H1-176				..	1067	2.18	27.7	
H2-176				..	669	2.20	26.6	
407 V1	vf-f con lam r sd		NY47655461	o/c	188	2.21	25.0	
V2				..	181	2.22	25.3	

AREA 8 Formation : ST BEES SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
407 H1-121	vf-f con lam r sd	Great Corby, Cumberland	NY 47655461	o/c	293	2.22	25.8	
H2-121				"	320	2.21	26.0	
H1-211				"	331	2.21	26.0	
H2-211				"	286	2.21	25.7	
409-V1	vf-f con r sd	Croglin, Cumberland	NY 57534744	o/c	174	2.22	24.9	
V2				"	203	2.22	25.4	
H1-127				"	137	2.22	25.0	
H2-127				"	249	2.21	25.7	
H1-217				"	344	2.20	26.4	
H2-217				"	217	2.22	25.2	
420 V1	y-br con vf-f sd slightly friable lam	Rockcliffe, Carlisle, Cumberland	NY 35606177	o/c	133	2.26	24.2	
V2				"	142	2.26	24.3	
H1-250				"	140	2.25	24.9	
H2-250				"	140	2.26	24.4	
H1-340				"	63	2.26	24.2	

AREA 8

Formation : ST BEES SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
420 H2-340	Y-br con vf-f sd lam slightly friable	Rockcliffe, Carlisle, Cumberland	NY 3560 6177	o/c	25	2.26	24.0	
H3-340				..	17 *	2.27 *	23.5 *	
422 V1	wg lam fels f pk sd con	Chalk Beck at East Curthwaite, Cumberland	NY 3389 4833	o/c	137	2.24	24.5	
V2				..	229	2.22	26.0	
H1-354				..	145	2.24	24.7	
H2-354				..	244	2.26	24.3	
H1-264				..	163	2.24	24.7	
H2-264				..	161	2.24	24.5	
425 V1	cs f r sd con	Milburn, Westmorland	NY 6565 2956	o/c	311	2.15	30.1	
V2				..	623	2.14	30.4	
H1-88				..	566	2.14	30.3	
H2-88				..	646	2.15	30.4	
H1-178				..	647	2.13	31.1	
H2-178				..	460	2.18	29.3	
426 V1	f con r	Blencarn Cumberland	NY 6366 3140	o/c	368	2.15	30.7	

AREA 8 Formation : ST BEES SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
426 V2	f con r sd	Blencarn, Cumberland	NY63663140	o/c	405	2.16	30.3	
H1-149				..	380	2.16	30.6	
H2-149				..	481	2.16	30.7	
H1-239				..	445	2.17	22.8	
H2-239				..	527	2.16	37.3	
428 V1	f fr cs dk r sd	Sunnygill Beck, Ousby, Cumberland	NY61953559	o/c	591	2.09	34.0	
V2				..	1017	2.08	34.2	
H1-133				..	1332	2.07	34.6	
H2-133				..	1291	2.08	34.6	
H1-223				..	–	2.08	34.3	
H2-223				..	1050	2.07	34.9	
429 V1	f wg cs r sd	Melmerby Hill, Cumberland	NY61943791	o/c	1393	2.10	32.9	
V2				..	2057	2.10	32.8	
H1-131				..	1433	2.11	32.7	
H2-131					1831	2.10	32.9	

AREA 8 Formation : ST BEES SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
429 H1-221	f wg cs r sd	Melmerby Hill,	NY61943791	o/c	1781	2.11	32.5	
H2-221		Cumberland.		"	1740	2.11	32.4	
431 V1	vf-f lam	Hazelrigg Beck,	NY59083998	o/c	523	2.20	27.2	
V2	con dk r sd	Glassonby, Cumbs.		"	427	2.22	26.4	
H1-254				"	265	2.19	27.8	
H2-254				"	448	2.21	26.9	
H1-164				"	275	2.19	27.5	
H2-164				"	139	2.20	27.2	
433 V1	f con cs	Robberby Water,	NY59283616	o/c	265	2.20	26.9	
V2	lam r sd green reduction spots	Ousby Moor, Cumbs.		"	336	2.20	27.3	
H1-113				"	281	2.20	27.0	
H2-113				"	368	2.20	26.8	
H1-23				"	401	2.19	27.1	
H2-23				"	390	2.20	27.0	
434 V1	f wg fels [illegible]	Little Briggle Beck.	NY58493417	o/c	430	2.17	28.6	

AREA 8

Formation : ST BEES SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
434 V2	f wg con fels r sd	Little Briggle Beck, Langwathby, Cumbs.	NY58493417	o/c	339	2.18	27.6	
H1-109				..	514	2.19	27.2	
H2-109				..	466	2.18	27.8	
H1-19				..	420	2.20	26.8	
H2-19				..	931	2.17	28.2	
440 V1	f wg fels lam con r sd	Hilton Beck, Hilton, Westmorland.	NY73162076	o/c	326	2.19	26.9	
V2				..	290	2.20	26.0	
H1-316				..	526	2.20	26.1	
H2-316				..	595	2.20	26.3	
H1-226				..	447	2.20	26.1	
H2-226				..	512	2.19	26.7	
550 V1	f wg fels wc lam pk sd	River Lyne at Clinty Ford, Cumbs	NY43546888	o/c	285	2.21	26.0	
HX				..	318	2.22	25.3	
HY				..	280	2.21	25.9	
[illegible]				..	[illegible]	[illegible]	[illegible]	

AREA 8 Formation : ST BEES SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
560 H136	f wg fels wc lam pk sd.	River Lyne at Clinty Ford, Cumberland.	NY 43546188	o/c	351	2.22	26.0	

This sandstone which is virtually restricted to the Annan district, is the lateral equivalent of the St. Bees Sandstone of north Cumberland which it resembles in colour, grain size and bedding, although the degree of cementation is slightly higher. Owing to a thick mantle of drift deposits and the rather low relief of the outcrop area, samples were difficult to obtain and restricted to surface material. At the present time, the thickness variation in the sandstone is unknown.

Further problems were encountered during sampling on account of the method of working the formation for building stone in large, very deep quarries with vertical sides which are now flooded and disused. The free faces in these pits may be up to 25 m high, rising out of as much as 25 m of water; sampling in such places is very hazardous without special equipment. The same problem was encountered at Corncockle Muir, near Lochmaben, where no in-situ blocks of the formation could be obtained.

Aquifer properties in the Annan Sandstone, however, are clearly lower than those in the St. Bees Sandstone, even on the basis of outcrop samples only. Permeability ranges between 10 and 80 md, porosity varies only slightly between 17 and 23 per cent and density is moderate to high at about 2.35 gms cc^{-1}. To some extent, the formation resembles the harder, more well cemented parts of the St. Bees Sandstone, and no major facies change has been identified.

AREA 8

Formation : ANNAN SANDSTONE (= ST BEES SANDSTONE)

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
417 V	wc cs r lam c slt-vf sd	Corsehill Quarries, Annan, Dumfries	NY 206 701	o/c	12	2.34	18.5	
HX1				[loose block]	15	2.37	17.5	
HX2				..	13	2.36	17.1	
HY1				..	64	2.23	23.5	
HY2				..	53	2.25	23.4	
418 V1	wc c slt-vf r sd cs	Kirtle Water, Annan, Dumfriesshire	NY 26437035	o/c	34	2.33	19.0	
V2				..	36	2.34	18.9	
H1-85				..	46	2.33	19.3	
H2-85				..	31	2.34	18.5	
H1-175				..	34	2.33	19.0	
H2-175				..	28	2.34	18.8	
419 V	lam wg vf pk sd wc		NY 26427029	o/c	41	2.29	22.7	
HX1				..	36 *	2.29 *	22.0 *	
HX2				..	59	2.28	22.6	
HY[illegible]				..	5[illegible]	2.2[illegible]	22.[illegible]	

AREA 8

Formation : ANNAN SANDSTONE (ST. BEES SANDSTONE)

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
457-1V1	wg wc vf pk sd lam	Loganburn at Loganhouse Farm, Annan	NY 30287322	o/c	13 *	2.37 *	22.9 *	
1V2				..	26	2.34	20.0	
1HX				..	25	2.34	20.1	
1HY1				..	74	2.35	19.4	
1HY2				..	33	2.33	20.7	
457-2V1	wg wc vf pk lam sd			o/c	140 *	2.38 *	18.3 *	
2V2				..	30	2.35	19.7	
2HX				..	31	2.36	18.8	
2HY				..	18	2.38	18.1	

Little can be said about the properties of this subdivision, which is the name applied to the upper part of the St. Bees Sandstone. The 3 outcrop samples obtained, are, however, not completely without significance. Those from Ruleholme Bridge, Brampton (405) and Carwinley Burn (412) brought to mind the softer beds of the Upper Mottled Sandstone in the Bridgnorth - Wolverhampton district (Area 3) and were found to have broadly similar properties, viz. low intergranular permeability despite a soft friable state of consolidation, considerable porosity and moderate density. It is thought that units of this type are interbedded with the more indurated St. Bees Sandstone to form a passage group (see page 37).

The third sample, from Cargo near Carlisle, was a classic millet seed sand, grey-green in colour and friable. The extent of this highly permeable rock type is not known but if widespread in the Kirklinton Sandstone, the formation would clearly be a highly significant aquifer. Here again, the suggested cored borehole near Carlisle would produce very interesting and valuable data.

AREA 8

Formation : KIRKLINTON SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
405 V1	vf-f fr cs lam r sd	Rukholme Bridge, Brampton, Cumbs	NY 49256022	o/c	–	2.25	24.7	
V2				..	15	2.25	24.7	
V3				..	540	2.18	27.8	
HX1				..	347	2.18	27.6	
HX2				..	118	2.23	24.5	
412 V1	wg vf fr r sd fels	Carwinley Burn, Carwinley, Cumbs	NY 40327290	o/c	81	2.11	31.0	
H33				..	97	2.12	30.1	
H123				..	121	2.12	30.0	
421 V	cn fr wg f-m gy sd ms	River Eden, Cargo, Carlisle.	NY 37045972	o/c	6987	2.18	27.0	
H1-80				..	5397	2.18	27.6	
H2-80				..	6135	2.16	26.9	
H1-170				..	4941	2.18	27.5	
H2-170				..	6922	2.18	26.7	

From examination of the samples obtained from the Permian outcrops in southern Scotland, it appears that two quite different litho-facies are present, viz. a lower well cemented mainly poorly graded sandstone-breccia sequence, and an upper well graded laminated medium sand sequence characterised by a distinct lack of cementation. The possibility that these two facies are diachronous cannot be ruled out.

Whereas in the present study, both surface and subsurface samples were obtained of the breccia facies, only surface outcrop material was obtained of the uncemented sandstone facies, and the doubt remains as to whether the latter exist underground. It is important that this uncertainty is resolved in view of the promising nature of the uncemented sandstone facies as far as permeability is concerned.

With reference to the correlation of physical properties with lithology in detail, the sandstone-breccia sequence was examined in the borehole cores from No. 2 Well at the Imperial Chemical Industries factory at Drungans, near Dumfries (samples 329-1 to 329-24 and Fig.27). The coarse well cemented breccias have an intergranular permeability close to zero md; the cores however show in places complete gradation from breccia to pebbly sandstone, and as the proportion of finer grained matrix increases, permeability increases up to a maximum of about 50 md. Porosity in the breccias is very low, about 5-10%, with saturated density ranging from 2.52 to 2.65 gms cc^{-1}.

Certain poorly graded laminated sands, resembling units in the Penrith Sandstone (Area 8) have a permeability of between 10 and 100 md with porosity only rising from 12 to 15%. Examples of these types are 329-2, 329-3, 329-8 and 448.

The majority of the sandstones in the Dumfries section appear to be fine to medium grained well cemented types containing much locally derived clastic material, especially low grade metamorphic and feldspathic fragments. These units have a permeability of between 10 and 300 md, porosity generally between 10 and 18% and saturated density about 2.40 gms cc^{-1}.

Medium coarse friable sands of the type encountered so commonly at outcrop elsewhere, are restricted to few horizons, one of which is paradoxically very close to the bottom of No. 2 Well in the lowest proven part of the Basin. Inter-granular permeability however is still only moderate owing to the very poor grading of the material, (eg samples 329-7 and 329-24) in which permeability ranges between 300 and 1300 md. These sands display a striking texture of large 'millet seeds' up to granule size (2 mm) embedded in much finer grained angular material. Similar sandstones were also observed at the Kennel Bridge site near Comber in

Northern Ireland (sample Nos. 326) and in the Penrith Sandstone in Cumberland.

In marked contrast, the outcrop samples examined both from the Dumfries Basin, and from the related basins of Lochmaben, Thornhill and Mauchline are texturally quite different from the borehole and outcrop material from the vicinity of Dumfries. These outcrop samples were taken chiefly from disused quarries; the material tested was cut from the centre regions of quite large blocks and the plugs appear fresh and unweathered under the binocular microscope. Owing to their generally clean well-graded nature, these sands have been found to have a particularly high permeability ranging between 5000 and 10000 md, with porosity generally very much higher than in the Dumfries factory cores at between 25 and 30 per cent. In some of the coarser well graded but slightly cemented sands, porosity is slightly reduced to 18-23 per cent although permeability is in excess of 10000 md (eg samples 444 and 459).

Owing to the occurrence of laminae of fine cemented sand interbedded with the clean well graded and well rounded medium material, most of the outcrop samples were found to be markedly anisotropic with respect to permeability (cf samples 443, 444, 445 and 454).

On the basis of the physical property evidence alone, there is clearly a need to reconsider the stratigraphy of the Permian Sandstone in the Dumfries Basin.

AREA 9

Formation : PERMIAN SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
329-1HX	vc wc b	Drungans No. 2 B.H.,	NX94717486	27.1m	<1	2.65	5.8	
329-2V1	f-c lam wc br sd	Dumfries Factory (ICI), Dumfries		33.5m	17	2.40	14.1	
2V2				"	55	2.38	14.9	
2HX				"	80	2.53	16.2	
2HY				"	38	2.53	15.0	
329-3V1	f-c lam wc br sd			35.3m	40	2.39	14.4	
3V2				"	35	2.39	14.6	
3HX1				"	73	2.41	13.6	
3HX2				"	96	2.41	13.5	
3HY				"	52	2.43	12.2	
329-4V1	f-m pb wc br sd			43.2m	18	2.42	12.9	
4V2				"	34	2.40	14.2	
4HX1				"	38	2.43	14.3	
4HX2				"	37	2.41	13.4	
[illegible]					[illegible]	[illegible]	[illegible]	

AREA 9 Formation : PERMIAN SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
329-4HY	f-m pb wc br sd	Drungans No.2 B.H.,	NX 94717486	43.2m	3	2.47	10.5	
329-5V	vf br-gy wc sd	Dumfries Factory, (ICI), Dumfries		45.1m	<1	2.57	6.7	
5HX				"	<1	2.56	7.1	
5HY				"	<1	2.55	7.4	
329-6V	c slt-vf sd br wc			48.2m	2	2.48	10.1	
6HX1				"	1.4	2.46	10.4	
6HX2				"	–	2.50	11.5	
6HY				"	1.2	2.47	10.0	
329-7V1	vc fr pk sd lam			59.1m	–	2.31	18.0	
7V2				"	–	2.32	17.7	
7HX1				"	298 *	2.36	17.3	
7HX2				"	1335	2.32	18.4	
7HY				"	1198	2.31	18.5	
329-8V1	f-vc fr lam br sd			64.0m	82	2.30	18.4	
8V2				"	[illegible]	[illegible]	[illegible]	

AREA 9

Formation : PERMIAN SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
329-8HX1	f-vc fr lam br sd	Drungans No.2 B.H., Dumfries Factory, (ICI), Dumfries	NX94717486	64.0m	346	2.29	20.9	
8HX2				"	283	2.30	20.5	
8HX3				"	215	2.31	20.1	
8HX4				"	311	2.29	20.8	
329-9V1	f-c r sd mt with patchy cementation			68.2m	190	2.38	16.2	
9V2				"	241	2.39	15.3	
9V3				"	157	2.40	14.4	
9V4				"	197	2.41	14.0	
9V5				"	139	2.42	13.2	
9HX1				"	199	2.41	14.0	
9HX2				"	305	2.37	16.2	
9HX3				"	271	2.38	15.6	
9HX4				"	66*	2.41	15.1	
329-10V1	c wc b			70.0m	<1	2.52	11.9	
10V2					[illegible]	[illegible]	[illegible]	

AREA 9 Formation : PERMIAN SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
329-10H1	c wc b	Drungans No. 2 B.H., Dumfries Factory (ICI), Dumfries.	NX94717486	70.0m	6*	2.55	9.0	
10H2				"	29	2.52	9.6	
329-11V1	f-c dk r wc pb sd			122.0m	280	2.35	17.6	
11V2				"	284	2.34	18.2	
11HX1				"	77*	2.38	16.7	
11HX2				"	84	2.37	16.1	
11HX3				"	189	2.34	17.8	
11HY1				"	309	2.33	18.5	
11HY2				"	264	2.33	18.6	
329-12V1	f-c con dk r sd pb			123.2m	802	2.34	17.9	
12V2				"	862	2.35	17.5	
12V3				"	1229	2.35	15.5	
12HX1				"	133*	2.40	15.8	
12HY1				"	817	2.33	18.7	
12HY2				"	434	2.35	17.2	

AREA 9

Formation : PERMIAN SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
329 - 13V	f-m pb	Drungans No. 2 B.H.,	NX94717486	127.5 m	168	2.34	15.5	
13HX	fels dk r	Dumfries Factory, (ICI)		..	327	2.33	16.2	
13HY	sd wc	Dumfries		..	321	2.33	16.1	
329 - 14V	f-m gy			129.3 m	160	2.32	16.1	
14HX	wc sd			..	172	2.33	16.2	
14HY				..	195	2.33	16.4	
329 - 15V1	f-c wc			137.8 m	126	2.43	11.1	
15V2	dk r pb			..	46	2.48	8.9	
15HX	sd			..	150	2.41	12.1	
15HY				..	141	2.41	12.1	
329 - 16V1	dk r wc			138.1 m	35	2.55	9.6	
16HX1	cg with wc sand matrix			..	20 *	2.53	10.3	
16HX2				..	43	2.52	7.5	
329 - 17HX1	f-m pb			165.6 m	98	2.38	16.0	
17HX2	fels dk r			..	130	2.34	14.4	

AREA 9

Formation : PERMIAN SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Gentrifuge Specific Yield per cent
329 - 17HY1	f-m pb fels dk r wc sd	Drungans No. 2 B.H.,	NX 94717486	165.6m	170	2.34	15.3	
329 - 18V1	f-m pb fels dk r wc sd	Dumfries Factory (ICI),		167.8m	26 *	2.41	14.2	
18V2		Dumfries.		..	150	2.34	14.5	
18HX1				..	4	2.43	12.9	
18HX2				..	139	2.35	14.4	
18HY1				..	33	2.36	12.8	
18HY2				..	26	2.38	12.3	
329- 19V1	f wc fels pk sd			176.9m	75	2.33	15.3	
19V2				..	112	2.32	15.2	
19V3				..	81	2.33	14.9	
19V4				..	71	2.33	14.7	
19HX1				..	50	—	—	
19HX2				..	22	2.35	13.7	
19HX3				..	80	2.36	17.0	
329 - 20V[illegible]	f-c wc [illegible]			[illegible]	[illegible]	2.39	13.7	

AREA 9

Formation : PERMIAN SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
329- 20HX	f-c wc pb dk r sd	Drungans No. 2 B.H., Dumfries Factory (ICI), Dumfries	NX94717486	186.1m	14	2.40	13.1	
20HY				..	14	2.40	13.2	
329- 21V	f-c wc pb dk r sd			191.3m	11	2.40	13.1	
21HX1				..	18	2.39	13.8	
21HX2				..	11*	2.41	13.9	
21HY				..	24	2.38	13.7	
329- 22V1	vf lam wc br-r sd			197.3m	<1*	2.41	14.1	
22V2				..	5	2.37	14.5	
22HX				..	36	2.40	12.7	
22HY				..	11	2.42	11.9	
329- 23V	f wc lam dk r sd			198.6m	8	2.34	16.6	
23HX				..	45	2.35	16.2	
23HY				..	51	2.35	15.9	
329- 24V1	f-m lam con br sd			207.4m	663	2.30	20.3	
24V2				..	319	2.28	20.5	

AREA 9

Formation : PERMIAN SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air pemeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
329 - 24V3	f-m lam con br sd	Drungans No.2 B.H., Dumfries Factory (ICI) Dumfries.	NX94717486	207.4m	571	2, 29	20,3	
24HX1				..	665	2,29	20,6	
24HX2				..	623	2,29	20,8	
24HY1				..	552	2,29	20,0	
24HY2				..	1035	2, 29	20.0	
442 V1	f-m con br-r sd cn	Kilroy, Holywood, Dumfries	NX91738342	o/c	1553	2, 25	24.3	
V2				..	1776	2, 24	24.8	
HX1				..	1309	2, 24	25,1	
HX2				..	2428	2, 23	25, 3	
HY1				..	1601	2, 25	24.4	
HY2				..	2243	2, 23	25,4	
443 V1	cn m r sd fr with f lam	Milligranton Quarry, Milliganton, Dumfries	NX90958354	o/c	198	2. 28	22.9	
V2				..	276	2, 28	22,8	
HX1				..	5329	2, 27	22,9	
HX				..	6072	2, 27	23,0	

In those areas away from culminations in the uneven pre-Permian surface in Ulster, where extensive deposits of breccias lithologically similar to those in the Dumfries Basin occur, beds of friable Permian sandstone are known to be present. The true geographical extent of these sandstones has yet to be determined, and in view of the almost complete lack of exposure, this will have to be accomplished by drilling.

All the small amount of data presented in this account has been obtained from a single partially cored borehole drilled at Kennel Bridge, near Comber, Co. Down. Such was the state of knowledge on the three dimensional distribution of these sandstones that their presence at this locality was unexpected.

The samples from the lower half of the Kennel Bridge BH (Nos. 326-1 to 326-9) suggest that these sandstones are particularly permeable; intergranular permeability is between 2000 and 12000 md and on textural grounds they are likely to be markedly anisotropic, although this was not demonstrated by the laboratory data. Porosity, ranging from 25 to 30% is moderate to high. The sandstones are similar in both lithology and physical properties to the more poorly graded, outcrop samples from the Permian of south of Scotland (Area 9).

AREA 10

Formation : PERMIAN SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
326-1HX	fr f-m r sd	IGS Kennel Bridge	J 455 700	51.2m	4001	2.12	30.2	
326-2	m-c br r cs sd	BH. Comber, Co. Down		53.3m	970	2.22	26.8	
326-3	br-r pb sd			55.5m	3385	2.40	17.5	
326-4V1	cn m wg fr r sd			56.7m	6382	2.12	28.6	
4V2				..	4750	2.12	28.9	
4CD				..	6337	2.19	26.2	
4TT				..	2297	2.18	25.6	
4HX				..	6373	2.13	29.0	
4HY				..	7710	2.16	29.8	
326-5CD	f-c lam fr r sd			59.7m	1781	2.23	22.3	
326-6	m lam r-br sd			61.3m	841 *	2.20	28.2	
326-7HX	f-c lam fr r sd			63.1m	12268	2.22	24.4	
326-8V1	f-c fr r sd			64.6m	–	2.15	28.6	
8V2				..	3759	2.16	27.4	
8V3				..	–	2.19	27.8	

AREA 10 Formation: PERMIAN SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
326-9	dk r b con	IGS Kennel Bridge, BH, Comber, Co. Down	J455700	66.1m	—	2.37	15.7	

The Bunter Sandstone in Northern Ireland was studied mainly from subsurface samples, owing to the scarcity of surface outcrops and the thick mantle of drift deposits. A large amount of core material was available from a series of deep cored boreholes drilled in Ulster by the Institute in the early 1960s.

The material recovered from most of these holes showed the Bunter Sandstone to be generally fine grained, with a significant proportion of siltstone and very fine sand. The thick sequences in Tyrone, samples in the Kingsmill, Twyfords Mill and Ballyloughan Bridge B.Hs are particularly uniform; the new Haw Hill B.H. in the Newtownards Basin, Co. Down produced sandstone only slightly coarser in grain size, whereas the few samples available from Portmore on the north coast of Ulster gave a totally different impression of the formation.

In the Kingsmill B.H., much of the sandstone has a low permeability of less than 20 md, but porosity is generally moderate ranging from 20 to 30 per cent. Density is moderate also at about 2.25 gms. cc^{-1}. In slightly better graded fine sands, permeability rises to a few hundred md (669-8 and 669-19), and these preliminary results suggest that anisotropy is probably very common, induced by the widespread lamination of many of the sandy units.

In the Twyfords Mill B.H. also in Tyrone, the same picture of low to very low intergranular permeability and medium porosity prevails. The sequence is slightly less permeable than at Kingsmill, only two sampled horizons having a permeability approaching 100 md, with many being below the limit of resolution ($<$ 1 md). There is no tendency for aquifer properties to have higher values near the surface.

Again in Tyrone, the sandstone in the Ballyloughan Bridge B.H. produced very disappointing results for aquifer properties; the bulk of the formation has a permeability here of only about 10 md with porosity of 20-24 per cent and density of 2.25-2.30 gms cc^{-1}. A sample of clean medium sand from near the base gave much higher values (671-13) but this particular type of lithology apparently forms only a very small part of the total thickness of the formation.

The few samples examined from the Portmore B.H. were too unrepresentative to form the basis of a reliable evaluation of the Bunter sequence in this area. Unfortunately, much of the core material had been disposed of prior to the start of the Northern Ireland operation for the project. Fine to coarse sandstone from between 1350 and 1675 m was found to have a permeability of between 100 and 500 md, porosity reduced by cementation to between 13 and 24 per cent, and density rather high at between 2.35 and 2.40 gms. cc^{-1}. In view of the current commercial interest in the Irish continental shelf, it is most unfortunate that the Portmore cores and, indeed, those from Larne were not available for this project.

They would have yielded much valuable information on off-shore hydrocarbon prospects.

Finally, in the Newtownards Basin, the Bunter Sandstone was fully cored in the Haw Hill B.H. near Comber (see Fig.28). Results from this site suggest that the Bunter is significantly more permeable here than in Tyrone, with intergranular permeability commonly between 100 and 300 md, porosity very constant at 25-28 per cent and density again moderate at 2.20 to 2.30 gms cc^{-1}. The principal cause of the rise in permeability is better sorting, slightly coarser grain size and less induration. Anisotropy is common with horizontal permeability significantly higher than vertical in many units. As elsewhere, however, mudstone and siltstone bands are common in the sequence, becoming dominant over sandstone towards the base. These presumably reduce vertical permeability to effectively zero except where jointing allows movement of ground water across bedding planes.

Summarising therefore, the intergranular permeability of the Bunter Sandstone in Ulster is low to very low almost everywhere, a reflection of poor sorting, fine grain size and rather widespread induration. Rather surprisingly, porosity remains moderate which suggests that ramifying systems of pore channels are present in the sandstone, but that these have extremely small dimensions. There is some evidence to suggest that although deeply buried, the formation may have a much higher permeability offshore.

AREA 10 Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
668-2V	cn f-m lam r sd	IGS Larne B.H., Larne, Co. Antrim.	D4010 0239	1104m	164	2.22	25.1	
2HX				..	438	2.21	25.1	
2HY				..	244	2.21	25.5	
668-3V	cn f-m lam r sd			1110m	159	2.24	24.1	
3HX				..	245	2.21	25.4	
3HY				..	235	2.21	25.6	
669-1H	f lam con r sd	IGS Kingsmill BH, Grange, Co. Tyrone	H 864759	13.0m	27	2.12	32.4	
669-2V	f con r. sd			30.2m	3	2.27	24.0	
2H				..	8	2.27	24.0	
669-3V	f-c lam fr r sd			41.3m	13	2.16	28.8	
3H				..	–	2.17	28.2	
669-4V	vf-f lam con r sd			45.0m	<1	2.22	26.4	
4HX				..	3	2.19	27.7	
4P				..	–	[illegible]	[illegible]	
669-5	f-m la [illegible]			49.2m	2	[illegible]	26.0	

AREA 10

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth - or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
669-5H	f-m lam con r sd	IGS Kingsmill B.H., Grange, Co. Tyrone	H 864759	49.2m	102	2.22	26.1	
669-6H	f con r sd			62.2m	6	2.22	25.6	
669-7V	f con r sd			74.7m	<1	2.26	24.1	
7H				..	<1	2.27	23.5	
669-8V	f-m con r sd cement patches			84.9m	245	2.21	27.2	
8H				..	276	2.18	28.9	
669-9V	c slt dk br mic lam			91.3m	<1	2.24	9.4	
9H				..	<1	2.26	5.8	
669-10V	vf-f lam r con sd			106.7m	7	2.17	29.1	
10H				..	16	2.16	29.5	
669-11V	vf-c lam fr r sd			111.9m	–	2.31	21.3	
11H				..	424	2.29	22.0	
669-12V	vf-m wc pk sd			129.8m	8	2.35	19.9	
12H				..	7	2.36	14.5	
669-13V	f con r sd			142.6m	114	2.21	26.1	

AREA 10 Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
669-13H	f con r sd	IGS Kingsmill BH, Grange Co. Tyrone	H864759	142.6m	184	2.21	26.6	
669-14V	c slt-vf lam r sd			153.8m	-	2.30	21.5	
14H				..	-	2.32	21.0	
669-15V	wc c slt-vf sd lam			163.1m	<1	2.45	13.7	
15H				..	<1	2.46	13.1	
669-16H	wc c slt lam gy-br			166.0m	<1	2.49	3.8	
669-17V	wc vf-f sd mf			184.7m	0.5	2.32	20.4	
17H				..	11	2.31	21.1	
669-18V	vf-f lam pk sd wc			192.3m	<1	2.41	15.8	
18H				..	<1	2.40	16.5	
669-19V	f mic con cs r sd			206.4m	142	2.19	27.3	
19H				..	157	2.20	27.3	
669-20V	c slt-vf r con sd			220.7m	<1	2.25	23.8	
20H				..	0.4	2.26	23.5	

AREA 10 Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
670-4V	f lt br sd	IGS Twyfords Mill BH, Laghey Corner, Co. Tyrone.	H842630	75.6m	–	2.15	28.3	
4H				"	–	2.17	28.2	
670-5V	vf-c lam ?fels lt br sd con			92.1m	<1	2.23	24.1	
5H				"	<1	2.27	22.3	
670-6V	con f-m fels lt br sd			132.9m	8	2.21	25.6	
6H				"	138	2.20	26.9	
670-7V	md f-m con lt br sd			143.3m	94	2.16	28.6	
7H				"	89	2.15	29.2	
670-8V	r-gy mt lam mic slt			154.5m	<1	2.19	16.5	
8H				"	<1	2.19	19.4	
670-9V	con vf-f r sd			167.6m	<1	2.15	29.3	
9H				"	0.4	2.15	28.9	
670-10V	con vf-f r sd			185.9m	14	2.15	29.4	
10H				"	13	2.16	28.6	
670-11V	con vf-f [illegible]			200.7m	<1	2.27	22.5	

AREA 10 Formation: BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
670-11HX	con vf-f r sd	IGS Twyfords Mill BH, Laghy Corner, Co. Tyrone	H842630	200.7m	1	2.22	25.9	
11HY				"	<1	2.22	25.2	
670-12V	wc vf-f lt r sd			213.7m	<1	2.33	20.3	
12HX				"	0.4	2.29	22.1	
12HY				"	<1	2.27	23.2	
670-13V	vf-f wc lt br sd			231.5m	7	2.19	27.3	
13H				"	11	2.19	27.3	
670-14V	dk r-gy lam mt slt			242.5m	<1	2.27	18.9	
14H				"	<1	2.35	4.7	
670-15V	dk-r gy lam mt c slt-vf sd			259.1m	<1	2.25	8.1	
15H				"	<1	2.26	8.9	
670-16V	vf con mic r sd			274.3m	10	2.22	25.9	
16H				"	20	2.20	26.5	
670-17V	r lam c slt-vf sd			289.9m	<1	2.33	19.6	
17H				"	<1	2.36	19.2	

AREA 10

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
670-18H	wc vf-f sd	IGS Twyfords Mill BH.	H 842630	304.8m	<1	2.38	17.5	
671-1V	fr md m-c r sd	IGS Ballylougham Bridge BH., Co. Tyrone	H 847804	9.4m	33	-	-	
1H				..	311	-	-	
671-2V	wc m-c r sd			18.6m	<1	2.28	21.3	
2H	f-m lam fels r-gy sd			..	14	2.22	24.3	
671-3V	f m lam fels sd o-br			30.5m	<1	2.23	23.1	
3H				..	<1	2.25	22.8	
671-4V	mt c slt-f sd y-br			45.7m	<1	2.30	19.2	
4H				..	<1	2.29	21.1	
671-5V	f-m wc fels br sd			47.8m	7	2.22	23.7	
5H				..	4	2.22	23.7	
671-6V	vf-m wc fels r sd			62.6m	4	2.24	24.0	
6H				..	6	2.24	23.0	
671-7V	wc f lam cs fels sd			76.2m	2	2.26	22.3	
7HX				..	13	2.27	22.4	

AREA 10 Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-3}	Porosity per cent	Centrifuge Specific Yield per cent
671-7HY	wc f lam cs fels sd	IGS Ballylunghan Bridge BH. Co.Tyrone	H 847804	76.2m	7	2.27	21.8	
671-8V	f lam wc dkr sd			92.4m	<1	2.26	22.8	
8HX				..	17	2.25	24.4	
8HY				..	2	2.26	24.2	
671-9H	vf-m mt r-gy sd wc			106.8m	14	2.32	20.6	
671-10V	vf-m lam wc r sd			121.0m	1	2.28	22.7	
10H				..	19	2.28	22.8	
671-11V	f-vf lam wc r sd			137.0m	<1	2.27	23.3	
11H				..	18	2.27	23.4	
671-12V	vf con r sd cement clots			155.1m	30	2.21	27.2	
12H				..	38	2.20	27.8	
671-13V	m wg cn fr pk-br sd			167.5m	2210	2.19	28.9	
13H				..	3607	2.20	28.9	
672-1V	lam con vf-f sd	IGS Portmore B.H., Portmore, Co.Antrim.	D069435	1260.5m	60	2.33	19.7	
1HX				..	131	2.32	19.9	

AREA 10 Formation: BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
672-1HY	lam con vf-f sd	IGS Portmore B.H., Portmore, Co. Antrim.	D069435	1260.5m	96	2.33	19.7	
672-2V	bf f-c wc sd gn mud flakes			1351.2m	105	2.35	18.8	
2HX				"	298	2.40	19.1	
2HY				"	532	2.34	19.4	
672-3V	f-m wg wc r sd			1376.2m	591	2.38	24.3	
3HX				"	710	2.28	22.8	
3HY				"	727	2.29	22.1	
672-4V	wc m-c pb dk r sd			1557.0m	103	2.39	16.3	
4HX				"	109	2.36	16.4	
4HY				"	378	2.36	18.1	
672-5V	c dk r wc sd muddy matrix.			1674.8m	-	2.45	13.8	
5HX				"	2	2.47	13.3	
5HY				"	24	2.45	14.6	
672-6V	wc vf-f p-r sd			1698.0m	<1	2.52	11.2	
6HX				"	<1	2.52	12.6	

AREA 10 Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
672-6HY	wc vf-f p-r sd	IGS Portmore B.H., Portmore, Co. Antrim.	D069435	1698.0m	<1	2.52	11.6	
672-7V	f-vc pb r sd			1801.6m	76	2.36	18.8	
7HX				..	100	2.35	18.9	
7HY				..	–	2.34	19.3	
672-8V	wc c pb r sd			1883.7m	3	2.52	9.6	
8HX				..	–	2.53	8.5	
673-1V	vf lam con r sd	IGS Haw Hill B.H., Comber, Co. Down	J48306952	29.6m	–	2.28	24.6	
1H				..	27	2.27	24.5	
673-2V	f lam mic r sd			30.6m	81	2.27	25.7	
2H				..	111	2.28	26.8	
673-3V	wg f pk sd cement clots			31.5m	336	2.27	24.1	
3H				..	458	2.24	26.0	
673-4V	wg f pk sd cement clots			32.2m	200	2.20	28.0	
4HX				..	304	2.21	27.6	
673-5V	wg f pk sd			33.4m	145	2.25	24.9	

AREA 10 Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
673-5H	wg f pk sd mic lam	IGS Haw Hill BH, Comber, Co. Down	J48306952	33.4m	95	2.24	25.5	
673-6V	lam c slt-fsd r con			35.1m	–	2.34	20.1	
6H				..	8	2.34	20.2	
6CD				..	33	2.26	24.7	
673-7V	wg f pk sd with cement clots			36.8m	272	2.26	24.8	
7H				..	173	2.24	25.3	
673-8V	wc wg f lt br sd			38.2m	262	2.28	24.5	
8H				..	232	2.29	23.8	
673-9V	f lam r sd con			39.6m	188	2.15	30.2	
9H				..	429	2.14	30.9	
673-10V	cs wg f lam r sd			41.3m	424	2.13	32.0	
10H				..	487	2.14	31.6	
673-11V	vf-f lam Con r sd cement clots			42.1m	168	2.18	28.7	
11H				..	184	2.20	27.5	
673-12V	vf-f con mic r sd			45.9m	23	2.26	24.8	

AREA 10

Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density $g\ cc^{-1}$	Porosity per cent	Centrifuge Specific Yield per cent
673-12H	vf-f con mic r sd	IGS Haw Hill B.H., Comber, Co. Down	J48306952	45.9m	74	2.24	25.6	
673-13V	vf-f con mic r sd			47.4m	106	2.21	27.4	
13H				"	167	2.20	27.9	
673-14V	vf-f con lam mic r sd			48.7m	15	2.24	25.6	
14H				"	168	2.23	26.0	
673-15V	vf-f con lam mic r sd			50.2m	29	2.25	25.3	
15H				"	120	2.26	25.3	
673-16V	vf-f pk-gy con sd cement clots			51.9m	64	2.26	25.3	
16H				"	54	2.27	24.7	
673-17V	vf-f lam con r sd			53.4m	159	2.20	28.3	
17H				"	140	2.20	27.8	
673-18V	vf-f lam pk-gy con sd			54.4m	65	2.26	25.0	
18H				"	364	2.22	26.9	
673-19V	vf-f r sd slt seam			55.4m	2	2.24	25.9	
19H	f wg r sd			"	584	2.13	31.9	

AREA 10 Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
673-20V	f wg con r sd	IGS Haw Hill B.H., Comber, Co. Down	J48306952	56.4m	575	2.14	31.3	
20H				..	644	2.14	31.2	
673-21V	wc vf-f lam r sd			58.0m	4	2.32	21.1	
21H				..	16	2.34	20.1	
673-22V	vf-f lam con r sd cement clots			59.4m	90	2.23	26.5	
22H				..	139	2.24	25.7	
673-23V	vf-f lam con r sd cement clots			60.8m	117	2.20	27.6	
23H				..	91	2.23	26.3	
673-24V	vf lam con mic r sd			62.5m	3	2.29	22.3	
24H				..	-	2.28	23.2	
673-25V	vf lam con r sd			64.0m	109	2.23	25.8	
25H				..	139	2.23	25.6	
673-26V	f-m wc pk-gy sd mf			65.2m	9	2.39	17.5	
26H	vf-f wc pk sd			..	184	2.29	23.1	
673-27V	f gn-gy wc mic sd			44.1m	22	2.31	20.5	

AREA 10 Formation : BUNTER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
673-27CD	vf mic lam sd r con	IGS Haw Hill B.H.	J48306952	44.1m	30	2.32	21.4	
674 V	vf-m lam gy-p sd bleached & ? recrystallized	Scrabo Hill, Newtonards, Co. Antrim		o/c	<1	2.28	22.8	
HX				[loose block]	8	2.26	23.7	
HY				"	15	2.28	23.2	
675 Y	f-m lam con pk sd			o/c	22	2.24	24.5	
HX				"	163	2.25	24.4	
HY				"	121	2.26	23.6	
691 V	c slt-m lam r sd	New Dry Dock Site, Belfast B.H.1	J363768	34.1m	<1	2.31	20.5	
H				"	<1	2.40	10.6	
692-1V	vf-f con r sd lam	New Dry Dock Site, Belfast, B.H.2	J363768	28.7m	<1	2.31	21.1	
1H				"	<1	2.30	21.5	
692-2V	vf-m lam cs r sd con			29.3m	-	2.30	21.2	
2H				"	20	2.27	23.1	
693 H	c slt-m lam con r sd	New Dry Dock Site, BH3	J363768	26.8m	<1	2.38	17.8	

The study as regards the Keuper Sandstone of Northern Ireland was hampered by lack of samples. Unfortunately the project was begun too late to obtain cores produced during the drilling by IGS of the series of deep boreholes around the margins of the Antrim Plateau.

In fact only 5 samples were obtained and these showed a wide range of physical properties. All that can be concluded is that some parts of the Keuper Sandstone particularly in the Larne and Macgilligan areas, are relatively poorly consolidated, of moderate to high porosity and moderately permeable. Elsewhere, for example in Co.Tyrone, the permeability can be extremely low, although porosity remains moderate - a situation caused by much finer grain size.

Small segregations of rock salt were present in the sample from the Larne BH. In the Magilligan BH sample, numerous small vugs seemed to point to the original presence of saline blebs there also. In fact, sample 676 is extremely salty although no crystalline halite is present. Some of the blebs in sample 668-1 have been partially dissolved, no doubt during the porosity measurement process, and here vugs of the type seen in the Magilligan sample appear to be in an incipient stage.

Similar small vugs have been noted in quite a large number of samples from Permo Triassic sandstones in other regions of the UK where today there is no close stratigraphic or structural connexion with the salt-bearing members of the Triassic sequence. Is it possible that these formations too once contained halite blebs and saline ground water? This theory has important implications in regard to the palaeogeography of Triassic and post-Triassic times.

AREA 10

Formation : KEUPER SANDSTONE

Plug Code	Lithology	Locality	National Grid Reference	Depth or Outcrop	Intergranular air permeability, millidarcys	Saturated density g cc^{-1}	Porosity per cent	Centrifuge Specific Yield per cent
668-1V	f-c con r sd with blebs of rock salt	IGS Larne B.H., Larne, Co. Antrim.	D40100239	1088m	65	2.27	22.8	
1HX				"	93	2.28	22.4	
1HY				"	78	2.28	22.5	
670-1V	bf f-m fr sd	IGS Twyfords Mill B.H. Laghey Corner, Co. Tyrone	H 842630	39.7m	-	2.10	31.9	
1H				"	842	2.09	32.2	
670-2V	bf vf lam sd			49.1m	<1	2.15	29.2	
2H				"	<1	2.18	27.7	
670-3V	vf-f pk-gy wc sd			61.1m	<1	2.26	23.3	
3H				"	<1	2.29	22.0	
676 V	f-m fr r sd	IGS Magilligan B.H., Co. Londonderry.	C68303534	between 622&637m	31	2.18	27.9	
HX				"	483	2.19	26.9	
HY				"	211	2.22	25.5	

5.4. CONCLUSIONS

The data presented in this section demonstrates that in the Permo-Trias in the United Kingdom, lithology is the major factor controlling aquifer properties. Within the general term 'lithology' should be included grain size distribution, sorting and the effect of diagenetic changes such as cementation and consolidation. Clearly, the sandstones, breccias and conglomerates as we see them today are the product of both the processes operating at the time of deposition, and diagenetic processes which have had a period of over 150 million years in which to bring about their changes.

The ranges over which the values of physical properties vary testify, however, to the rather heterogeneous nature of the deposits and it will be shown in the following chapter that, many parts of the sequence can be expected to yield ground water only by fissure flow.

Finally, within Area 5 there is a measure of agreement between the data presented by Bow, Howell and Thompson (1970) and that presented here for the sandstone subdivision. Their conclusion that the Keuper is more permeable than the Bunter has been confirmed, also that the Keuper shows a greater degree of anisotropy that the middle part of the Bunter series (referred to here as Bunter Pebble Beds).

CHAPTER SIX : Statistical distribution of aquifer property data

CHAPTER SIX : STATISTICAL DISTRIBUTION OF AQUIFER PROPERTY DATA

6.1. INTRODUCTION

In view of the deficiency of data on the formations under review, it is considered justifiable at the present time to come to some general conclusions about the observed variation in the physical properties. This can be most easily accomplished by considering the test results as probability distributions, log-normal in the case of permeability, and arithmetic-normal in the case of porosity.

Clearly, there are some gross assumptions involved in adopting this method of analysis, the principal of which is that the samples tested were statistically representative of the formation being studied. In other words, to take an example, if the lower 40% of the formation thickness was uniformly cemented over the whole of an Area, then 40% of the samples taken should have been of the cemented type. This is a serious problem as in some areas, particularly in the north of England and Scotland, the actual lithological variation of the formation in three-dimensions is very imperfectly known.

The second assumption is that the properties of outcrop samples are essentially the same as those from boreholes. On the whole, serious differences between surface and subsurface samples have not been observed,but there is no doubt that complete sequences of borehole cores provide the best basis for an analysis of the variation of the physical properties of formations on a probability basis. Such has been the case with work carried out on oil reservoirs, referred to by Davis (1969).

Fortunately, a significant number of samples examined during the project were borehole cores and these were to as great an extent as possible, sampled at fixed intervals rather than at geologically interesting horizons.

In summary, therefore, it is thought that consideration of the data on a probability basis, although involving a number of assumptions is justified in the present state of knowledge and can be used to good purpose in predicting the likely magnitude of physical properties in a formation. Insufficient data was available for this method to be applied to all the subdivisions of the Permo-Trias, but it has been attempted for the following formations :

AREA 1	BUNTER PEBBLE BEDS (sand facies)
	UPPER MOTTLED SANDSTONE
	LOWER KEUPER SANDSTONE
AREA 2	BUNTER PEBBLE BEDS
AREA 3	LOWER MOTTLED SANDSTONE
	BUNTER PEBBLE BEDS
AREA 4	LOWER MOTTLED SANDSTONE
	BUNTER PEBBLE BEDS (sand facies)

AREA 5	BUNTER PEBBLE BEDS
	UPPER MOTTLED SANDSTONE
	KEUPER SANDSTONE
AREA 6	BUNTER SANDSTONE (SOUTH OF YORK)
	BUNTER SANDSTONE (NORTH OF YORK)
AREA 7	BUNTER SANDSTONE
	ST. BEES SANDSTONE
AREA 8	PENRITH SANDSTONE
	ST. BEES SANDSTONE
AREA 9	PERMIAN SANDSTONE (outcrop)
	PERMIAN SANDSTONE (subsurface)
AREA 10	BUNTER SANDSTONE

6.2. THE PROBABILITY CURVE

Many types of statistical distributions may be distinguished by plotting data on probability paper. The charts are so designed that a normal (or Gaussian) distribution produces a virtually straight line on the paper when probability is plotted against the parameter whose frequency distribution is being investigated. The slope of the line is an indication of the spread of the values and the length of the line signifies the relative importance of the "tails" of the distribution.

	[illegible]	V	H	V	H	V	H	V	H	V	H
AREA 1	BUNTER PEBBLE BEDS *	-	-	1900	3300	4200	5550	6500	9500	-	-
	UPPER MOTTLED SANDSTONE	1.5	25	150	520	1260	1620	2630	3390	-	6920
	LOWER KEUPER SANDSTONE	-	-	120	260	830	1450	2400	3980	-	-
AREA 2	BUNTER PEBBLE BEDS	130	410	1150	1860	3550	4670	6300	8500	-	-
AREA 3	LOWER MOTTLED SANDSTONE	-	1300	-	2640	-	4300	-	7000	-	-
	BUNTER PEBBLE BEDS	-	-	38	280	1330	3240	-	5250	-	-
AREA 4	LOWER MOTTLED SANDSTONE	-	-	18	100	440	2040	4680	6600	-	-
	BUNTER PEBBLE BEDS	-	10	150	320	1620	2000	3720	5010	10000	-
AREA 5	BUNTER PEBBLE BEDS	-	1.5	32	150	380	670	1290	2690	3470	6460
	UPPER MOTTLED SANDSTONE	1.1	2.0	25	260	525	2240	3160	4370	8130	8320
	KEUPER SANDSTONE	5.3	11	380	1175	1500	2880	3160	4900	8500	9550
AREA 6	BUNTER SANDSTONE (south of York)	-	65	430	620	1250	1940	3100	4400	8500	-
	BUNTER SANDSTONE	-	-	22	67	120	266	750	1059	-	2512
AREA 7	BUNTER SANDSTONE	-	-	3.2	17	32	133	135	479	-	-
	ST. BEES SANDSTONE	-	0.02	0.19	0.4	1.3	4.7	11	36	102	251

* Sand facies only

	PROBABILITY	0.95		0.75		0.50		0.25		0.05	
		V	H	V	H	V	H	V	H	V	H
AREA 8	PENRITH SANDSTONE	-	1.8	65	340	440	1100	1700	3720	-	-
	ST. BEES SANDSTONE	48	58	170	220	295	400	560	740	-	-
AREA 9	PERMIAN SANDSTONE * (outcrop)	-	430	270	1680	1320	3760	2950	5370	-	8710
	PERMIAN SANDSTONE (subsurface)	2	-	39	32	100	85	210	230	690	-
AREA 10	BUNTER SANDSTONE	-	-	-	1.7	11	29	120	200	490	620

* Quantity of data inadequate.

The great advantage of this type of representation of data over either tables or histograms is that an estimate of the likely magnitude of a particular parameter can be read off as a probability. Thus, using these charts one can easily compare awkward distributionsof data which cannot be approximated to any of the common statistical distributions.

In the present study, these charts will be used to compare permeability and porosity in different formations on a probability basis. In this,way, the true differences between the various sandstones become immediately apparent whereas to arrive at the same conslusion by comparing lithology with aquifer properties would take a good deal longer and be much more laborious and susceptible to error.

6.3. PROBABILITY CURVE ANALYSIS : PERMEABILITY

Table 15 gives the results of analysing Figs. 50-69 which indicate the distribution of values(vertical and horizontal being considered separately) for the 20 sandstone subdivisions om which sufficient data was obtained. Probability is expressed as the likelihood that the intergranular permeability of a random sample of the formation will exceed the stated value. Points are plotted every half logarithmic cycle in order to improve the discrimination of the curve. This effectively describes the logarithmic variation in permeability values.

Table 16 lists in descending order of permeability, the subdivisions of the sandstone sequence, on the basis of their horizontal permeability value which has a probability of 0.50 :-

TABLE 16. VALUES OF HORIZONTAL PERMEABILITY & THE ANISOTROPY RATIO, K_H/K_V WITH A PROBABILITY OF 0.50

			K_H/K_V P = 0.50
BUNTER PEBBLE BEDS (sand facies)	AREA 1	5550 md	1.32
BUNTER PEBBLE BEDS	AREA 2	4670 md	1.32
LOWER MOTTLED SANDSTONE	AREA 3	4300 md	-
PERMIAN SANDSTONE (outcrop sands)	AREA 9	3760 md	2.85
BUNTER PEBBLE BEDS	AREA 3	3240 md	2.44
KEUPER SANDSTONE	AREA 5	2880 md	1.93
UPPER MOTTLED SANDSTONE	AREA 5	2240 md	4.27
LOWER MOTTLED SANDSTONE	AREA 4	2040 md	4.63
BUNTER PEBBLE BEDS	AREA 4	2000 md	1.24
BUNTER SANDSTONE	AREA 6 (south)	1940 md	1.55
UPPER MOTTLED SANDSTONE	AREA 1	1620 md	1.28
LOWER KEUPER SANDSTONE	AREA 1	1450 md	1.75
PENRITH SANDSTONE	AREA 8	1100 md	2.50
BUNTER PEBBLE BEDS	AREA 5	670 md	1.76
ST. BEES SANDSTONE	AREA 8	400 md	1.36
BUNTER SANDSTONE	AREA 6 (north)	266 md	2.22
BUNTER SANDSTONE	AREA 7	133 md	4.15
PERMIAN SANDSTONE (subsurface)	AREA 9	85 md	0.85
BUNTER SANDSTONE	AREA 10	29 md	2.64
ST. BEES SANDSTONE	AREA 7	4.7 md	3.55

Table 16 fulfils one of the principal objectives of the study, viz. the quantitative discrimination between the various sandstone subdivisions of the Permo-Trias sequence with respect to their permeability. This has now been accomplished, although nothing like sufficient samples have been examined in order for these results to be any more than a preliminary assessment.

Referring to the curves themselves, (Figs. 50-69), one or two points should be made.

i) Vertical permeability is exceeded by horizontal permeability in practically every curve, indicating that isotropic sandstone is very rare in the Permo-Trias sequence. The departure of the vertical curve to the right of the horizontal curve is an indication of the degree of anisotropy, which is expressed in terms of ratios on Table 16. It appears to reach a maximum in parts of the Lower and Upper Mottled Sandstone, which might be expected from their dominantly laminated texture. It is surprisingly high in the Bunter Sandstone of North Lancashire and of Northern Ireland, and again, as expected, is moderate to high in the Penrith Sandstone and Permian Sandstone of Southern Scotland. On the other hand, most of the Bunter Pebble Beds (sand facies) is only slightly anisotropic, a situation also found in the Keuper Sandstone. This is presumably related to the coarser grain size of these sandstones, and a relative absence of laminated material. The only subdivision showing virtual isotropy was the sub-surface material from the Dumfries Basin in Area 9, a rather unlikely place to discover it.

.) There is a tendency in some of the frequency distributions for anisotropy to decrease with increasing magnitude of permeability, eg in the Upper Mottled Sandstone of Area 1 (Fig.51), the Keuper Sandstone of Area 5 (Fig.60) and Bunter Sandstone (north) of Area 6 (Fig.62). This is again ascribed to very obvious increase in grain size in the more permeable sandy units.

i) The distribution curve for six of the sandstone subdivisions extends over the entire measured permeability range from less than 1 to over 10000 md. The formations are as follows :-

Lower Keuper Sandstone	Area 1	(Fig.52)
Upper Mottled Sandstone	Area 1	(Fig.51)
Lower Mottled Sandstone	Area 4	(Fig.56)
Bunter Pebble Beds	Area 5	(Fig.58)
Upper Mottled Sandstone	Area 5	(Fig.59)
Penrith Sandstone	Area 8	(Fig.66)

The presence of such wide variation in these beds is a direct reflection of marked lithological change within these designated Areas. This suggests that the designated Areas are not the zones of relatively constant lithology that they have been assumed to be in this study. However, further subdivision of the Permo-Trias outcrop is impracticable without a further even more intensive sampling operation. It is therefore, concluded that the extended range of these probability curves should be taken as a warning that within the Areas, considerable lithological variation does exist and that this has a direct effect on formation permeability. The assumption of a single value for this property, in, for example, the Penrith Sandstone is therefore most unwise and the whole distribution curve should be considered in relation to the lithology of the particular section of the formation under study. Further research is clearly required on such problems as aquifer property variation <u>within</u> the cemented zones of, for instance, the Penrith Sandstone and the Upper Mottled Sandstone.

6.4. SUMMARY : PERMEABILITY

The examination of the permeability data on a probability basis demonstrates that very marked differences exist between the sandstone formations in different parts of the country. The most permeable beds are without doubt the coarse friable Bunter sands of the English Midlands. These are closely followed by the Lower and Upper Mottled sandstones of the same area and by the Keuper Sandstones of Area 5 (north-west England). By contrast the formations in northern England, Scotland and northern Ireland are on the whole more cemented and therefore less permeable than comparable deposits further south.

Variations exist also within laterally equivalent units as follows :-

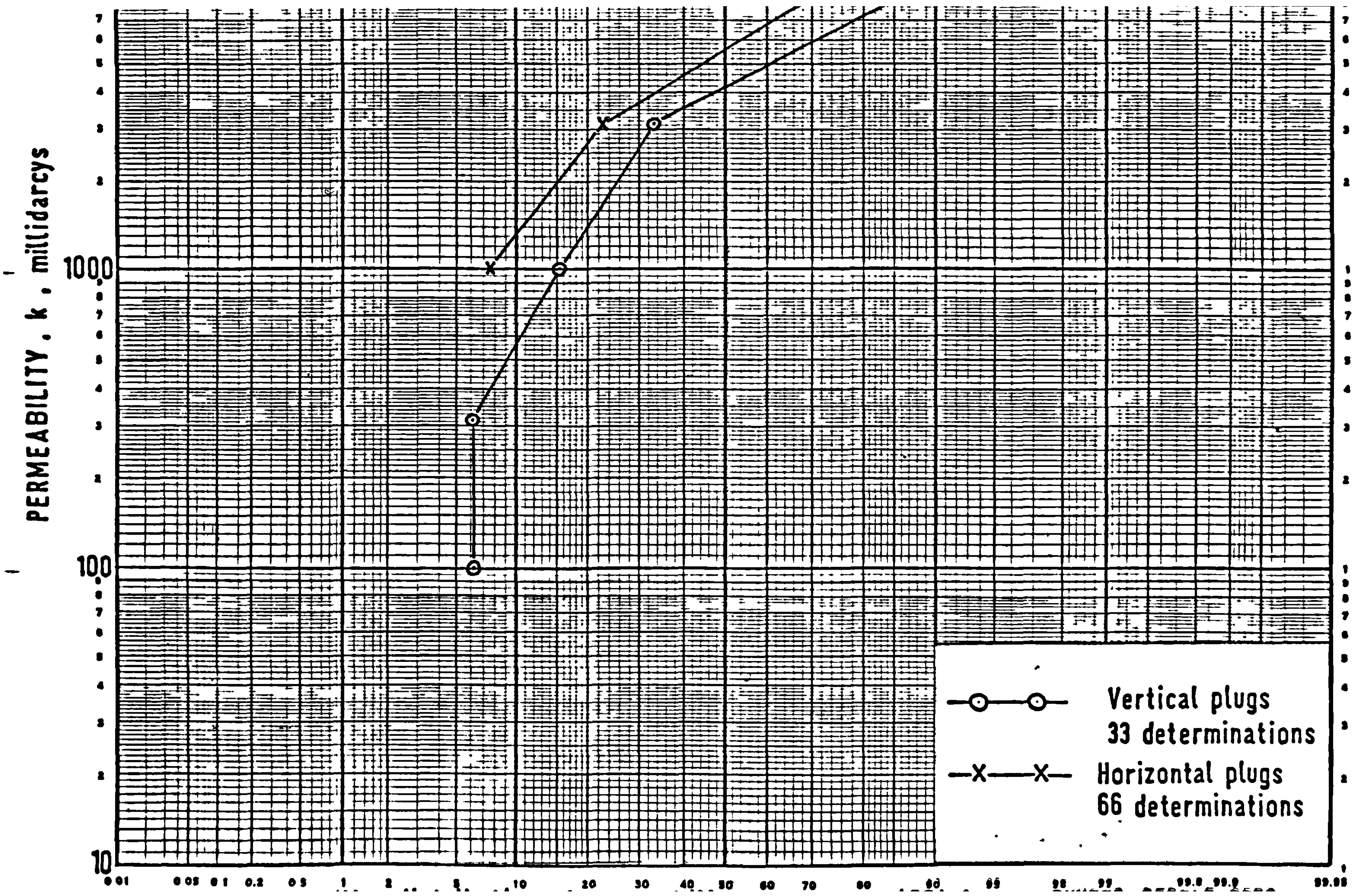
The Lower Mottled Sandstone is everywhere moderately permeable, but appreciably more so in the Severn valley than in mid-Shropshire.

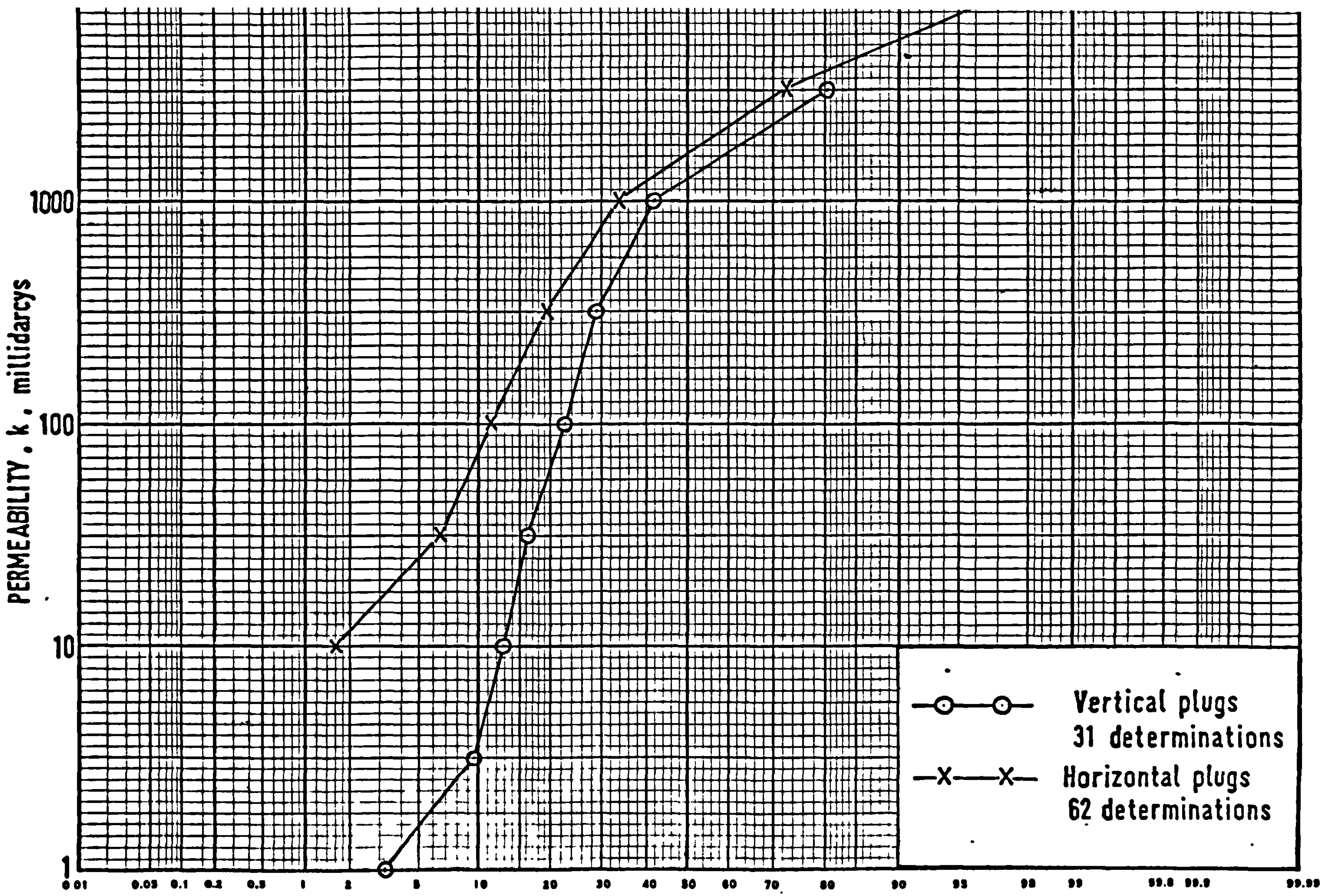
Bunter Pebble Beds show a general tendency towards lower permeability as they are traced from Warwickshire and Staffordshire (where we are speaking only of the sand facies), into Shropshire and northwards into Cheshire and Lancashire.

The Upper Mottled Sandstone is more permeable in the Cheshire-Merseyside area than in the Midlands, where, however, sampling was rather inadequate.

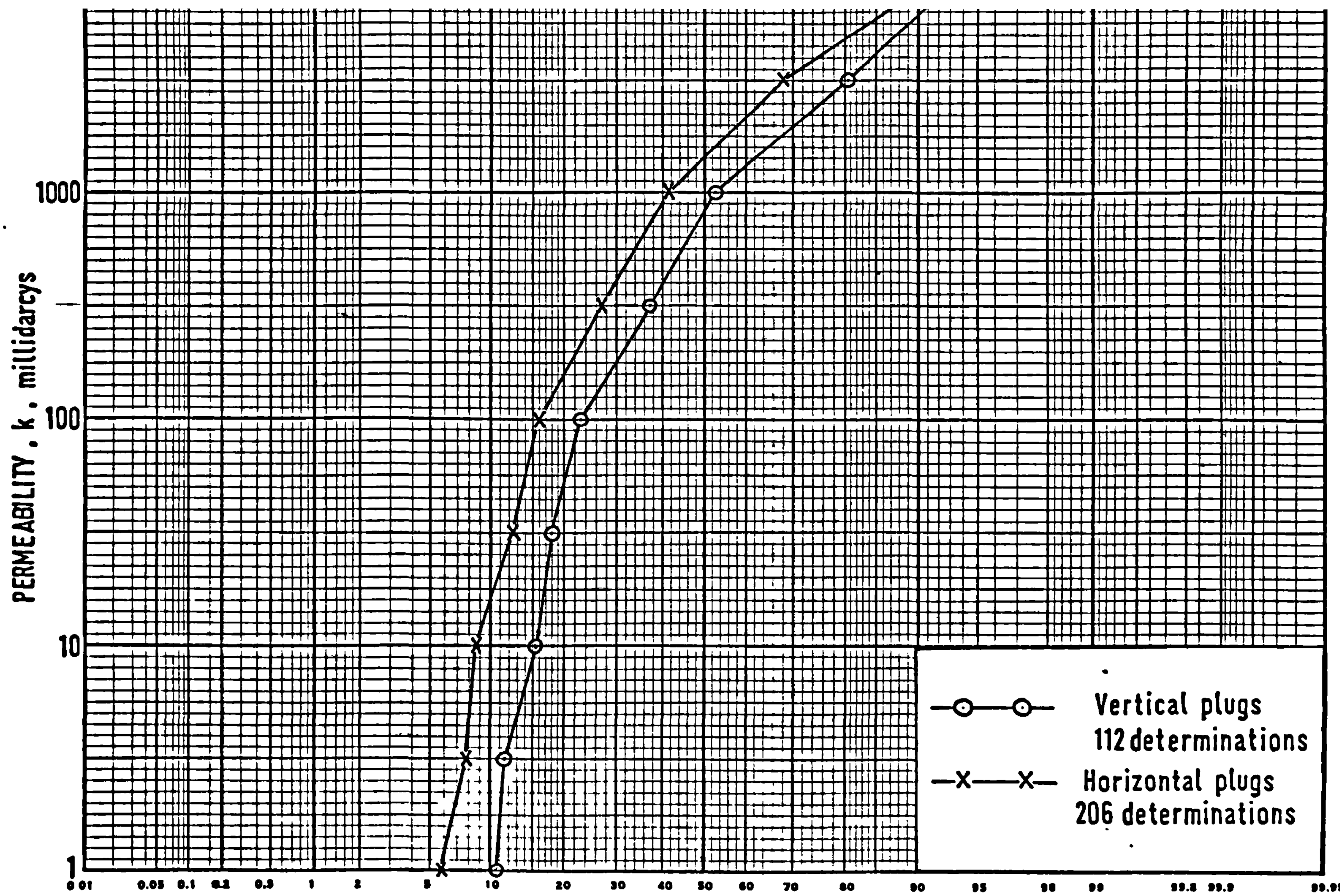
The Keuper Sandstone in Cheshire and Lancashire is more permeable there than further southeast in the Midlands. In the north, only the outcrop Permian sandstone samples from southern Scotland and the Penrith Sandstone were found to have a significantly high intergranular permeability. The Permo-Trias sandstones of the Vale of York, north Lancashire, west Cumberland and of northern Ireland have all been found to have a moderate to very low permeability, and in these formations, one can only conclude that ground water moves principally by fissure flow.

Much further work is obviously required in many parts of the country to reinforce the preliminary observations advanced here. But it is considered unlikely that future results will necessitate a drastic revision of these principal conclusions.

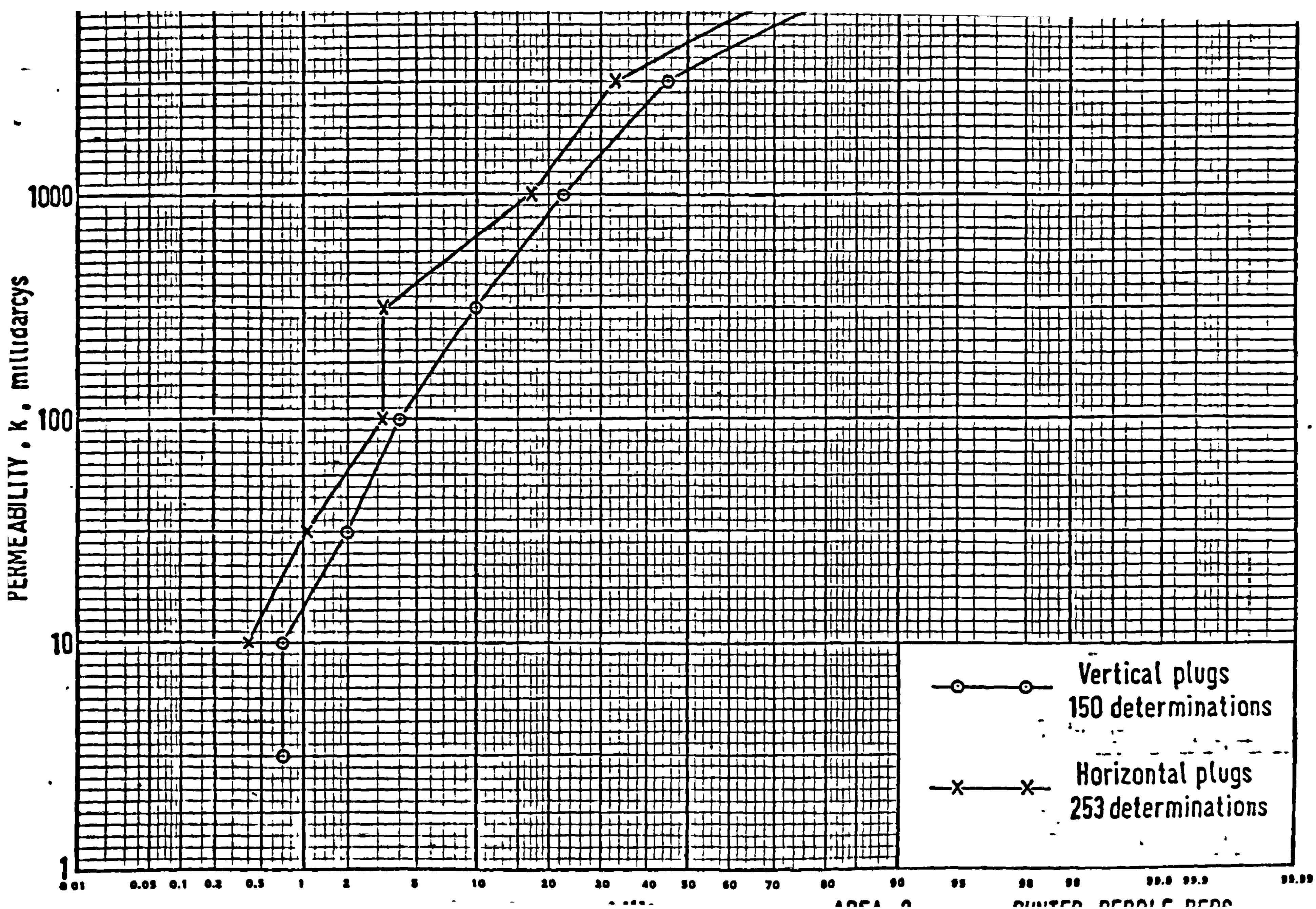

PERMEABILITY, k, millidarcys
1000
100
10
Vertical plugs
33 determinations
Horizontal plugs
66 determinations
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99



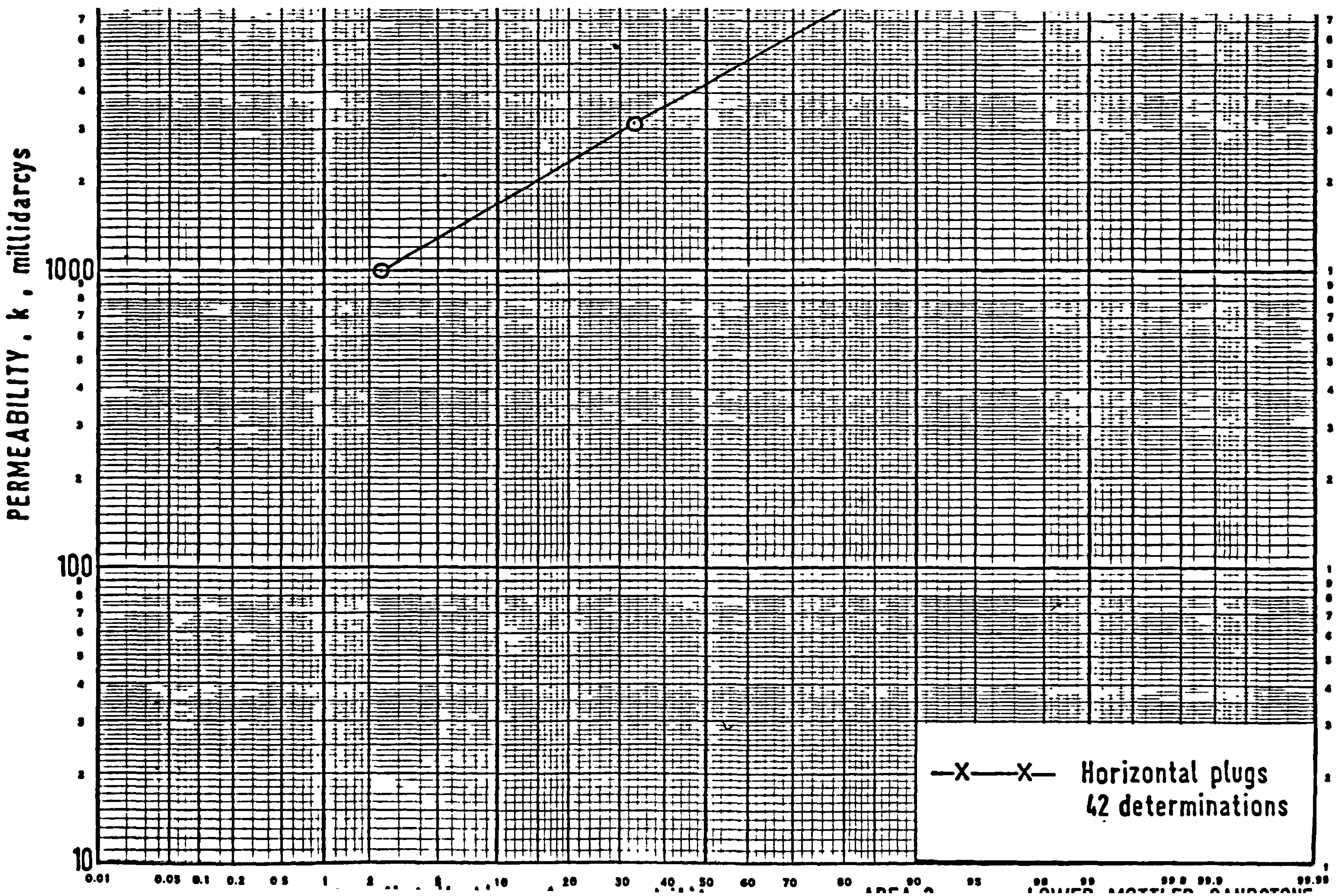
PERMEABILITY, k, millidarcys
1000
100
10
1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
Vertical plugs
31 determinations
Horizontal plugs
62 determinations



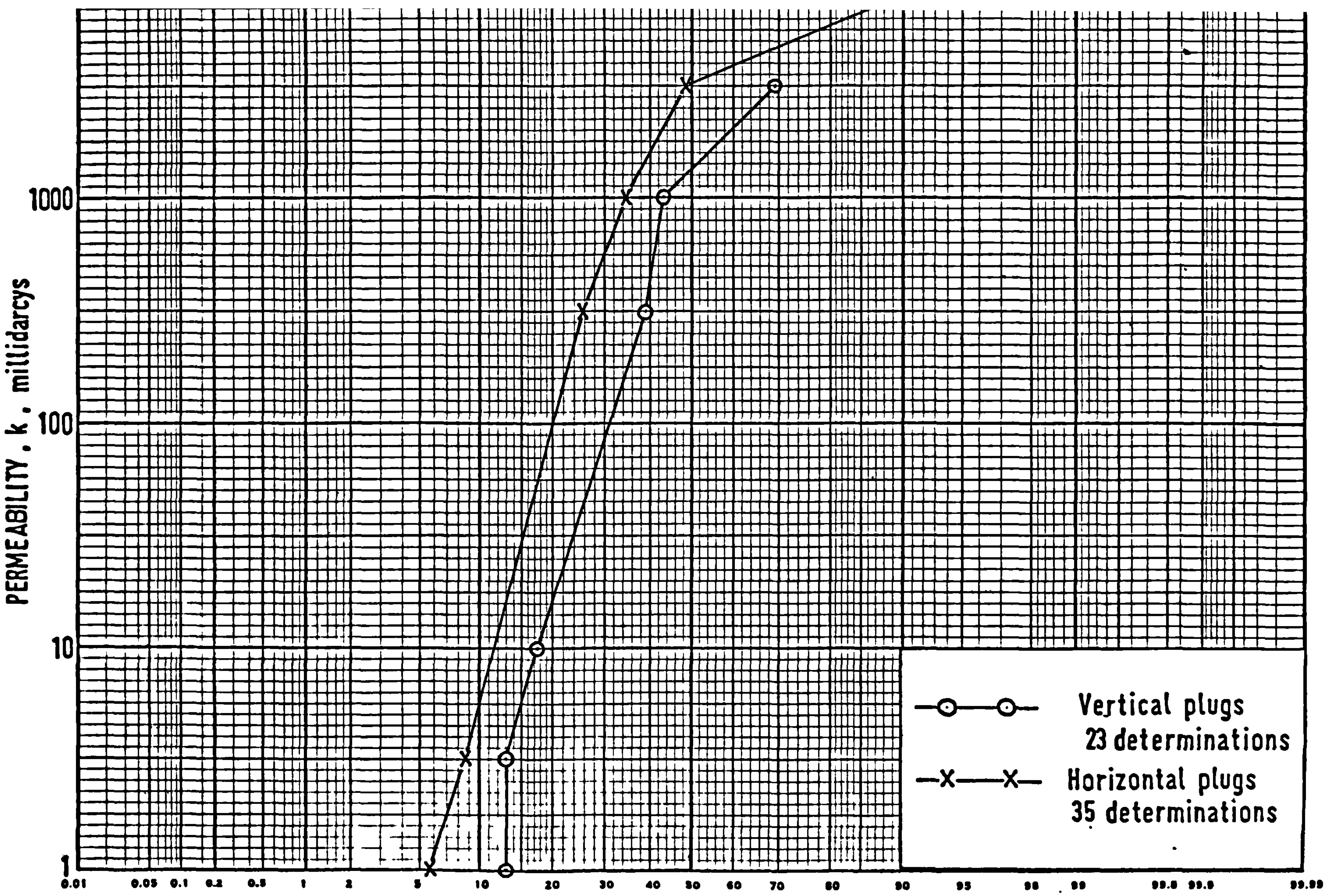
PERMEABILITY, k, millidarcys
1000
100
10
1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
Vertical plugs
112 determinations
Horizontal plugs
206 determinations

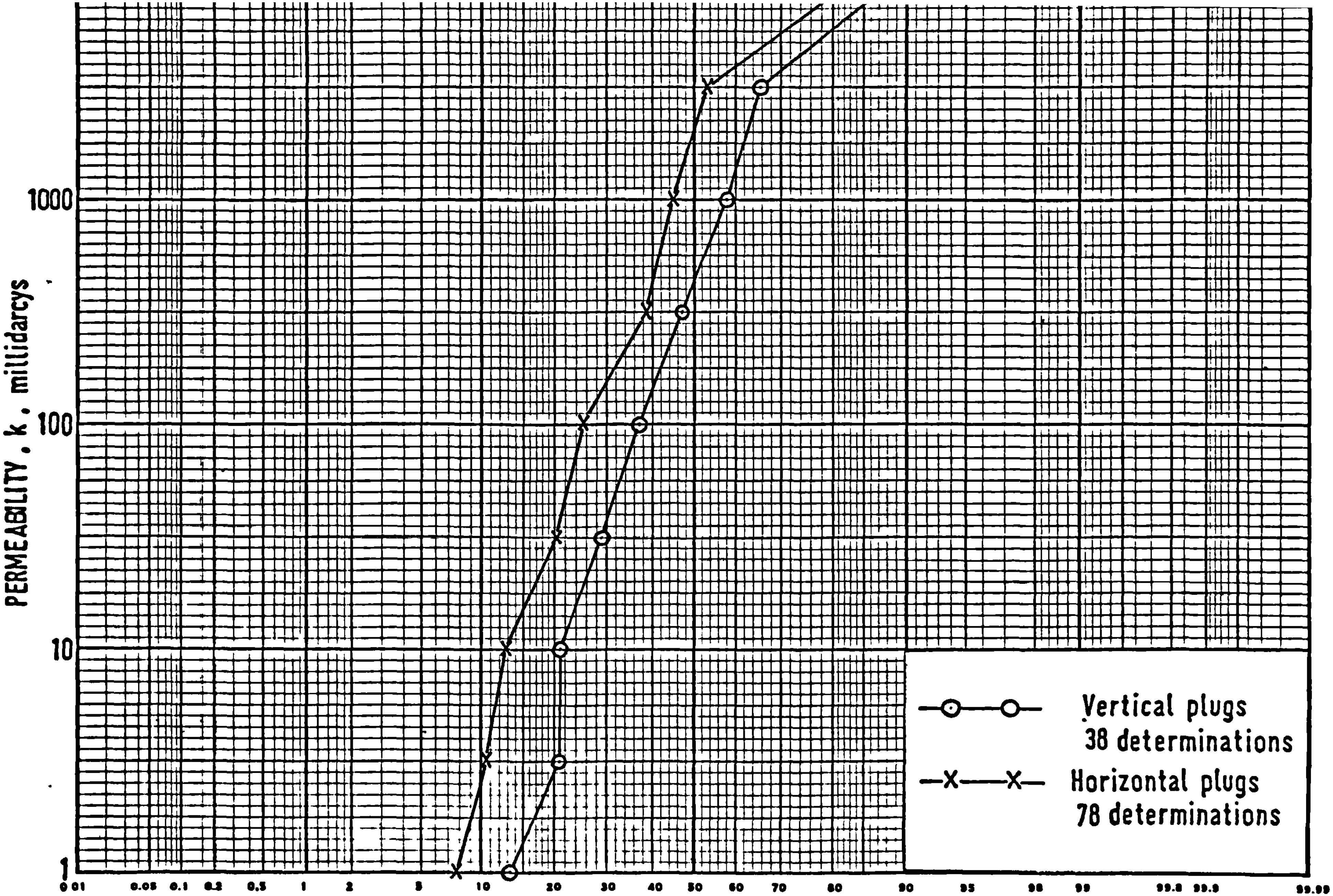


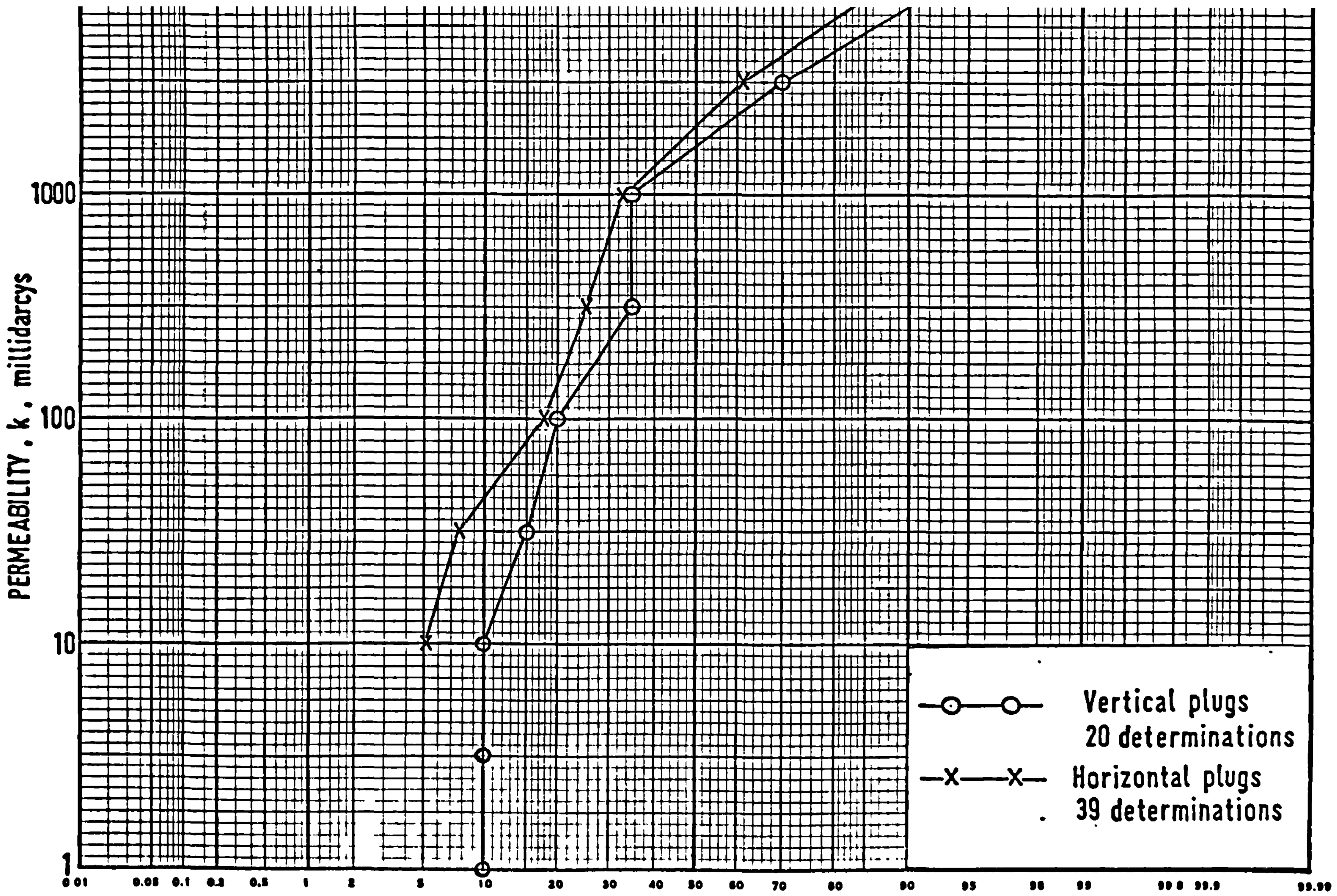
PERMEABILITY, K, millidarcys
1000
100
10
1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
Vertical plugs
150 determinations
Horizontal plugs
253 determinations



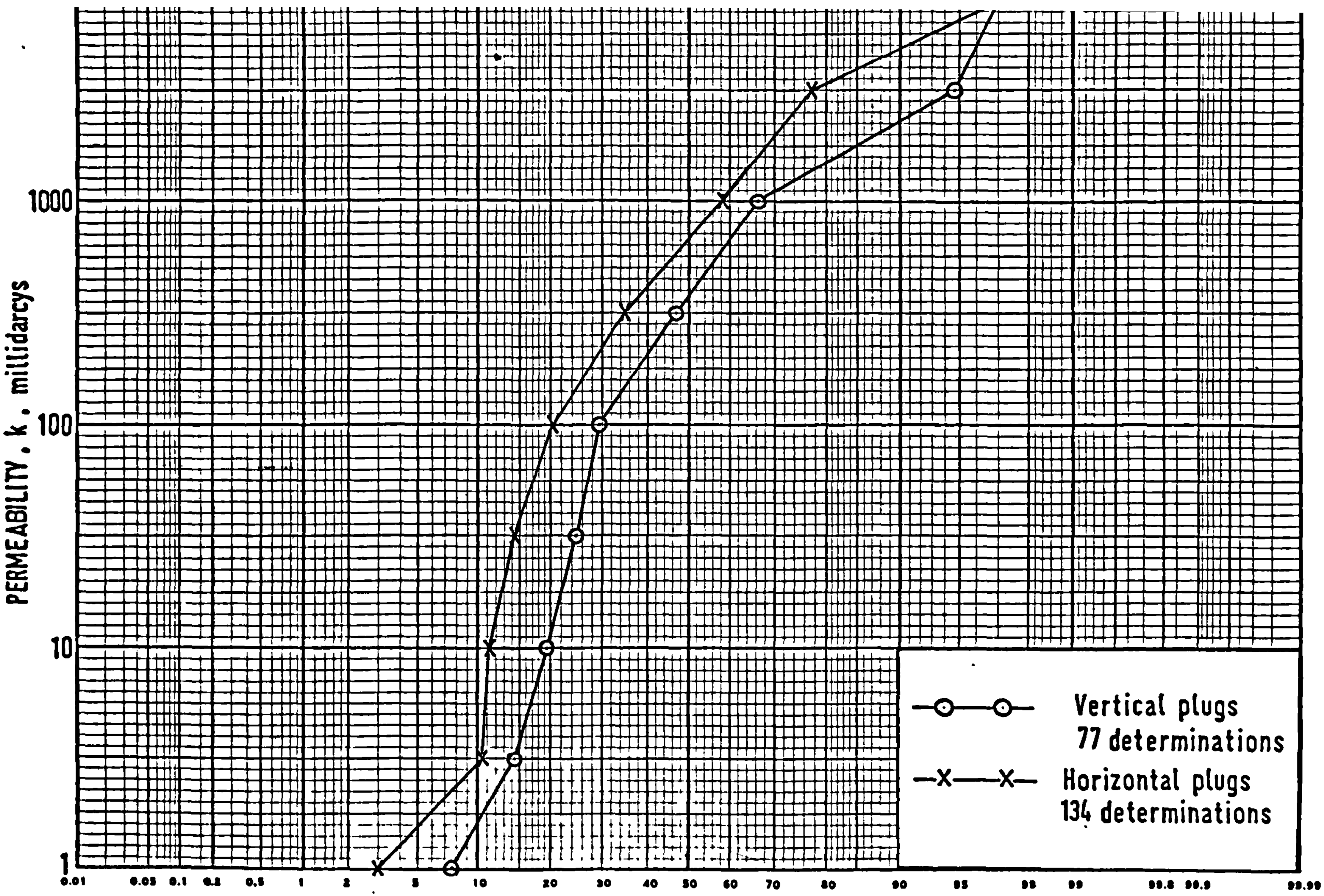
PERMEABILITY, k, millidarcys
1000
100
10
0.01
0.05
0.1
0.2
0.5
1
2
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
—X——X— Horizontal plugs
42 determinations


PERMEABILITY, k, millidarcys
1000
100
10
1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
Vertical plugs
23 determinations
Horizontal plugs
35 determinations


PERMEABILITY, k, millidarcys
1000
100
10
1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
Vertical plugs
38 determinations
Horizontal plugs
78 determinations



PERMEABILITY, k, millidarcys
1000
100
10
1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
Vertical plugs
20 determinations
Horizontal plugs
39 determinations



PERMEABILITY, k, millidarcys
1000
100
10
1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
Vertical plugs
77 determinations
Horizontal plugs
134 determinations

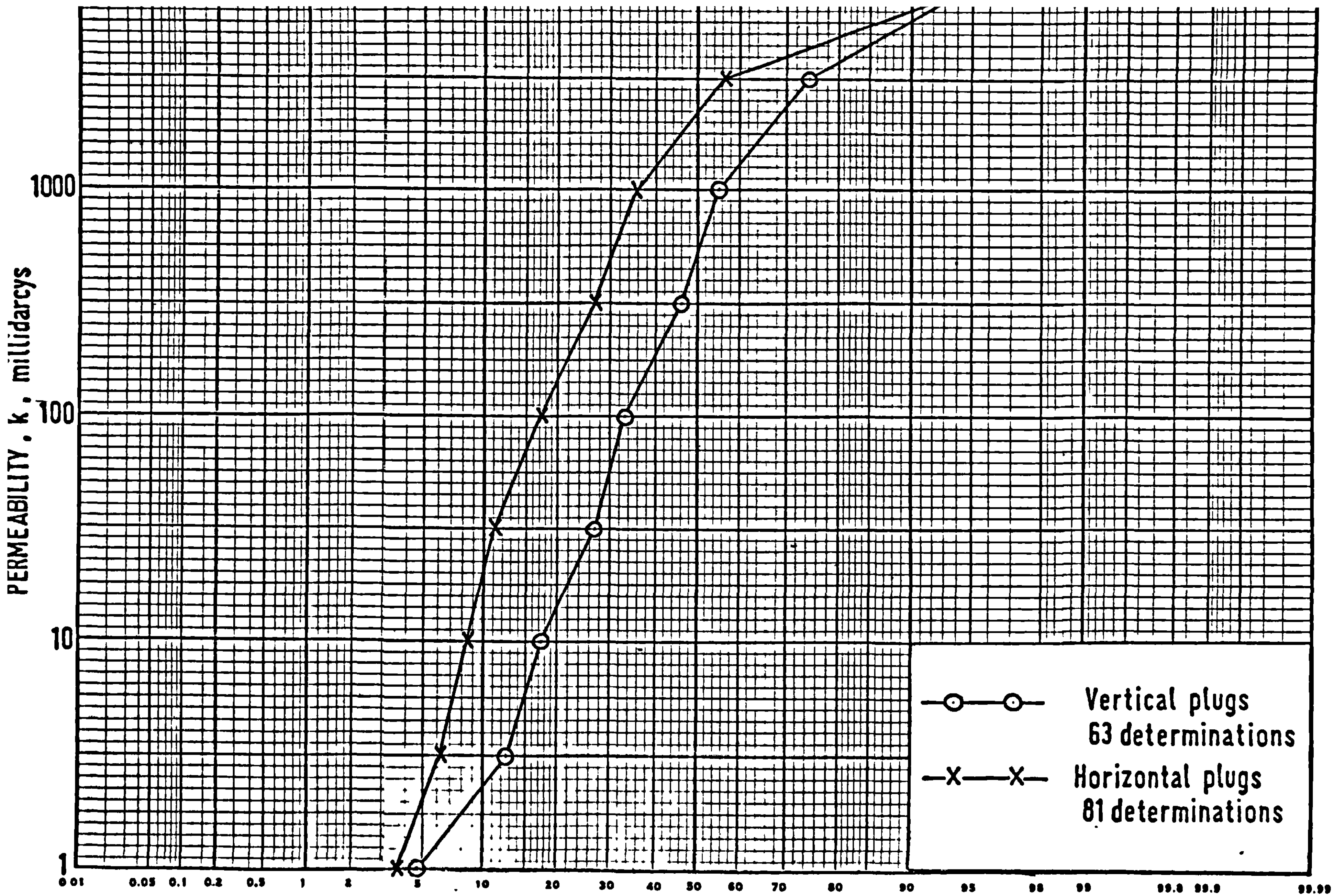
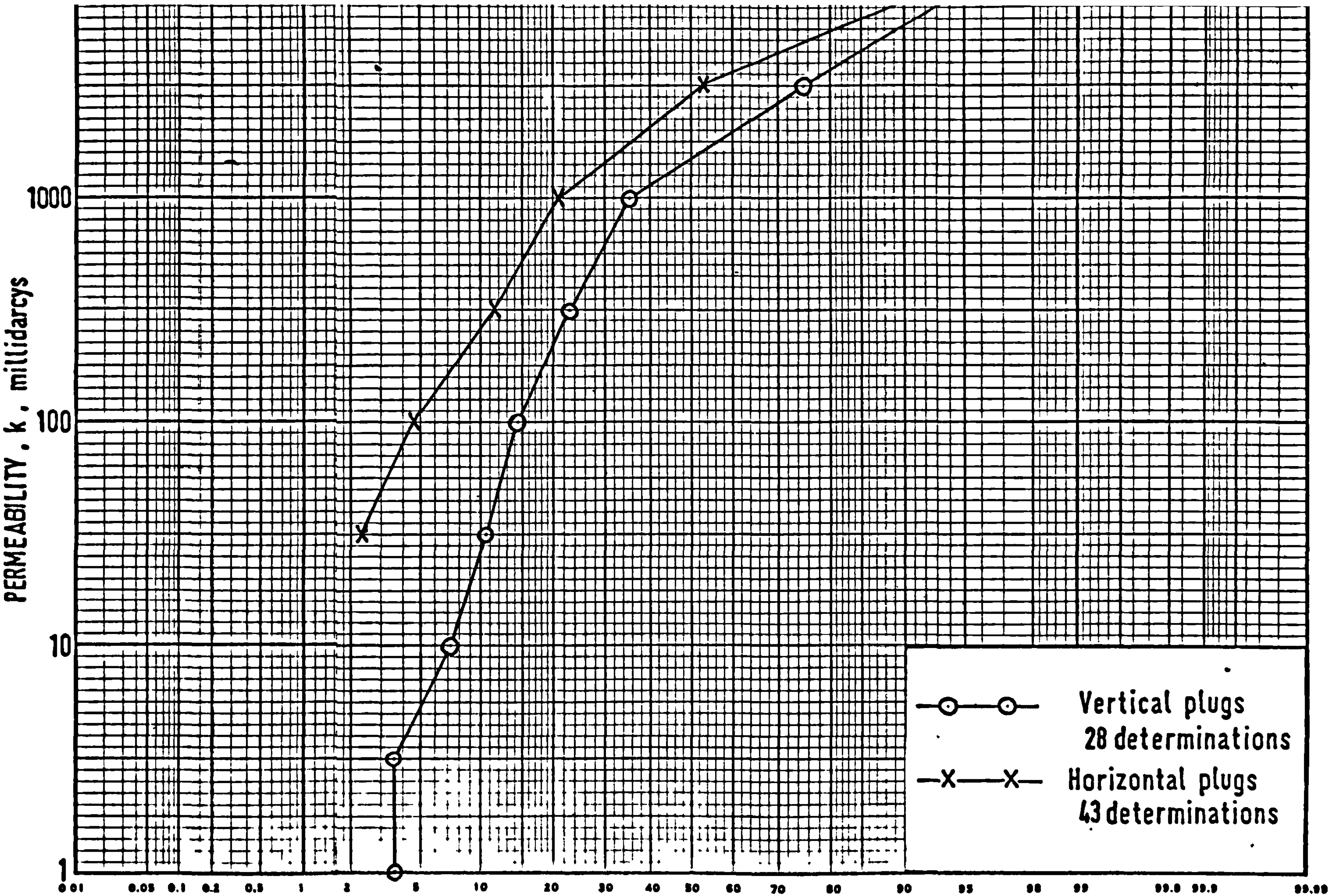
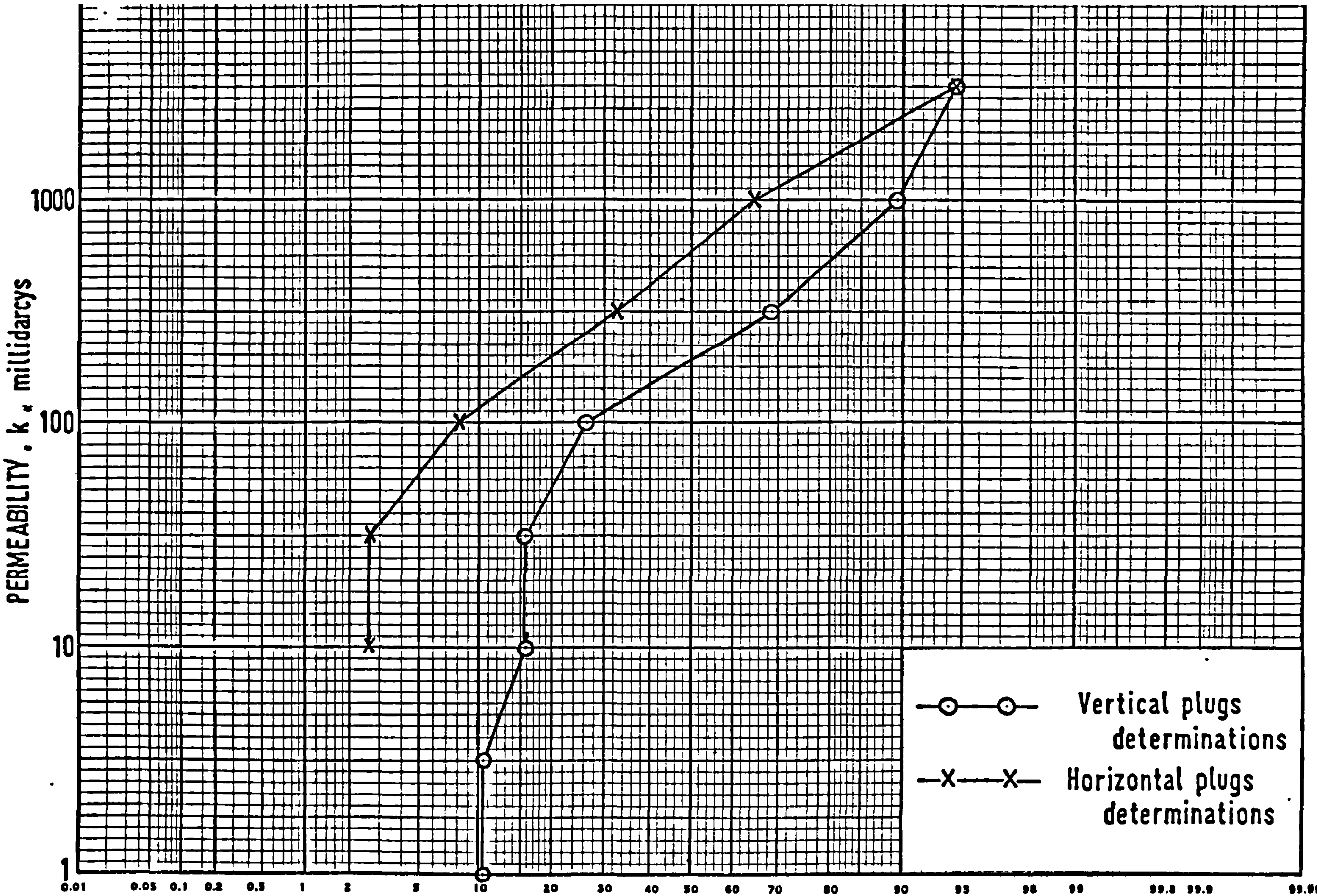
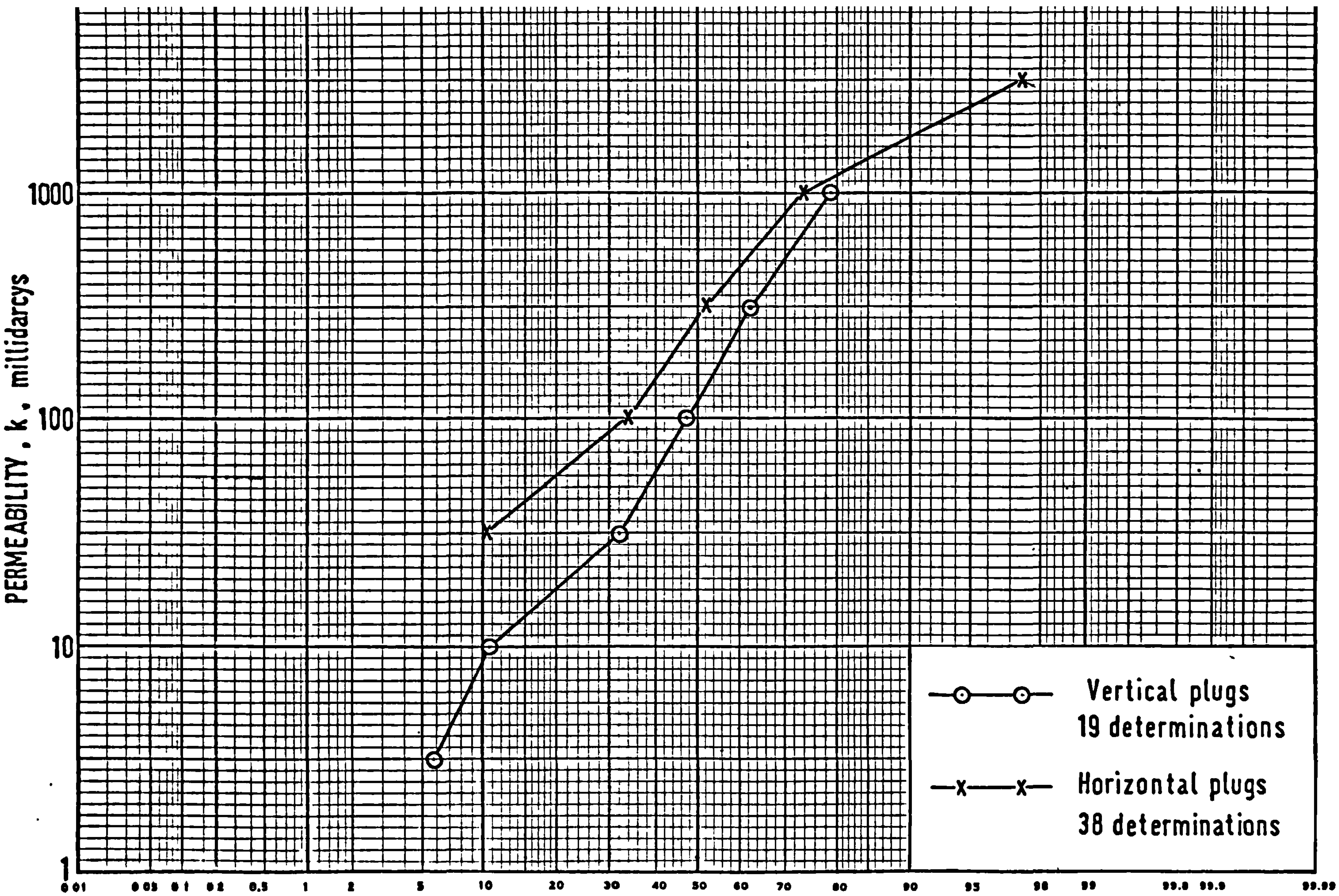


Fig 59 Log-normal probability distribution of permeability AREA F UPPER MOTTLED SANDSTONE

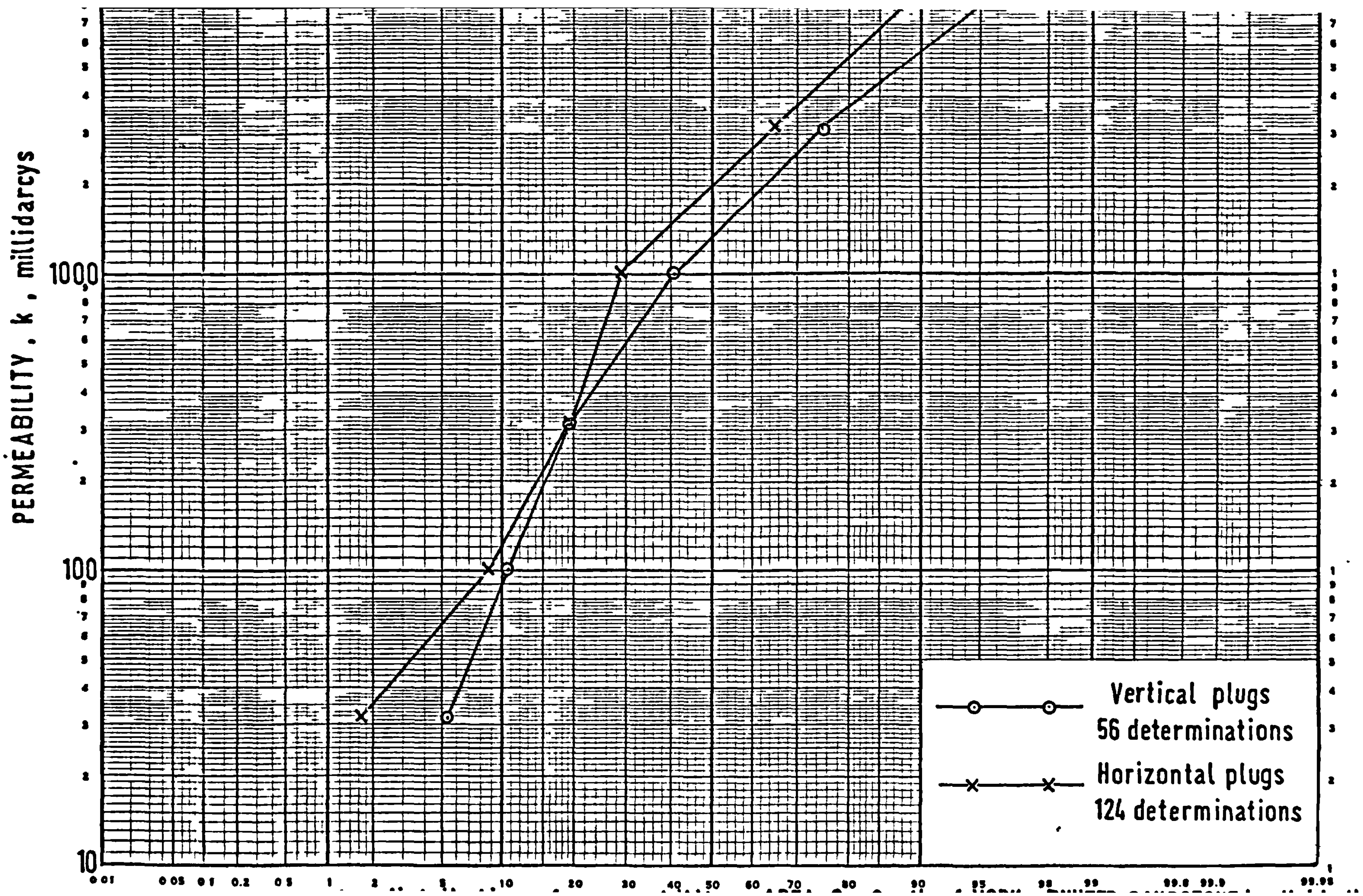

PERMEABILITY, k, millidarcys
1000
100
10
1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
Vertical plugs
28 determinations
Horizontal plugs
43 determinations

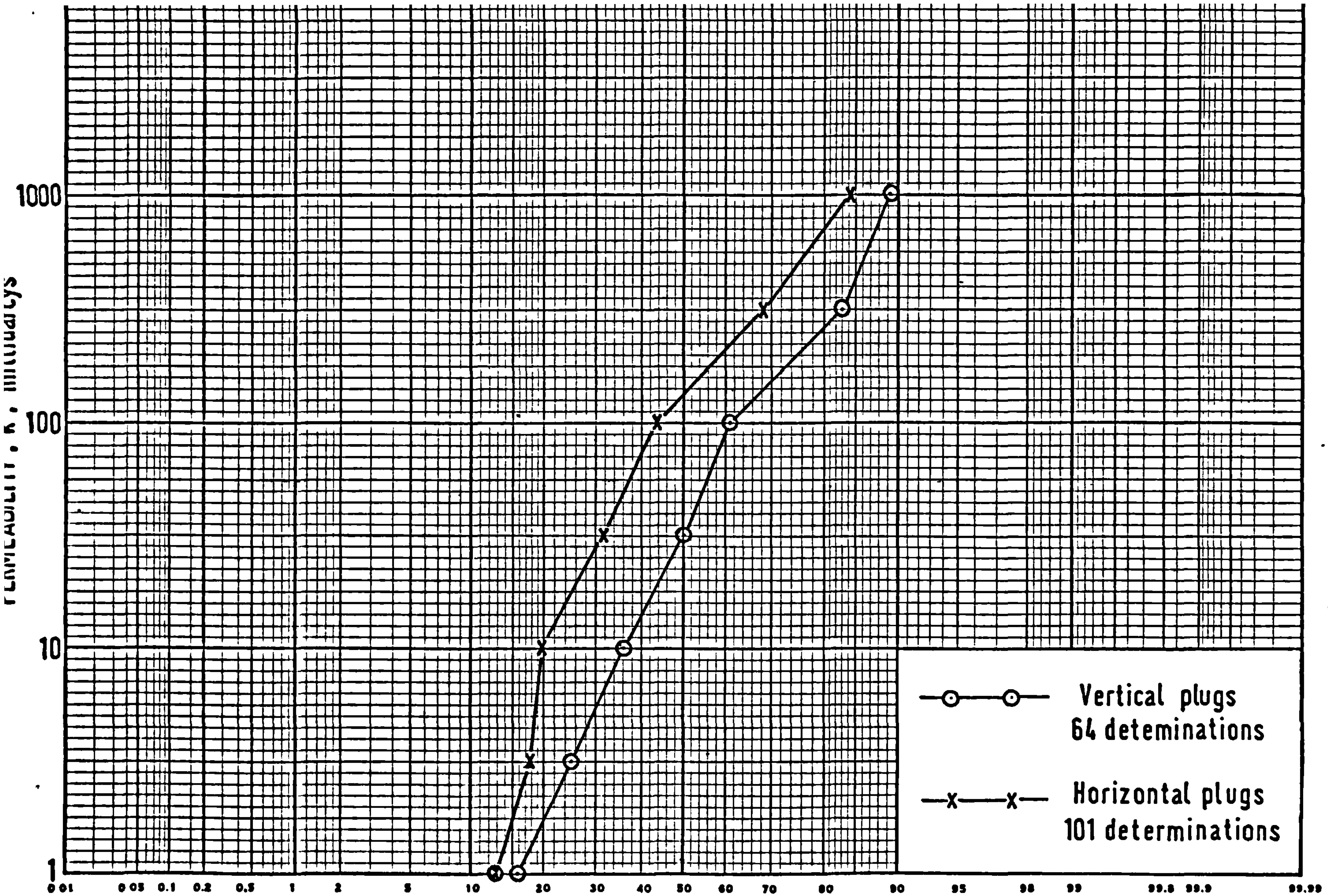


PERMEABILITY, k, millidarcys
1000
100
10
1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
Vertical plugs determinations
Horizontal plugs determinations



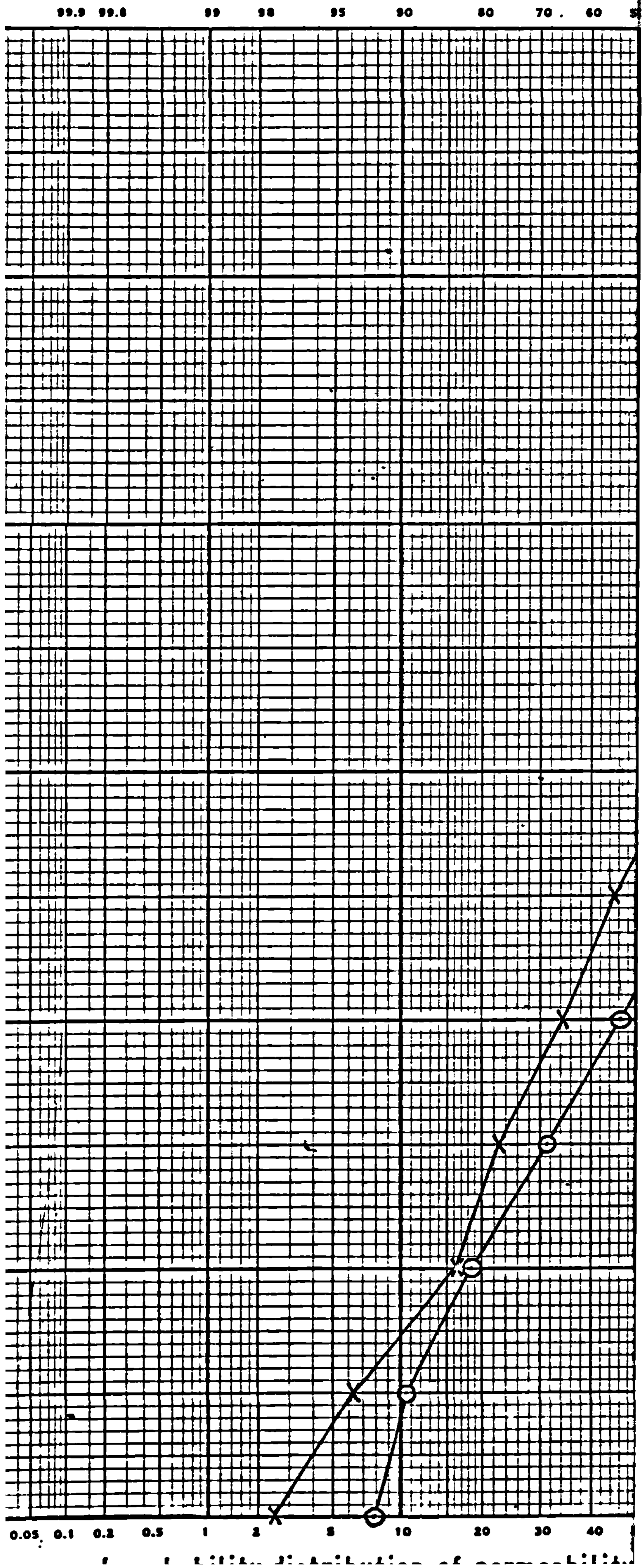
AREA 6 North of York BUNTER SANDSTONE


PERMEABILITY, k, millidarcys
1000
100
10
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
Vertical plugs
56 determinations
Horizontal plugs
124 determinations



AREA 7 – BUNTER SANDSTONE (undivided)

Probability that permeability will ex



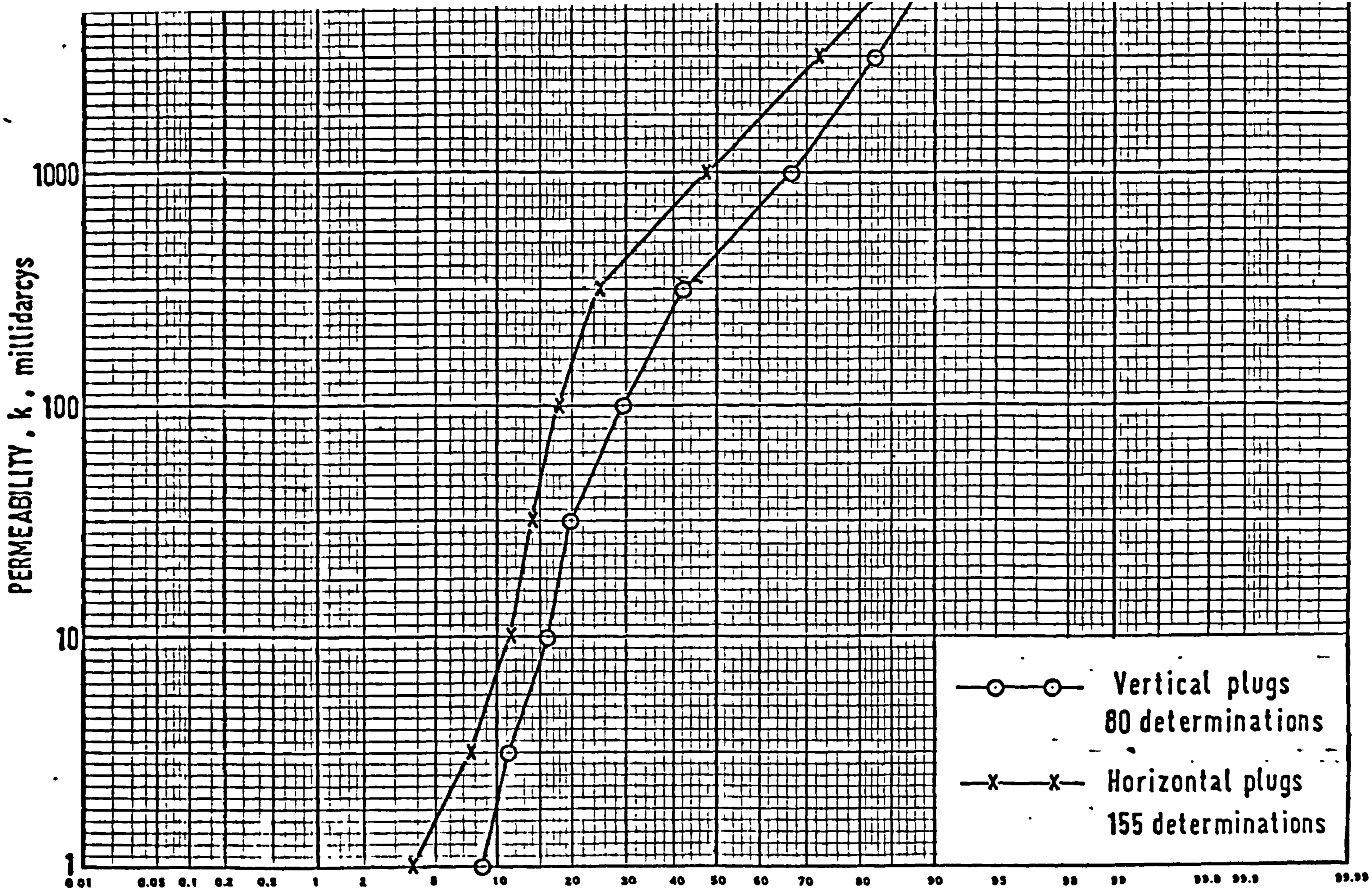


Fig.66 Log-normal probability distribution of permeability AREA B PENRITH SANDSTONE

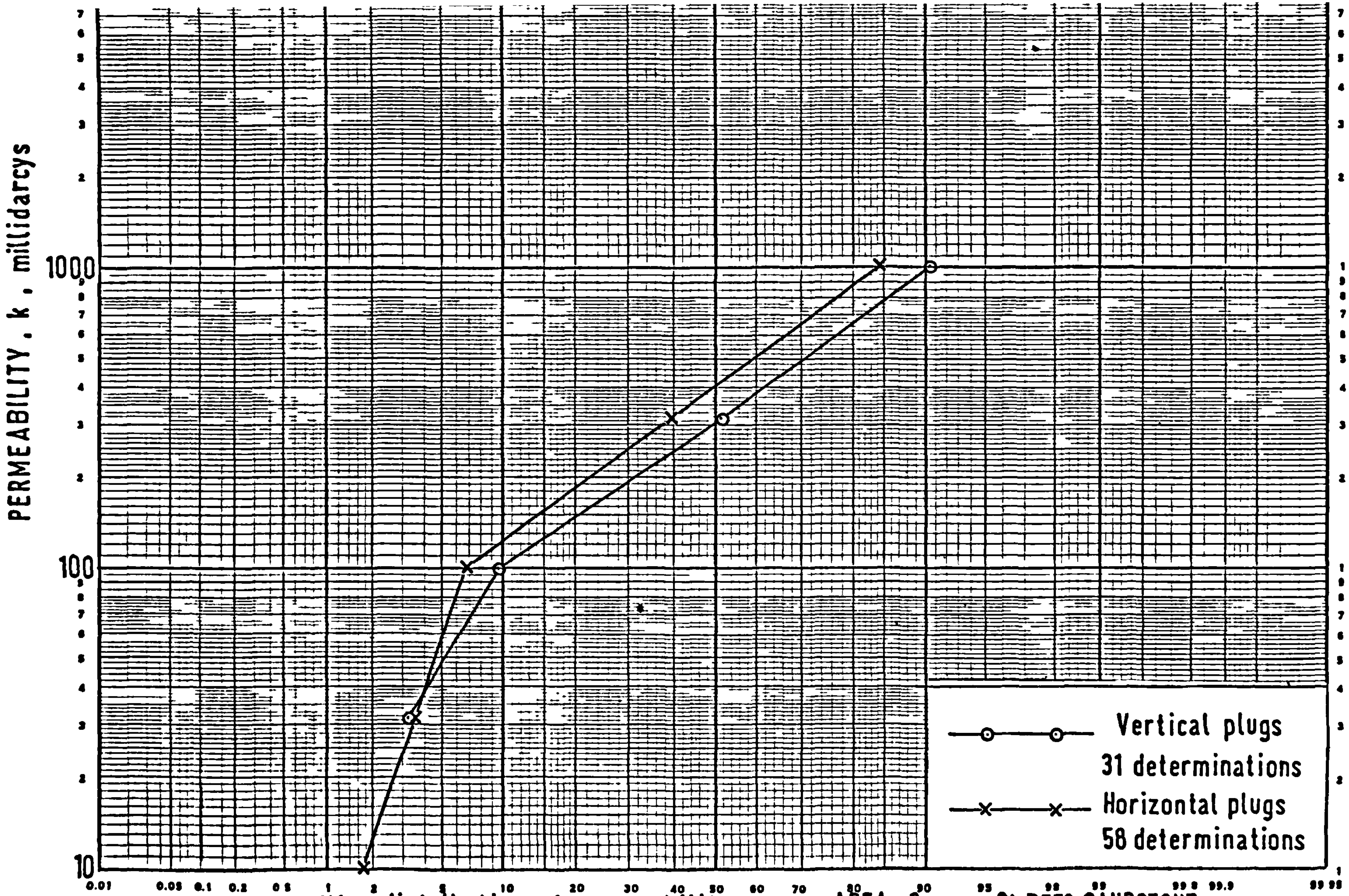
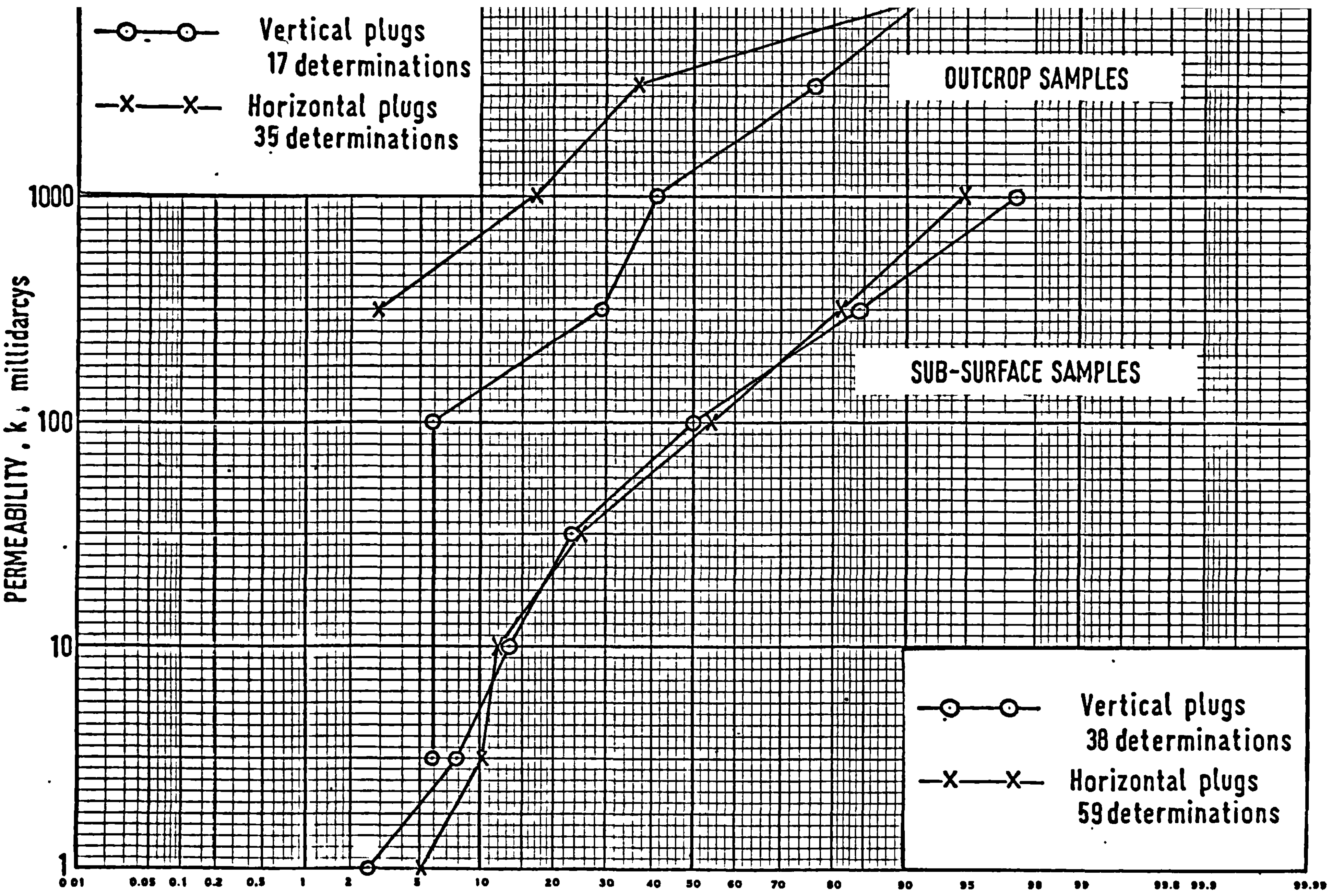
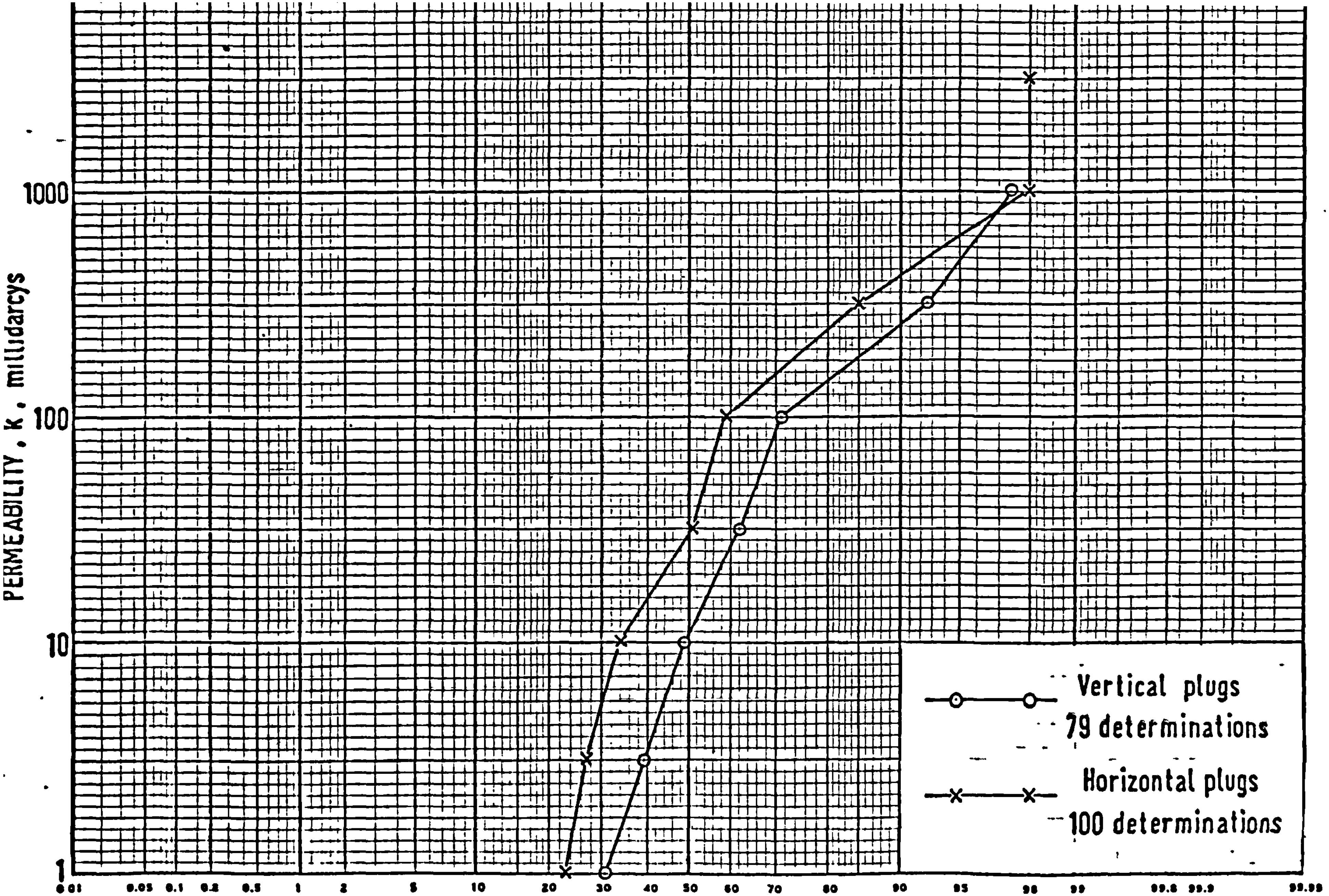


Fig 67 Log normal probability distribution of permeability AREA 'B' St BEES SANDSTONE



Vertical plugs
17 determinations
Horizontal plugs
35 determinations
OUTCROP SAMPLES
SUB-SURFACE SAMPLES
Vertical plugs
38 determinations
Horizontal plugs
59 determinations
PERMEABILITY, k, millidarcys
1000
100
10
1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99


PERMEABILITY, K, millidarcys
1000
100
10
1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
Vertical plugs
79 determinations
Horizontal plugs
100 determinations

6.5. PROBABILITY CURVE ANALYSIS : POROSITY

The distribution of porosity values in the various sandstones in the ten Areas are shown graphically in Figs. 70-88, and this data has been summarised in Table 17 which indicates mean values of porosity and equivalent saturated density in grams per cubic centimetre. Saturated density values have been listed both here and in the data sheets as it was felt these were of particular interest to geophysicists who may wish to use the values in gravity studies. It is clear even from Table 17 that considerable variation in porosity exists within the Permo-Triassic aquifers, and that this variation is directly related to changes in formation density which in turn reflect facies variation. The relationship between porosity and density is shown in Fig. 89 and it is easily seen that it is a simple inverse function. The good linearity may be taken to signify relatively uniform chemical composition, with density varying uniquely with porosity. Thus, the intercept on the density axis when porosity is zero should indicate the matrix density of the formation. In these sandstones it intersects at the expected value of 2.65 gms. cc^{-1} which approximates to the density of the major constituents of these sandstones, viz. quartz, feldspar and mica. The diagram is also instructive in that it shows that sandstone density increases towards the north of England.

The porosity distribution curves require the following explanatory comments :-

a) As a general rule, the variation of values within the chosen subdivisions is quite large, and for any particular sandstone a wide range of porosity may be expected.

b) With one or two exceptions which may possibly be explained by faulty sampling distribution, most of the frequency curves are approximately linear suggesting that porosity variation within the chosen subdivisions is essentially Gaussian. This is in general agreement with results on oil reservoirs (see Davis, in de Wiest, 1969) and is thought to be an objective indication of relatively uniform lithological conditions.

TABLE 17: PROBABILITY CURVE ANALYSIS : POROSITY

FORMATION	POROSITY WITH PROBABILITY OF 0.50 per cent	EQUIV.SATURATED BULK DENSITY · gms cc^{-1}
ΓER PEBBLE BEDS	28.5	2.17
ER MOTTLED SANDSTONE	26.8	2.20
ER KEUPER SANDSTONE	28.1	2.19
ΓER PEBBLE BEDS	30.0	2.15
ER MOTTLED SANDSTONE	30.2	2.15
ΓER PEBBLE BEDS	25.3	2.24
ER MOTTLED SANDSTONE	23.6	2.26
ΓER PEBBLE BEDS	23.9	2.25
ΓER PEBBLE BEDS	23.4	2.26
ER MOTTLED SANDSTONE	26.4	2.21
PER SANDSTONE	24.1	2.25
ER SANDSTONE (south of York)	30.0	2.16
ER SANDSTONE (north of York)	27.3	2.19
ER SANDSTONE	20.4	2.32
BEES SANDSTONE	15.4	2.40
ITH SANDSTONE	25.4	2.23
BEES SANDSTONE	26.9	2.20
IAN SANDSTONE (outcrop)	23.9	2.25
IAN SANDSTONE (subsurface)	15.0	2.33 - 2.41
ER SANDSTONE	24.3	2.25

c) The very extended scale of the distributions for the following subdivisions is caused by the presence, already referred to in Chap.V. of local cementation :

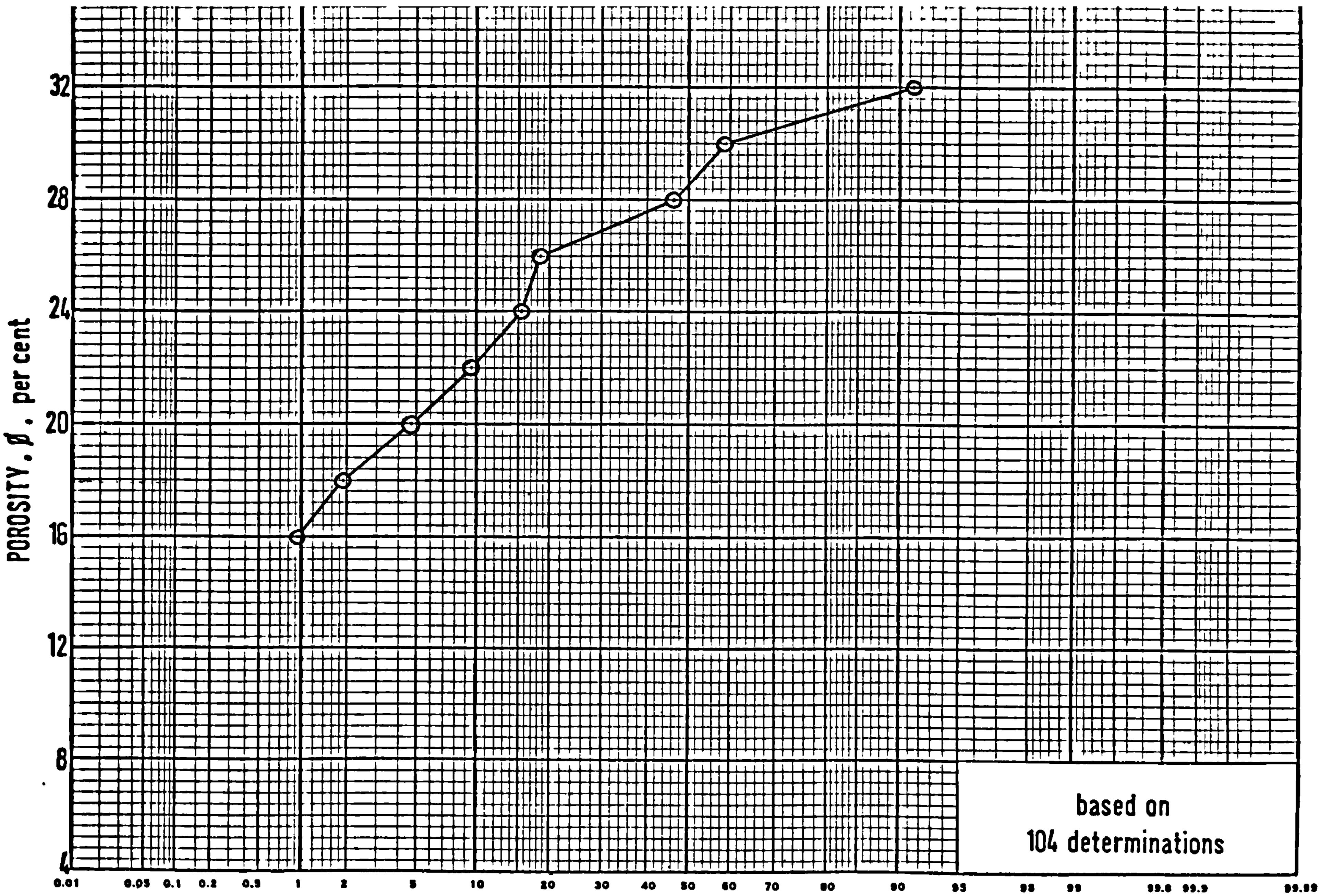
Lower Keuper Sandstone	Area 1	Fig.72
Bunter Pebble Beds	Area 3	Fig.75
Lower Mottled Sandstone	Area 4	Fig.76
Bunter Pebble Beds	Area 5	Fig.78
Bunter Sandstone	Area 6 (north of York)	Fig.82
Bunter Sandstone	Area 7	Fig.83
St. Bees Sandstone	Area 7	Fig.84
Penrith Sandstone	Area 8	Fig.85
Bunter Sandstone	Area 10	Fig.88

d) Porosity data is chiefly of value in assessing the total storage of a formation, or, in the absence of permeability data, of estimating an order of magnitude for permeability. The following table gives some idea of the quantity of storage involved for various values of porosity, and saturated thickness.

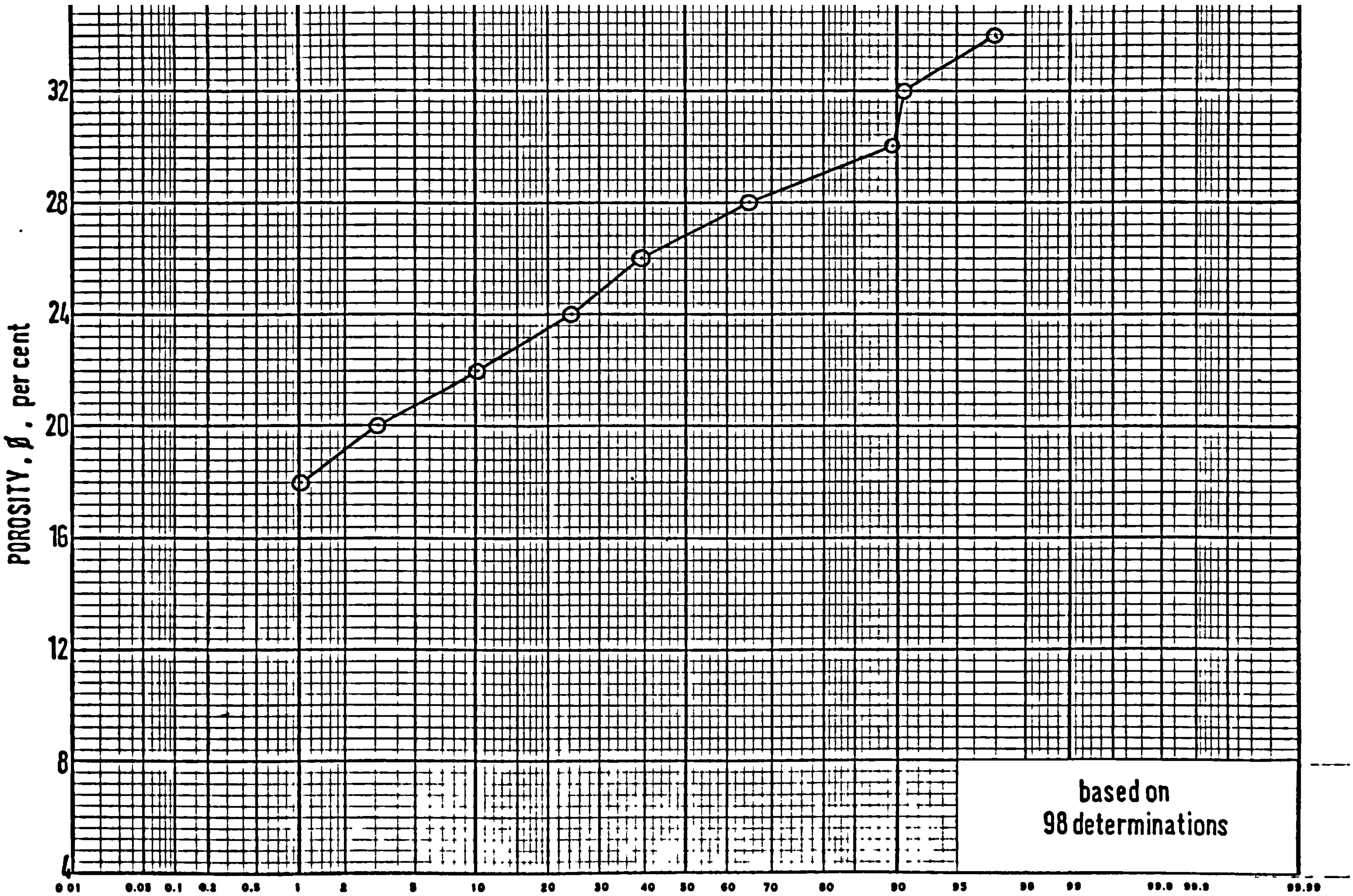
TABLE 18. POROSITY AS STORAGE

Porosity per cent	Thickness of formation		
	100 m	200 m	300 m
5	5×10^6	10^7	1.5×10^7
10	10^7	2×10^7	3.0×10^7
15	1.5×10^7	3×10^7	4.5×10^7
20	2.0×10^7	4×10^7	6×10^7
25	2.5×10^7	5×10^7	7.5×10^7
30	3.0×10^7	6×10^7	9×10^7

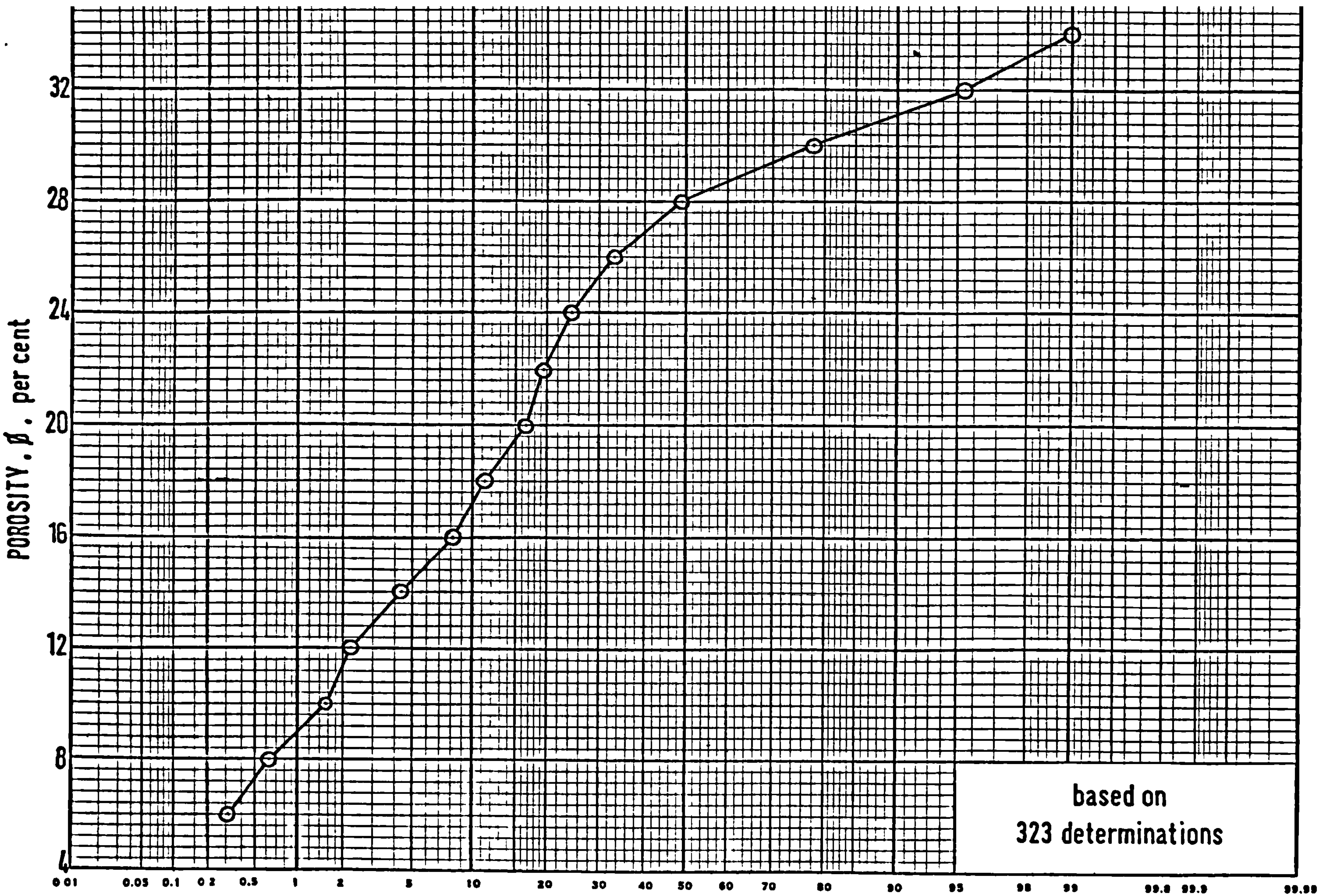
N.B. Quantities are given in m^3. The assumed area is 1 km^2.



POROSITY, Ø, per cent
32
28
24
20
16
12
8
4
0.01 0.05 0.1 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.9 99.99
based on
104 determinations



POROSITY, Ø, per cent
32
28
24
20
16
12
8
4
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
based on
98 determinations


POROSITY, Ø, per cent
32
28
24
20
16
12
8
4
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
based on
323 determinations

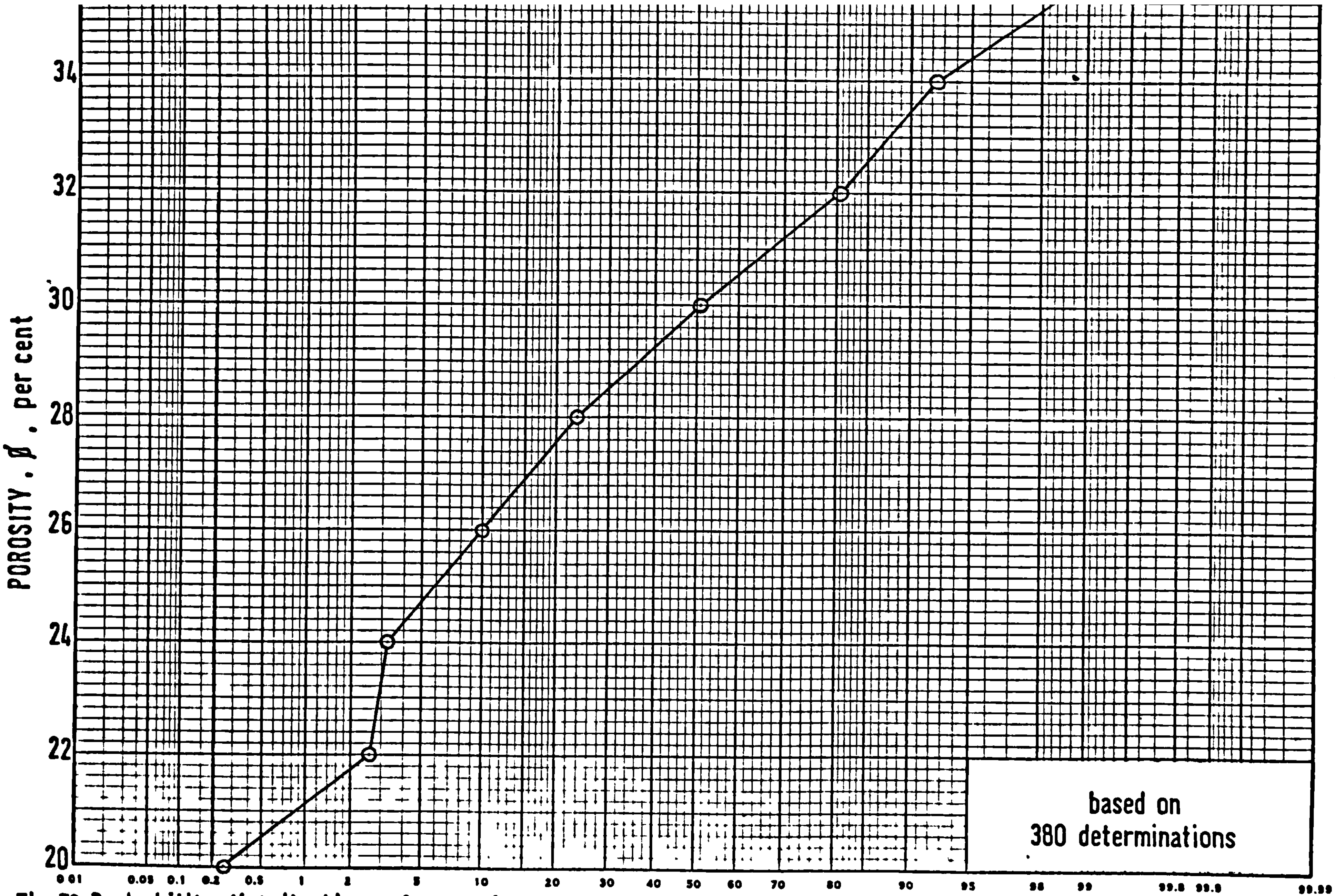


Fig.73 Probability distribution of porosity AREA 2 BUNTER PEBBLE BEDS

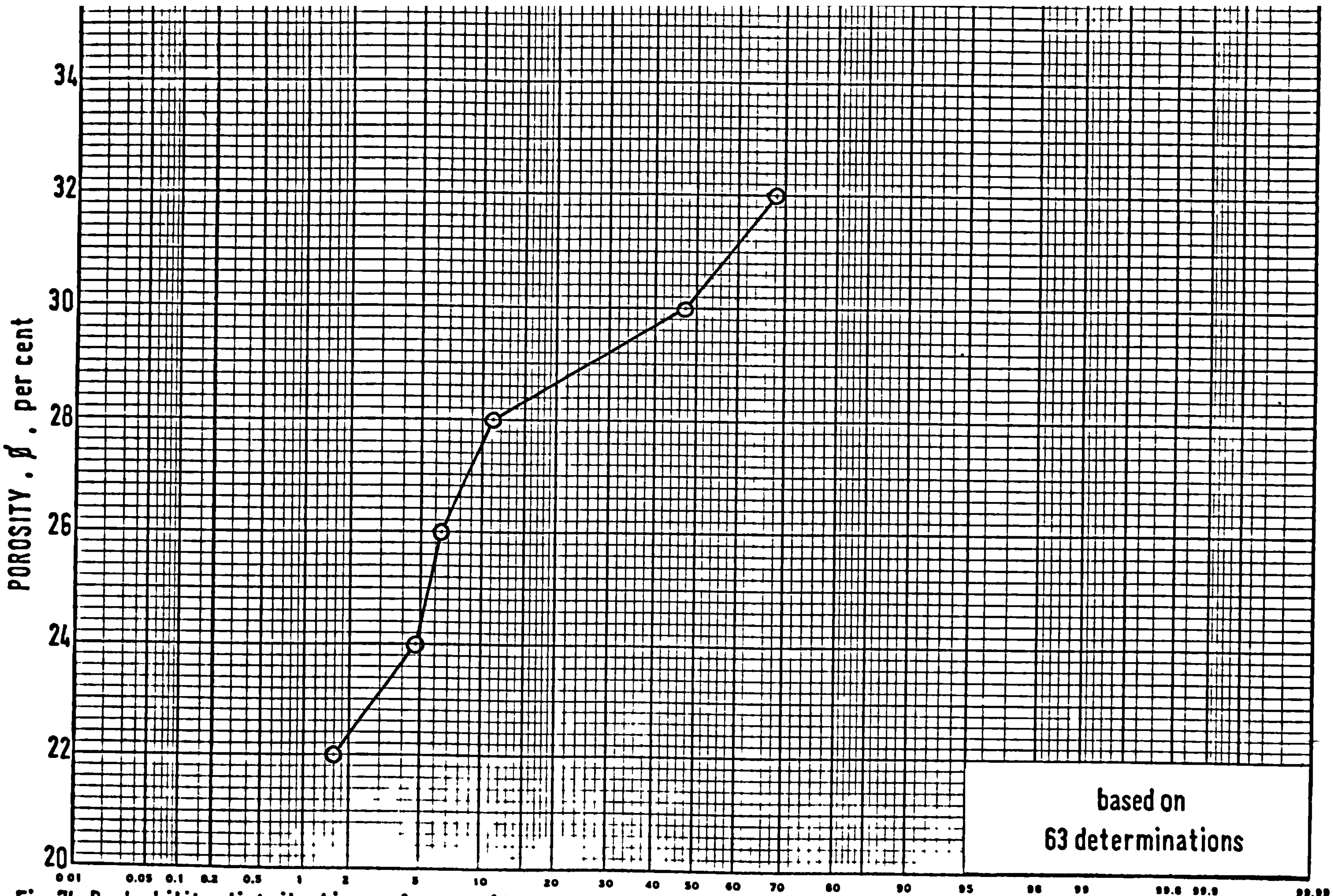


Fig.74 Probability distribution of porosity AREA 2 LOWER MOTTLED SANDSTONE

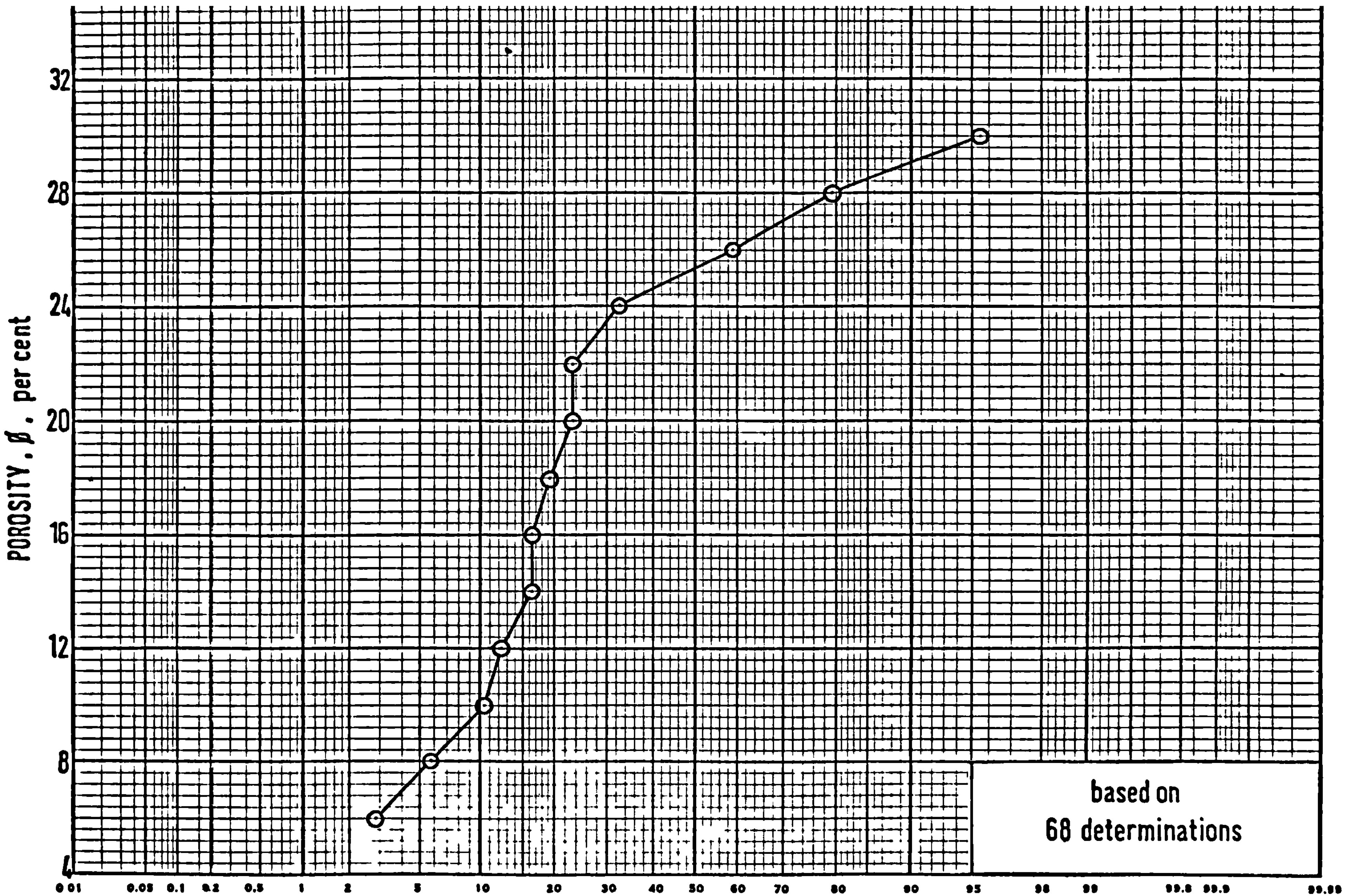


Fig 75 Probability distribution of porosity   AREA 2   BUNTER PEBBLE BEDS

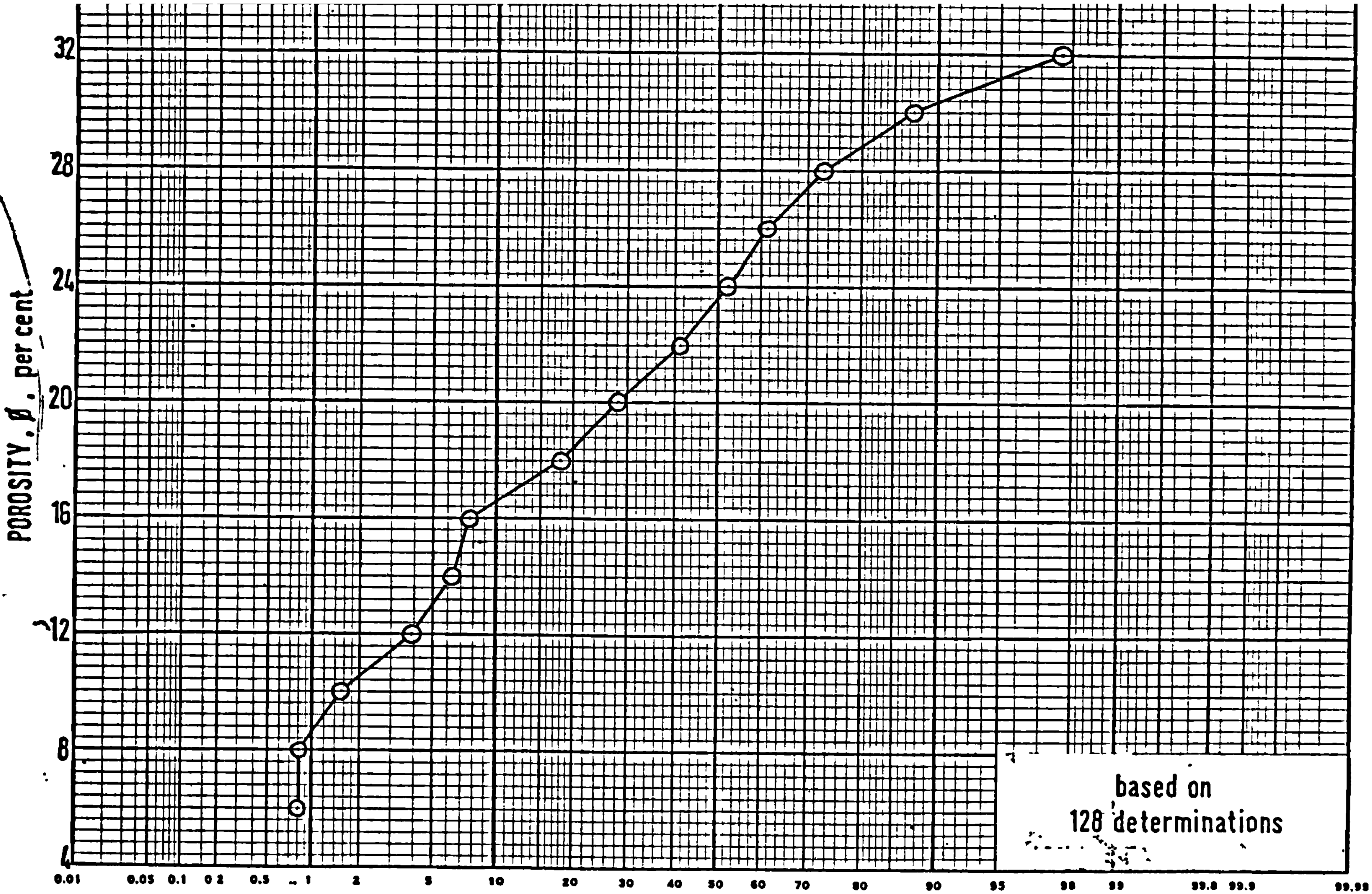


Fig.76 Probability distribution of porosity AREA 4 LOWER MOTTLED SANDSTONE

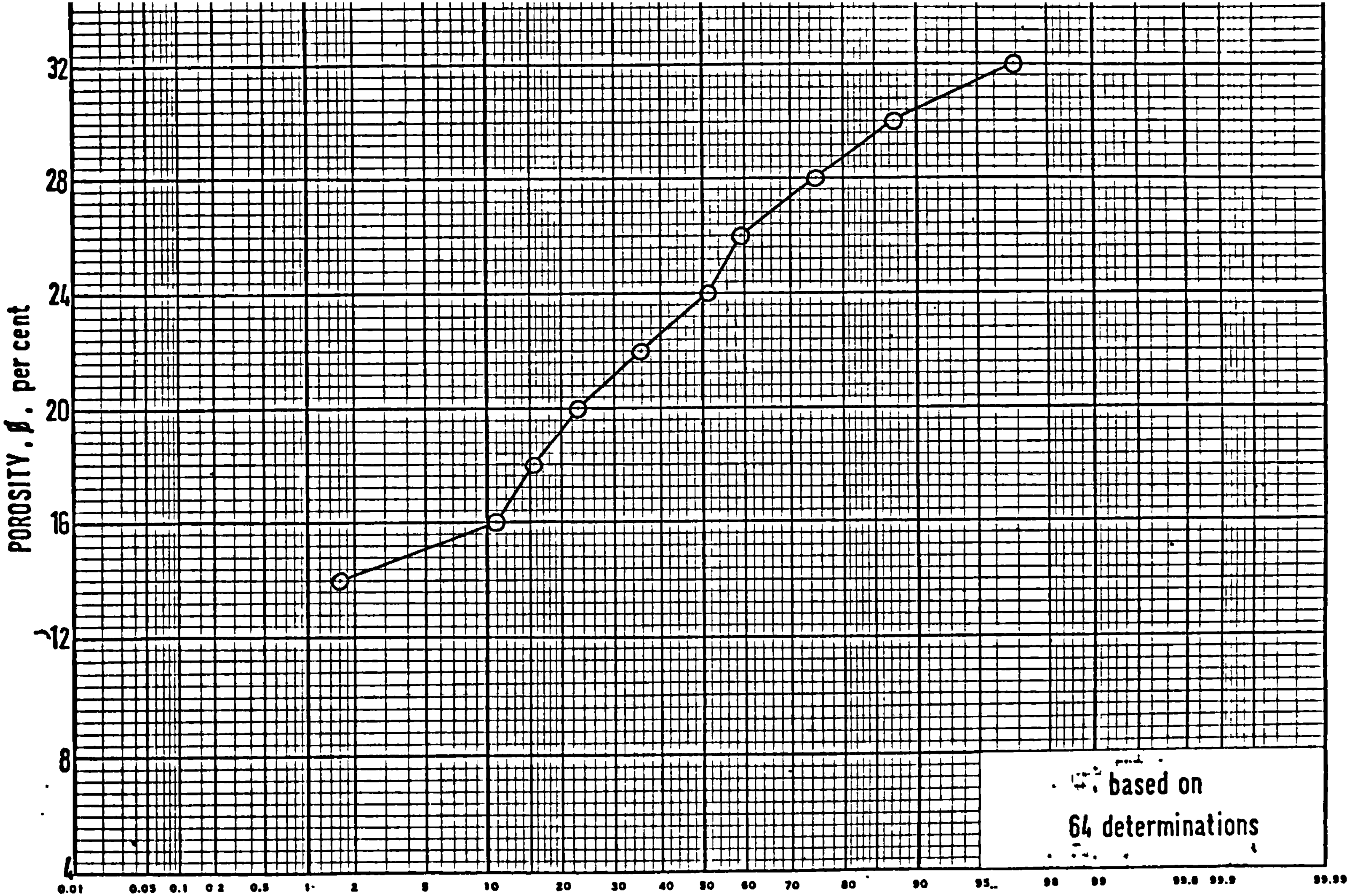


Fig 77 Probability distribution of porosity AREA 4 BUNTER PEBBLE BEDS

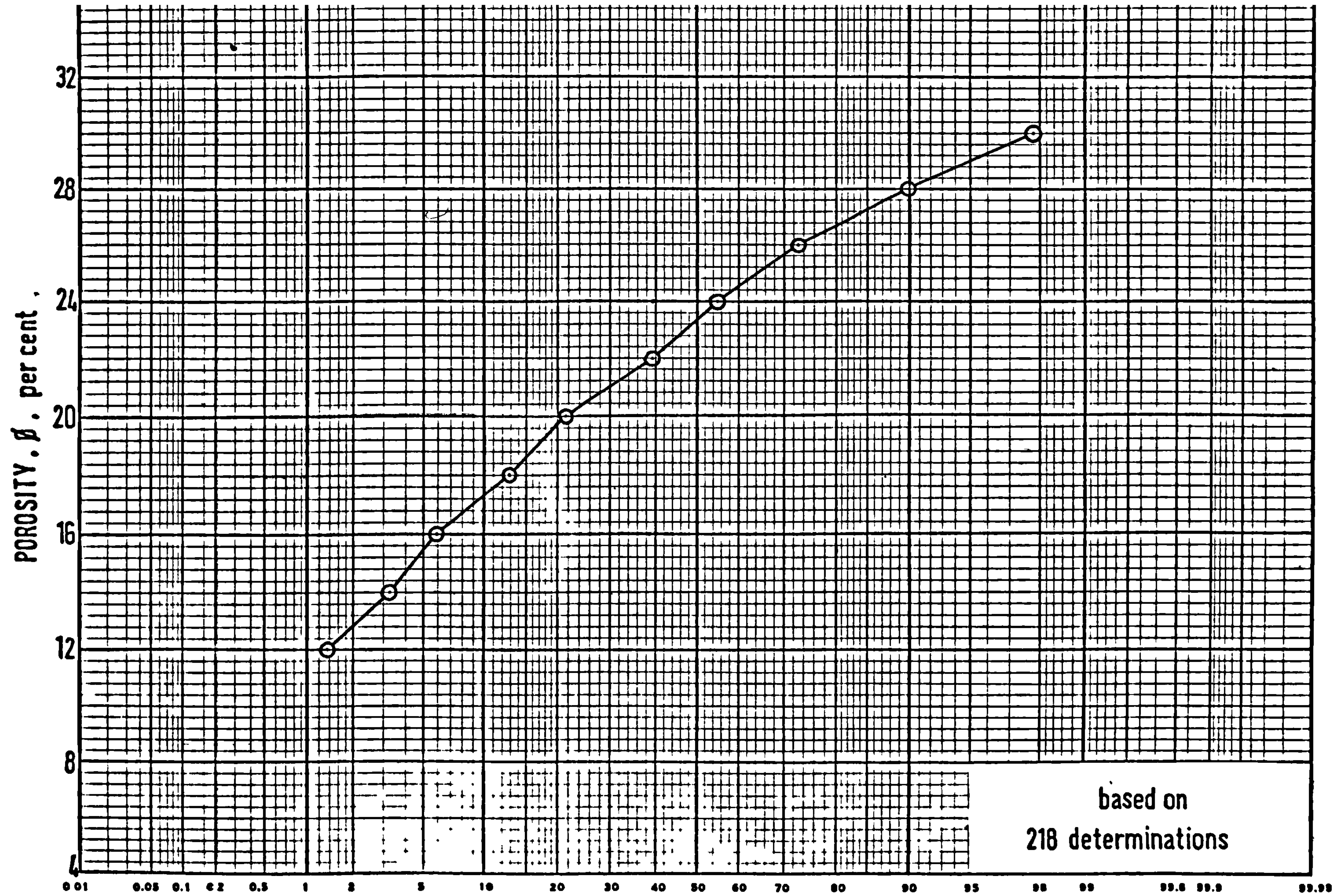
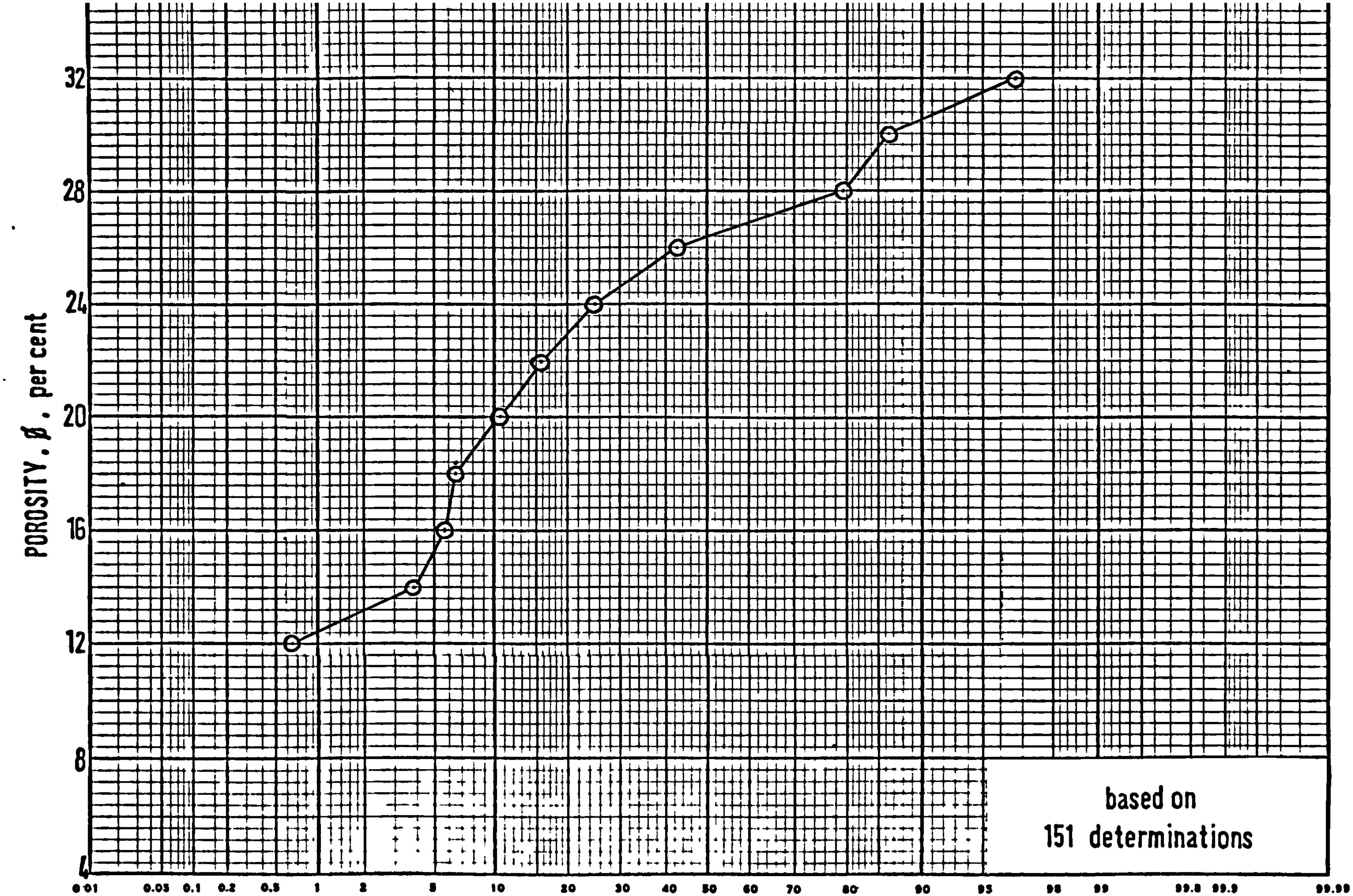


Fig. 70. Probability distribution of porosity AREA 5 BUNTER PEBBLE BEDS


POROSITY, Ø, per cent
32
28
24
20
16
12
8
4
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
based on
151 determinations

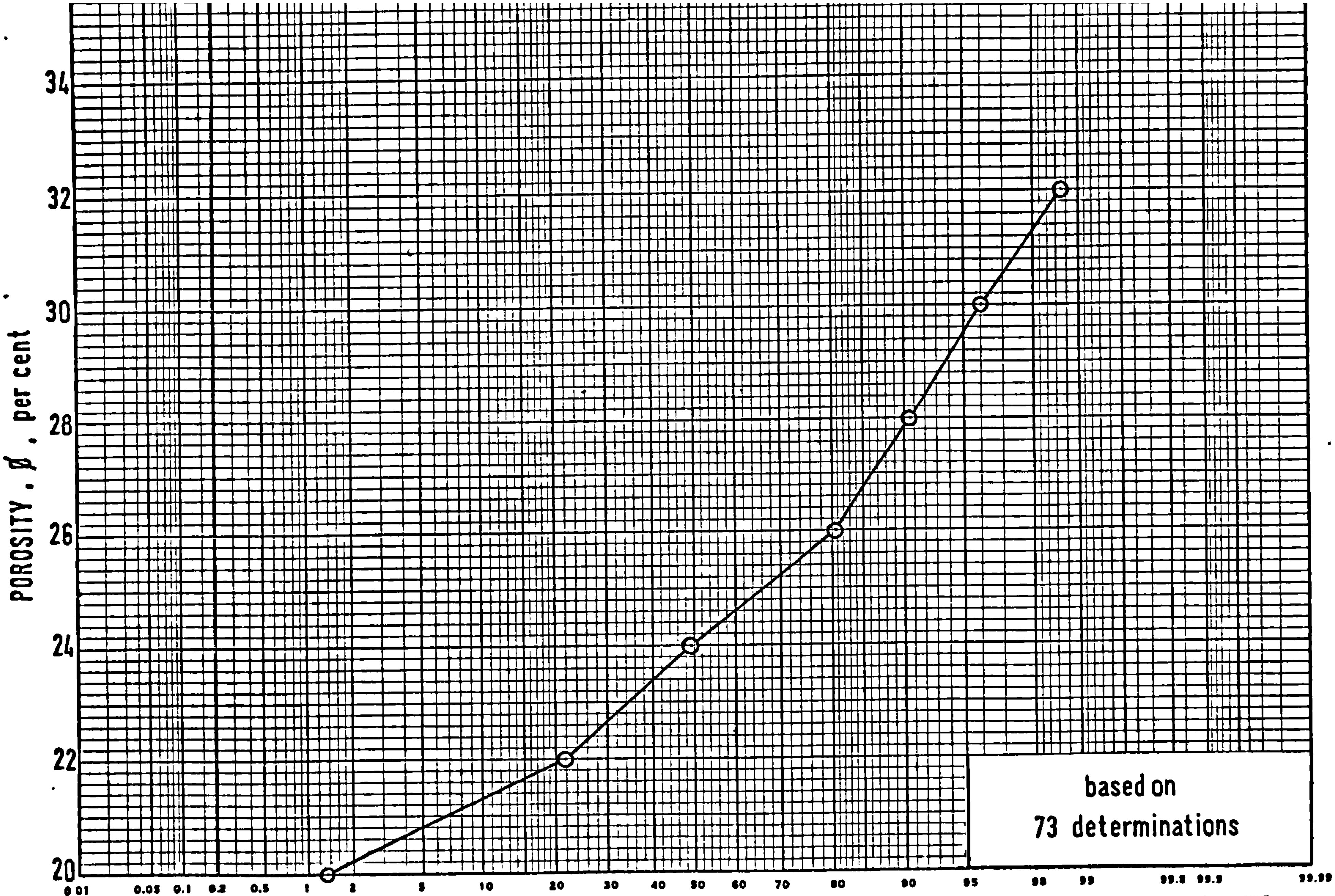


Fig 80 Probability distribution of porosity AREA 5 KEUPER SANDSTONE

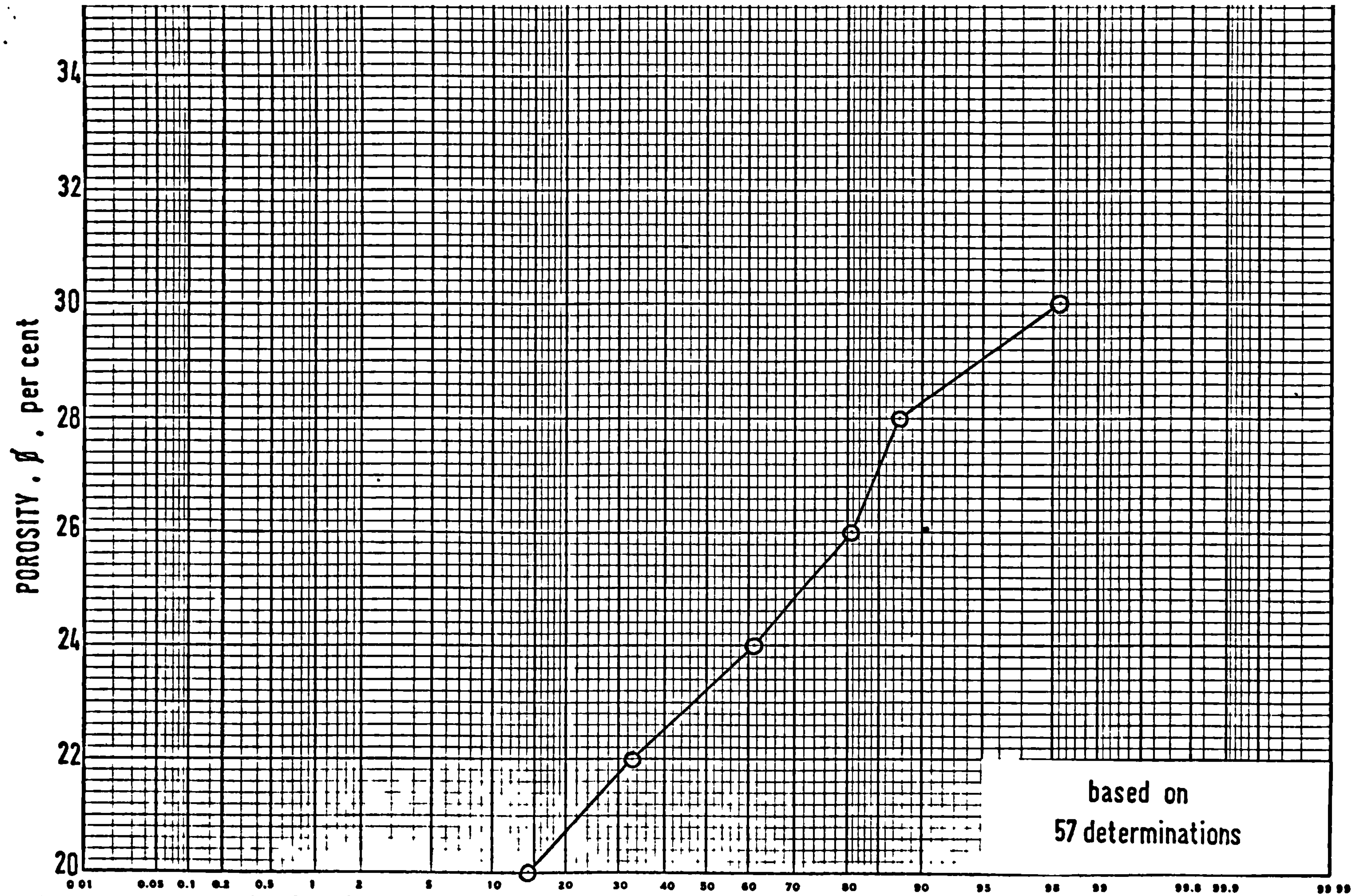
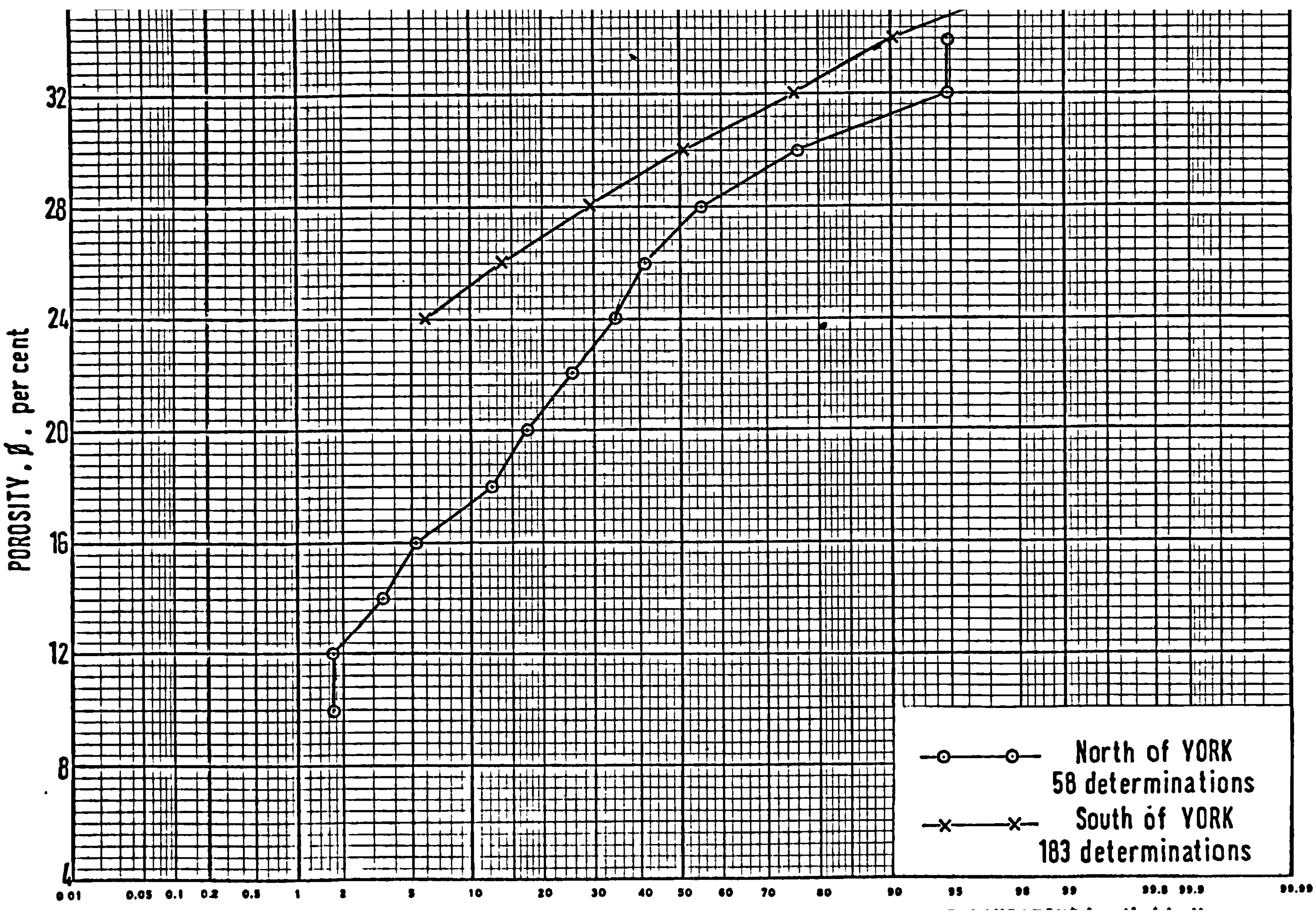
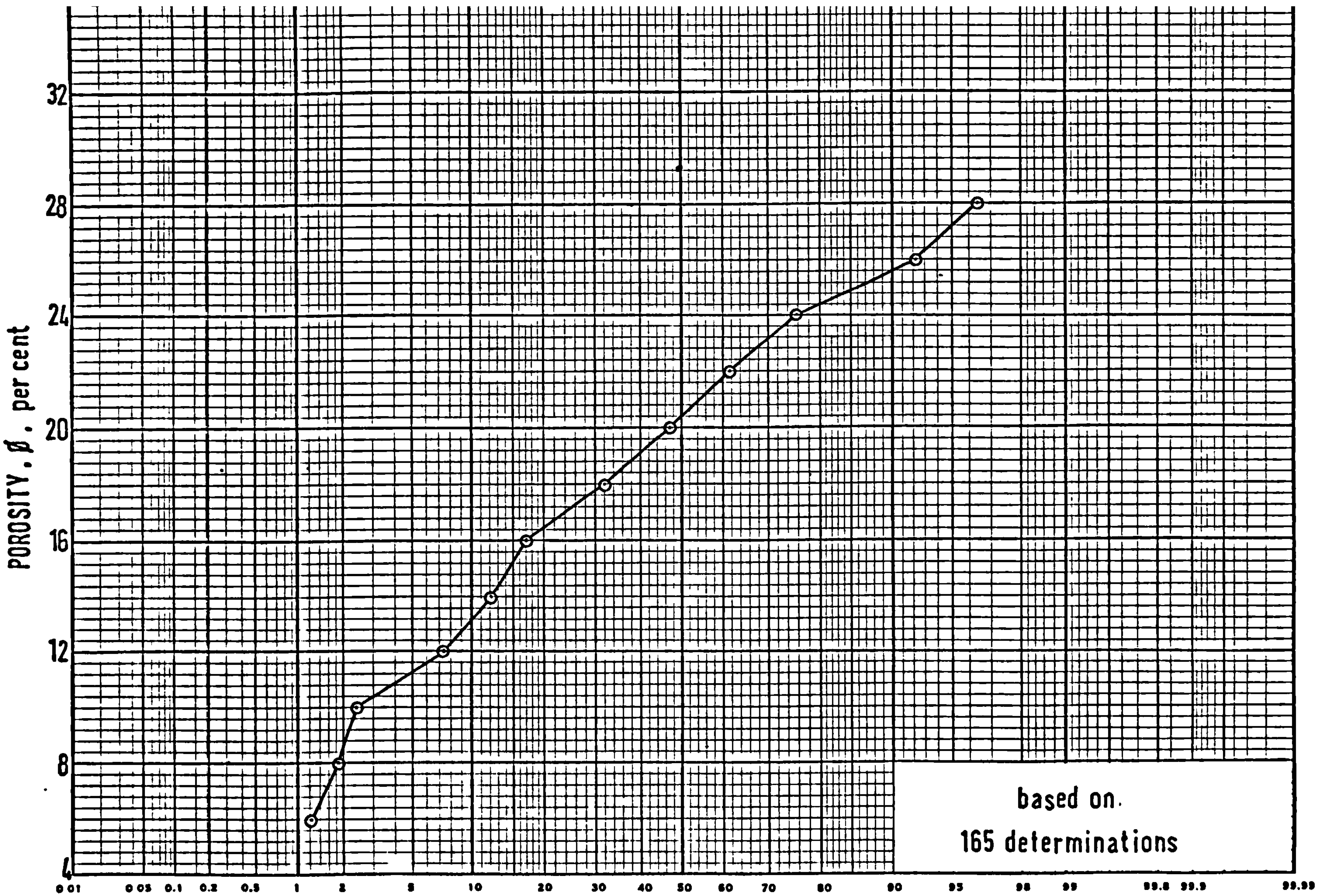


Fig. B1 Probability distribution of porosity AREA 5 Vale of Clwyd BUNTER SANDSTONE (undivided)



POROSITY, Ø, per cent
32
28
24
20
16
12
8
4
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
North of YORK
58 determinations
South of YORK
183 determinations



POROSITY, Ø, per cent
32
28
24
20
16
12
8
4
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
based on
165 determinations

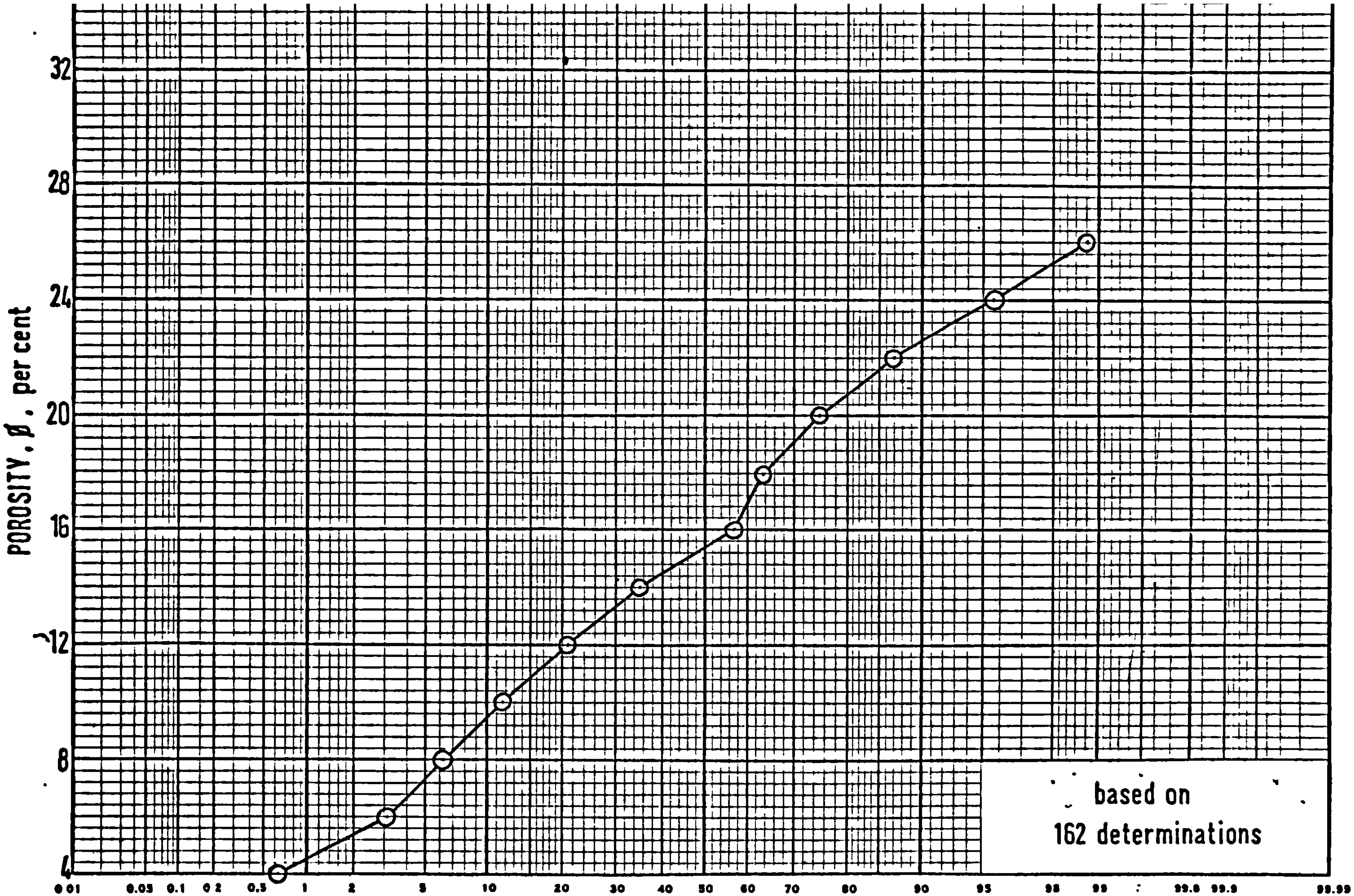
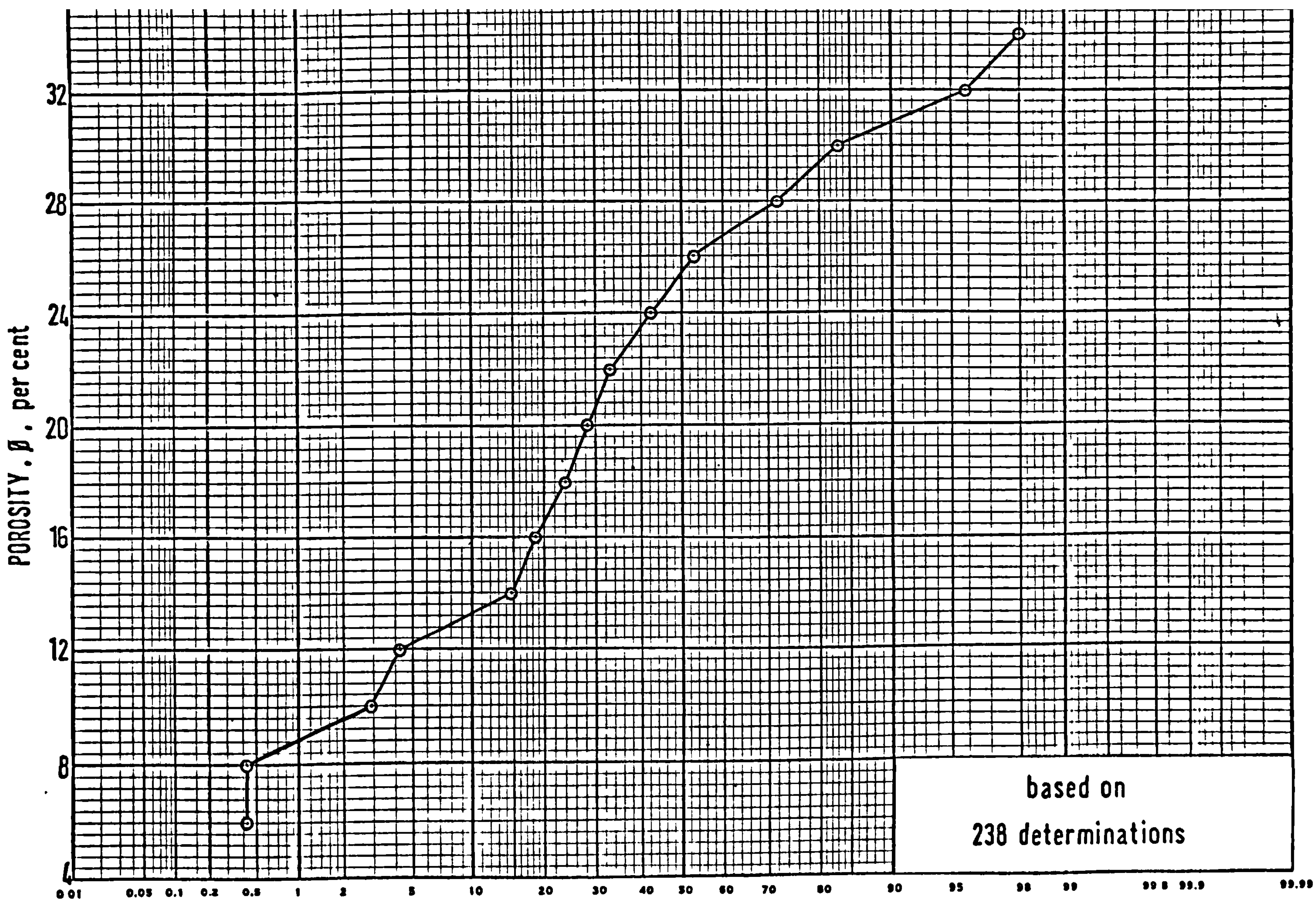


Fig 84 Probability distribution of porosity AREA 7 ST BEES SANDSTONE



POROSITY, Ø, per cent
32
28
24
20
16
12
8
4
0.01 0.05 0.1 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.9 99.99
based on
238 determinations

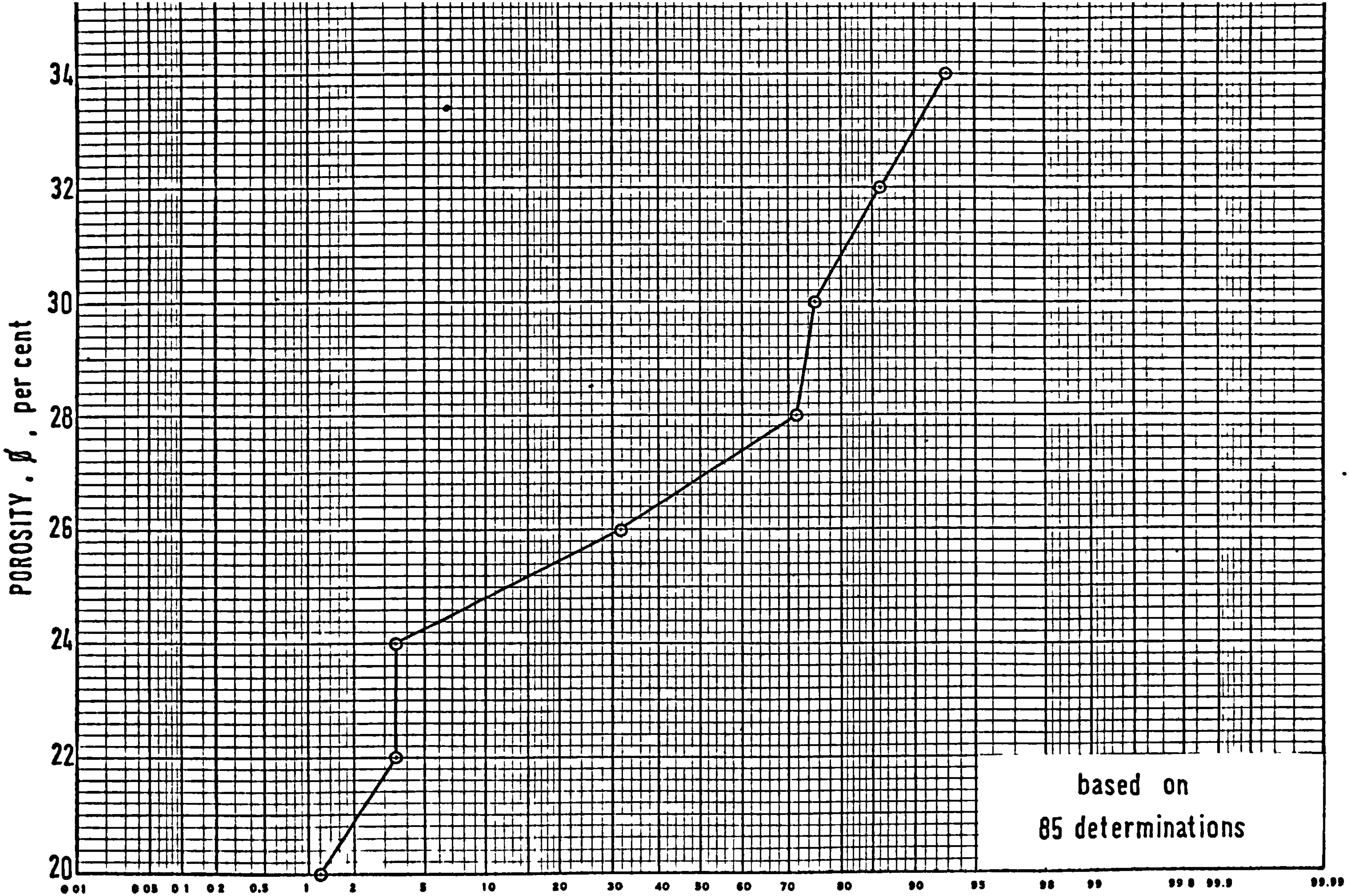
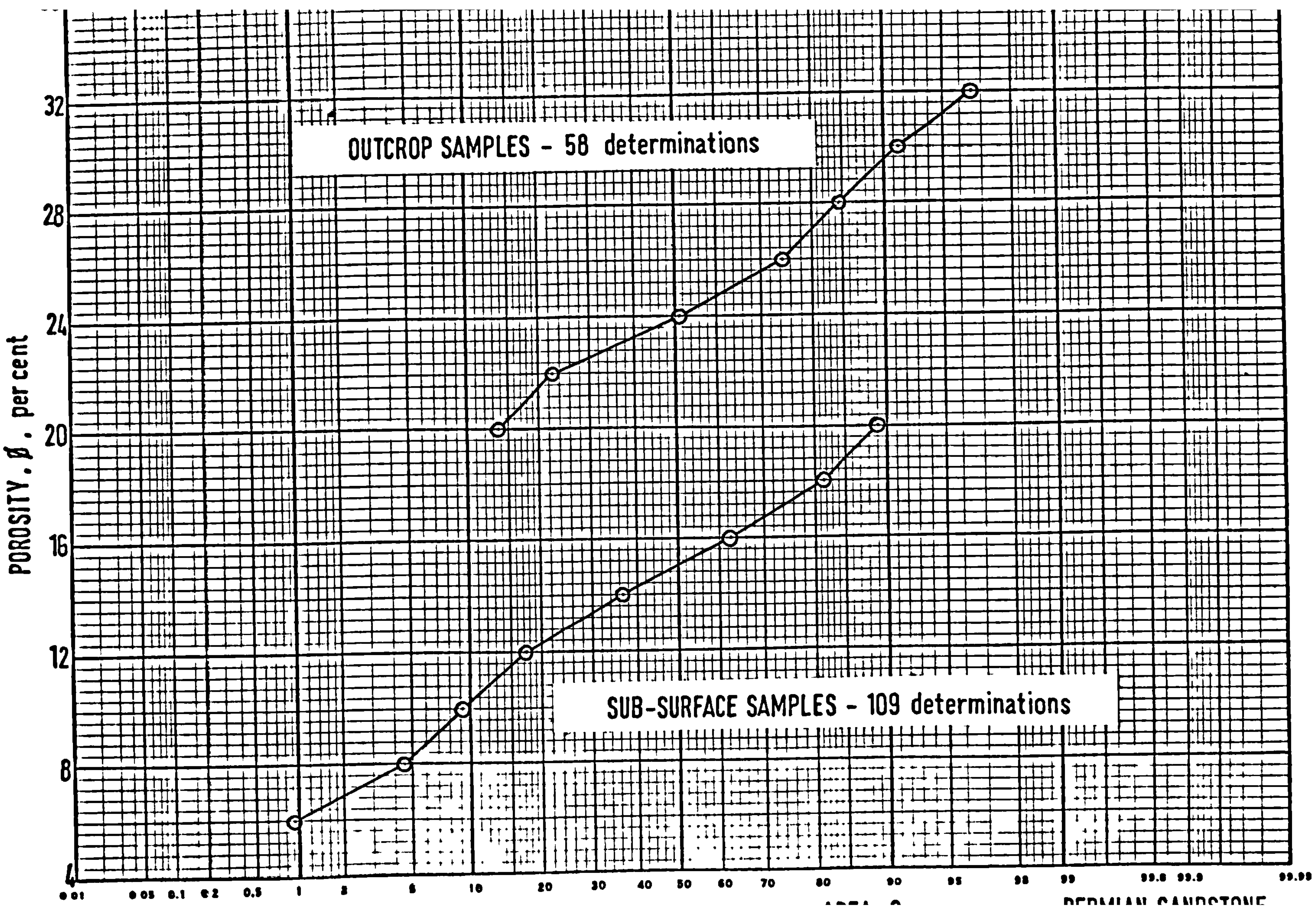
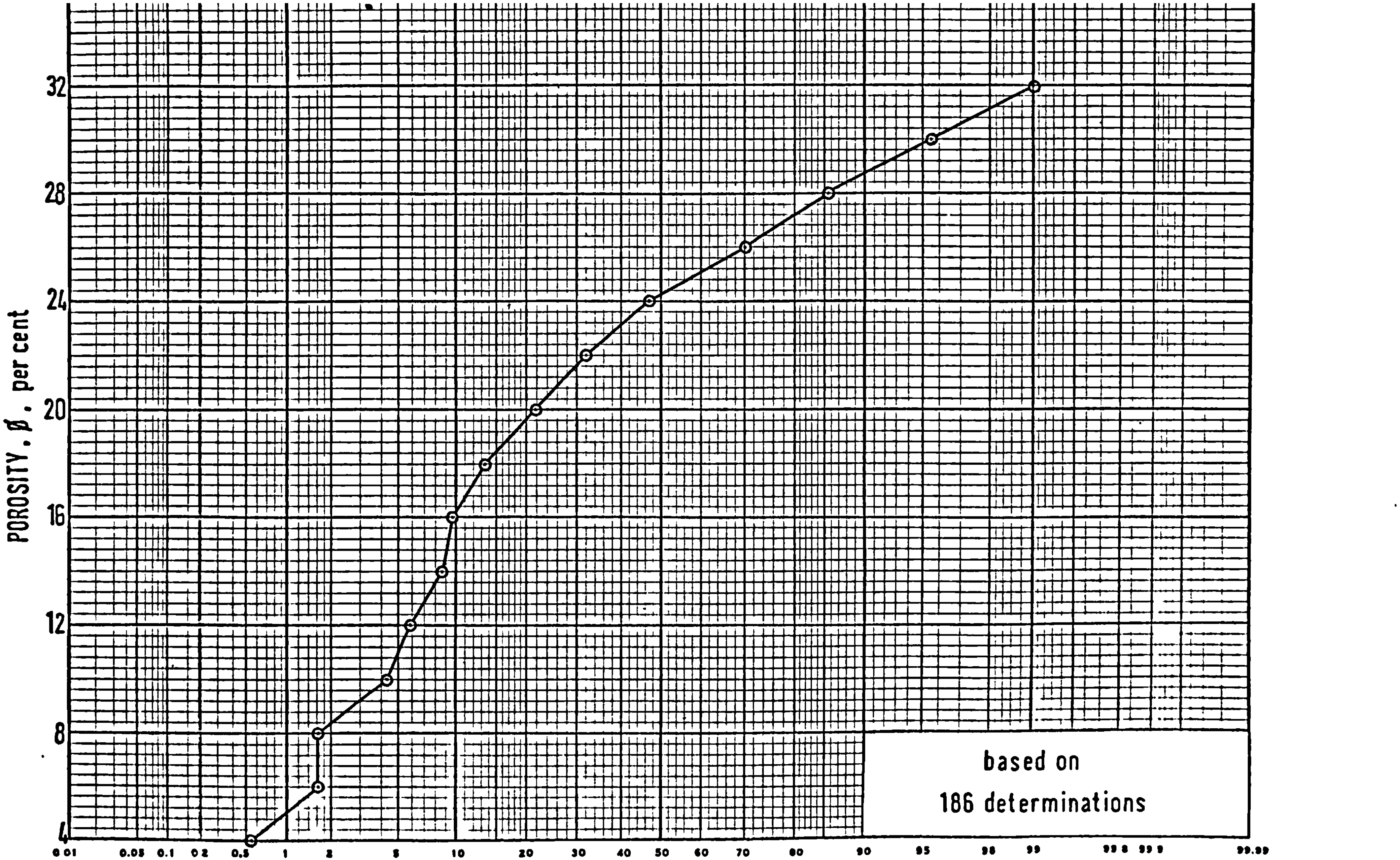


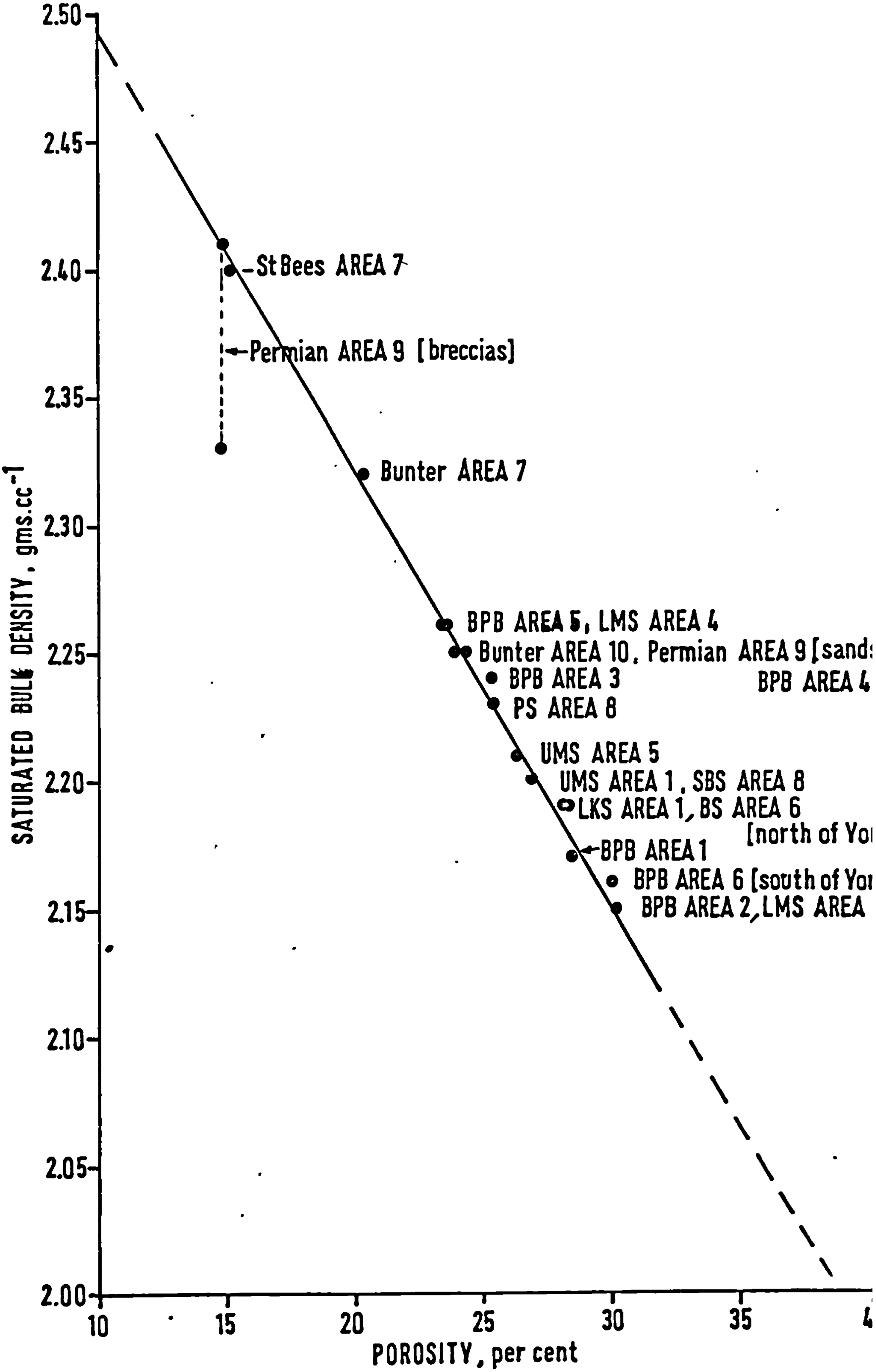
Fig 86 Probability distribution of porosity AREA 8 St BEES SANDSTONE



OUTCROP SAMPLES - 58 determinations
SUB-SURFACE SAMPLES - 109 determinations
POROSITY, Ø, per cent
32
28
24
20
16
12
8
4
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99



POROSITY, Ø, per cent
32
28
24
20
16
12
8
4
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
based on
186 determinations



Relationship between porosity and saturated bulk density

CHAPTER SEVEN : Comparison of field and laboratory values of permeability

CHAPTER SEVEN: COMPARISON OF FIELD AND LABORATORY VALUES OF TRANSMISSIVITY

7.1. INTRODUCTION

A logical development arising from the determination of the intergranular permeability distribution in a particular formation is to use the data to calculate values of transmissivity with differing probabilities. This is not, however, transmissivity in the usual sense of the term, since values for this property are normally obtained by the analysis of pumping test data obtained from boreholes in the field. The laboratory method can only provide a value for what may be termed "primary transmissivity" (Tp), ie the product of the saturated aquifer thickness and the intergranular geometric mean horizontal permeability of the formation.

A digression is required to consider whether this is a valid concept in well hydraulics. It is already well established that even in formations which possess a sizeable intergranular permeability, ground water enters production wells through discontinuities such as bedding plane fissures, inclined joints of either diagenetic or tectonic origin, or even natural pipes (as in Chalk). This has been demonstrated megascopically by the work of Farrell (1963), by Slater (1966) and by Tate, Robertson and Gray (1970). At the present time it is true to say that entry of water by microscopic flow has not been positively identified and indeed is rather unlikely to be, in view of the low velocities involved.

In formations of very low or negligible intergranular permeability, there is no conceptual problem in assuming that the aquifer yields water by transmission of water though an anastomosing system of fissures ranging in size from several centimetres down to hairline cracks. In spite of our total lack of knowledge of the detailed fluid pressure gradients within the fissure system, it still seems highly probable that seepage through the intervening blocks is negligible.

When the case of the formation with sizeable intergranular permeability is considered, we are dealing with material which will transmit considerable volumes of water under relatively low hydraulic gradients and yet in much of this type of material, there is a joint system present as well. The problem is to assess to what extent it is likely that the intergranular permeability interacts with 'free flow' along discontinuities. It is clear that such a problem can only be resolved by using rather indirect methods.

In the following analysis, it has been assumed that the transmissivity of a formation is in reality the sum of two fundamentally different components of flow, which under both natural and artificial (pumping) conditions interact with one another in what can only be described at present as a complex manner.

These two components are the microscopic or intergranular flow, and the megascopic or fissure flow. The results of the work of Tate et al (1970) suggest that the second component is almost always dominant during entry of water to pumping boreholes even in formations of high intergranular permeability and in their immediate vicinity. This conflicts with the view of Crook and Howell (1970) who consider, on the basis of studies they have carried out in the relatively cemented Bunter of South Lancashire, that intergranular flow is dominant throughout these sandstone sequences, and "except in a minority of occasions" fissure flow is not important.

7.3. CORRELATION BETWEEN LABORATORY AND FIELD VALUES OF TRANSMISSIVITY AT SIX SITES

During the course of the Project, correlation between laboratory and field values of transmissivity was attempted at six localities. These were as follows :-

1. LITTLETON COLLIERY, STAFFS	AREA 1	Bunter Pebble Beds
2. EDWINSTOWE, NOTTS	AREA 2	Bunter Pebble Beds
3. VALE OF CLWYD, DENBIGHS	AREA 5	Bunter Sandstone
4. WEST CUMBERLAND	AREA 7	St. Bees Sandstone
5. DUMFRIES	AREA 9	Permian Sandstone
6. HAW HILL, COMBER, Co.DOWN	AREA 10	Bunter Sandstone

With the exception of the investigation at Littleton Colliery, the correlations described below were based on -

a) laboratory data on numerous sequences of cores, and

b) the analysis of drawdown data from observation wells specially drilled in the vicinity of pumped boreholes.

The use of the Dupuit steady state method, as adopted by Payne (1968) and Crook and Howell (1970), was thereby avoided and a more precise comparison of field and laboratory values obtained.

7.3.1. LITTLETON COLLIERY, STAFFORDSHIRE

A comparison between the total transmissivity of the Bunter Pebble Beds, T_t and the intergranular or primary transmissivity, T_p was made in the vicinity of Littleton

Colliery near Cannock, Staffs. This study formed part of hydrogeological work carried out by IGS for the National Coal Board in connexion with the driving and possible dewatering of an inclined tunnel through the Pebble Beds (see Lovelock, 1971).

The formation at outcrop is shown in Plates 1A, 1B and 2A. It can be clearly divided into 3 sub facies :
i) the coarse shingle units with a sand matrix (Pl.1A)
ii) the sand-free shingle units (Pl.1B) and
iii) the interbedded coarse sandstone units (Pl.2A).

Because of the impossibility of testing the permeability of the shingle beds in the undisturbed state in the laboratory, a rather unusual procedure had to be adopted to determine T_p in these deposits; this may be summarised in the following steps:

a) The thickness ratio of sandstone to both types of shingle beds was determined by direct observation at a number of points in the extensive excavation known as Dunnings' Gravel Works, just to the south of the site of the proposed tunnel. The values of the ratio ranged from 1:10 to 3:7 and an average value of 1:4 was obtained (20% of the total formation thickness).

b) By means of particle size analysis, it was determined that the size distribution of the sand fraction of the shingle beds was closely comparable with that in the sandstone units. The relevant comparative data are given below :

	Sample No.	D10 mm	D50 mm	D60 mm
Pebble Bed - Sand fraction	708	0.142	0.275	0.32(
" "	711	0.120	0.267	0.33!
" "	713	0.154	0.270	0.30(
Sand Lens	707	0.145	0.265	0.29]
"	715	0.170	0.290	0.31(

c) The results of step 'b' permitted the use of the assumption that because the size distribution of the two sands was similar, then intergranular permeability values in the two media are alsc likely to be similar.

d) The cross sectional area of the pebble fraction of the shingle beds was then assessed. It was considered that, as a first approximation, the mean permeability value of the sandstone units (derived by core analysis) might be reduced by the average area of shingle-bed cross section occupied by pebbles. Since no flow can take place through the pebbles, their presence must reduce intergranular flow by an amount proportionate to and probably slightly in excess of their total cross-sectional area.

The cross sectional area was measured by preparing transparent overlays on photographs of vertical faces in the Pebble Beds in Dunning's Pit. The pebble areas in selected squares were marked in solid black and the proportion of pebble area (black) to sand area (clear) was directly measured in a Quantime 720 Image Analysing Computer. By examination of 11 photographs, a mean value of 33% for the pebble cross-section was obtained.

e) Core analysis was then carried out on samples of the sandstone units and this resulted in a geometric mean permeability of 8987 md which when reduced by 33% to produce an approximate value for intergranular permeabilit in the shingle beds became 6021 md.

From these values for permeability, theoretical primary transmissivity figures were obtained in the usual way by multiplying by an appropriate figure for saturated aquifer thickness.

This led to the following values of T_p in various units being obtained, assuming a thickness ratio of 1 : 4 sand to shingle, with actual values of 11 m for the sand thickness and 44m for the shingle thickness:

T_p, Sand	T_p, Shingle	Total T_p
8.44×10^{-4} $m^2 s^{-1}$	$2.26 \times 10^{-3} m^2.s^{-1}$	3.10×10^{-3} $m^2.s$
72.91 $m^2.d^{-1}$	195.36 $m^2.d^{-1}$	268.3 $m^2.d$
4879 Igpd/ft	13074 Igpd/ft	17953 Igpd/ft

Subsequent pumping tests in the formation in the immediate vicinity of the proposed tunnel were carried out and although the mathematical analysis of this data was complicated by the presence of multiple barrier boundaries, it is probable that the total transmissivity of the Pebble Beds is approximately 3.21×10^{-2} $m^2 . s^{-1}$ (or 2771 $m^2 . d^{-1}$ or 186000 Igpd/ft). This value for T_t is based on non-equilibrium analysis of early time-drawdown data for an observation well situated 386 m from the pumping well.

The result of this correlation, therefore suggests that the ratio of primary transmissivity to total transmissivity in the Bunter Pebble Beds in their type area has a value of 1 : 10. In other words, fissure flow is strikingly dominant over intergranular flow in this unit of the Triassic sequence long thought to be the classic case of dominant intergranular movement.

7.3.2. EDWINSTOWE, NOTTINGHAMSHIRE

A high proportion of the samples from the Bunter Pebble Beds in Nottinghamshire came from the Artificial Recharge Site of Water Resources Board at Edwinstowe near Ollerton where cores from 3 boreholes (serial Nos. 505, 508 and 509) were subjected to core analysis at closely spaced intervals.

The resulting permeability data were analysed using the probability method and a mean value of 4130 md (k_h at 0.50P and a field temperature of 11^{o}C) was obtained. Assuming a saturated thickness of 100m, this resulted in a value of $3.98 \times 10^{-3}\ m^2.s^{-1} = 344\ m^2.d^{-1}$ = 23093 Igpd/ft being obtained for T_p. This value compares with a figure of $1.74 \times 10^{-2} m^2.s^{-1} = 1500\ m^2.d^{-1}$ = 100,566 Igpd/ft for T_t, derived by staff of the Resources Division of Water Resources Board on the basis of pumping test data (personal communication).

The ratio $T_p : T_t$ therefore appears to have a value of 1 : 5 at the Edwinstowe site in spite of the unusually high intergranular permeability of the Bunter thereabouts. In view of the presence of coal mining beneath the Bunter at the site there are grounds for believing that the high T_t is partially a reflection of an induced fissure permeability in the formation caused by subsidence.

The Edwinstowe site is the subject of a forthcoming paper by Williams, Downing and Lovelock (in press). Whether the ratio 1 : 5 applies widely in the Nottinghamshire Bunter remains to be elucidated.

7.3.3. VALE OF CLWYD, DENBIGHSHIRE

A comparison of total and primary transmissivity was obtained in the Bunter beds of the Vale of Clwyd at 2 sites, through the work of Resources Division, Water Resources Board. Cores from Boreholes A1 and B2 were subjected to orthodox core analysis, and the data forms part of Chapter 5 of this thesis (P.161).

In order to compare the laboratory data with the field data, the horizontal permeability values obtained from each hole were averaged to produce a geometric mean value, since in this case there was insufficient data for a probability curve to be plotted.

The mean k values corrected to field ground water temperature were found to be as follows :-

	md	$m.s^{-1}$	$m.d^{-1}$	$Igpd/ft^2$
B.H. A1	554	5.35×10^{-6}	4.62×10^{-1}	9.46
B.H. B1	374	3.61×10^{-6}	3.12×10^{-1}	6.39

These values were then multiplied by appropriate values for saturated thickness, provided by Water Resources Board, (these were 122 m in the case of Site A, and 40 m in the case of Site B) in order to produce figures for T_p, which in the following tables are compared with field values for T_t.

	$m^2.s^{-1}$	$m^2.d^{-1}$	Igpd/ft	
T_p, Site A	6.53×10^{-4}	56.4	3784	- confine
T_t, Site A	1.38×10^{-2}	1192.0	80000	
T_p, Site B	1.44×10^{-4}	12.5	837	- unconfi
T_t, Site B	1.73×10^{-3}	149.0	10000	

It is clear from this table that there is a large difference between T_p and T_t at both sites, which leads one to conclude that fissure flow is dominant over intergranular flow in the Clwyd Trias. The fact that T_p varies in the same manner as T_t from site to site suggests, however, that T_p exerts a basic control over the total transmissivity of the formation.

7.3.4. WEST CUMBERLAND

In this area, the relationship between T_p and T_t was investigated in the St Bees Sandstone in collaborative work between IGS and Water Resources Board. Two sites in the confined aquifer were studied, to test the hypothesis that T_p was negligible and that therefore fissure flow was the dominant vehicle for ground water movement in this formation.

The same procedure adopted in the Vale of Clwyd was used. Mean k values, corrected to field ground water temperature were found to be :

	md	$m.s^{-1}$	$m.d^{-1}$	$Igpd/ft^2$
B.H. 1B	1.34	1.29×10^{-8}	1.11×10^{-3}	0.02
B.H. 2B	4.30	4.15×10^{-8}	3.59×10^{-3}	0.08

The saturated thickness of the formation at Site 1/1B is approximately 60 m, that at site 2/2B is approximately 175 m. Multiplication by these values results in the following data for T_p which is compared with values for T_t, obtained by pumping tests in the following table :-

	$m^2.s^{-1}$	$m^2.d^{-1}$	Igpd/ft
T_p, Site 1	7.74×10^{-7}	6.66×10^{-2}	3.94
T_t, Site 1	6.55×10^{-3}	565.9	37980
T_p, Site 2	7.26×10^{-6}	6.28×10^{-1}	45.9
T_t, Site 2	4.03×10^{-4}	34.8	2334

The results demonstrate conclusively that intergranular flow is practically irrelevant in the process of ground water movement through the St Bees Sandstone, at least in west Cumberland. It should be pointed out, however, that flow through a fault plane is at least partly responsible for the high T_t value at Site 1, and that therefore it is likely that the conditions at Site 2 are more typical of the formation as a whole. Even here, however, there is an enormous discrepancy between the T_p and T_t values.

7.3.5. DUMFRIES

In the breccia facies of the Permian Sandstone in Area 9 a correlation between T_p and T_t was obtained at the I.C.I. Factory at Drungans near Dumfries. Cores from the No. 2 Borehole at the factory, seen in Plate 12B and Fig.27 were subjected to core analysis (sample Nos. 329-1 to 329-24) and the results expressed in the form of a probability curve (Fig.68). From this curve, values of T_p have already been computed (in section 6) for a saturated thickness of 300 m. In fact for the purpose of an exact correlation with T_t

derived from pumping tests, these values must be reduced since the thickness of saturated aquifer actually penetrated at the site was 187.1 m (614 ft). Use of this figure leads to T_p values of 1.36×10^{-4} $m^2.s^{-1}$ = 11.7 $m^2.d^{-1}$ = 788 Igpd/:

Pumping tests at the site were carried out by IGS in July 1968 and a report on the investigation was prepared (Lovelock, 1968). Although pumping commenced from a very slowly recovering piezometric surface, a reasonably accurate solution for T_t was obtained, using the Theis and Jacob methods of analysis.

Subsequent continuously recorded water level data confirmed that confined conditions prevail at the site. The T_t values obtained were $1.09 \times 10^{-3} m^2.s^{-1}$ = 94.4 $m^2.d^{-1}$ = 6334 Igpd/ft, this figure being a geometric mean of the results using the Theis and the Jacob methods.

A large difference was therefore found to exist between the T_p and T_t values in this part of the Permo-Trias. Since the wells at the factory penetrate a proportion of sandstone as well as breccia, it could be expected that T_p would depart from T_t to an even greater extent in wells drilled only into breccia. Conversely, those penetrating only sandstone would show a closer agreement between T_p and T_t owing to the higher microscopic permeability of the sandstones, demonstrated in Chapter 5 (p.187). The result must, however, only be taken as a first approximation. Problems were encountered in the interpretation of the pumping test data which might affect the value of the ratio

$T_p : T_t$ quite significantly. Principal amongst these was the problem of dewatering caused by overdevelopment, and the large partial penetration effect. Although it is not known for certain, geophysical evidence (Bott and Masson Smith, 1960) suggests that the saturated thickness of the aquifer at the site may be as great as 500m, which compares with only 187 m actually intersected by the pumping and observation wells.

7.3.6. NEWTOWNARDS, COMBER, CO.DOWN

Correlations between T_p and T_t were attempted in both the buried Permian Sandstone and the Bunter Sandstone aquifers in the area east and south of Scrabo Hill in County Down, Northern Ireland. For the values of T_t, the Author is indebted to Stephen Foster of Hydrogeological Department IGS who supervised and interpreted the pumping tests.

The Permian Sandstone was investigated using wells drilled in the vicinity of Kennel Bridge, Comber. Laboratory determinations of permeability were made on 9 samples of the formation (Nos. 326-1 to 326-9) from depths of between 51.2 m and 66.2 m; these were unfortunately from only the lower third of the formation but the drilling conditions suggested that the upper two-thirds were of substantially similar lithology, viz. coarse friable sands and thin brockrams. A geometric mean value for horizontal permeability was calculated which when corrected to the field ground water temperature of 11^{o}C was found to have a value of 2410 md. The saturated thickness of the aquifer is approximately 61 m (200 ft) and, therefore, T_p was found to have a value of $1.42 \times 10^{-3} m^2.s^{-1} = 122.7 m^2.d^{-1}$ = 8242 Igpd/ft.

By comparison, the results of non-steady state analysis of time-drawdown data gave values of 1.29×10^{-3} $m^2.s^{-1}$ = $111.8 m^2.d^{-1}$ = 7500 Igpd/ft (Foster, 1968). The conclusion to be drawn is that T_p appears to be approximately equal to T_t and that therefore intergranular flow is the dominant process whereby water is transmitted in pumping wells in this formation. In view of the fact that T_p has not been found to equal T_t in any of the other studies reported here, it may be that it is incorrect to assume that the core samples examined are completely representative of the higher levels of the formation. On the other hand, those which were tested are particularly permeable, in cases reaching 12 darcys.

The study on the Bunter Sandstone was carried out using a fully cored well at Haw Hill (Irish Grid J48306952) (Fig.28) which provided the intergranular permeability data, and a pumping test at McAlpine's Farm about 2 km to the north. The geometric mean horizontal permeability of the formation at Haw Hill, based on 27 samples (Nos.673-1 to

673-27), corrected to field ground water temperature ($11^{o}C$) was found to be only 1.083×10^{-6} $m.s^{-1}$. The thickness of saturated aquifer in the well was 36.8m, resulting in T_p values of 3.99×10^{-5} $m^2.s^{-1}$ = 3.44 $m^2.d^{-1}$ = 231.25 Igpd/ft.

Pumping test data from McAlpines Farm (Foster,1969) resulted in values for T_t of $6.04 \times 10^{-3} m^2.s^{-1}$ = 521.5 $m^2.d^{-1}$ = 35000 Igpd/ft $\pm$ 20%. Although the saturated thickness of the aquifer at the site was 76.2 m (250 ft), it is clear that there is wide divergence between the T_p and T_t values. Part of the discrepancy may be related to the fact that the McAlpines Farm site is slightly higher in the Permo-Triassic sequence, but the principal factor must be the prevalence of ground water flow along discontinuities, especially bedding plane fissures as this formation tends to be thinly bedded (see Plate 13B). The conclusion therefore is that in contrast to the Permian, the Bunter in Northern Ireland is apparently a fissure flow aquifer.

7.4. CONCLUSIONS

The results presented in this chapter are best summarise by examining the regional variation in the value of the ratio $T_p : T_t$. These are tabulated overleaf and explanatory comments follow -

AREA	FORMATION	$T_p : T_t$ RATIO
1	BUNTER PEBBLE BEDS	1 : 10
2	BUNTER PEBBLE BEDS	1 : 5
5	BUNTER SANDSTONE (Vale of Clwyd) Site A	1 : 21
5	BUNTER SANDSTONE (Vale of Clwyd) Site B	1 : 12
7	St. BEES SANDSTONE Site 1	1 : 10000
7	St. BEES SANDSTONE Site 2	1 : 50
9	PERMIAN SANDSTONE	1 : 8
10	PERMIAN SANDSTONE	1 : 1
10	BUNTER SANDSTONE	1 : 150

The above table demonstrates the variability of conditions in the Permo-Trias aquifers in different parts of U.K. What we are considering here, is the areal variation in both primary and total transmissivity, which is influenced by all the factors affecting formation permeability, i.e. sedimentation, cementation, diagenetic processes and structural deformation. As might be expected, it is apparent that the ratio varies logarithmically and is closest to unity in those areas where the sandstones possess maximum intergranular permeability, and is smallest where the cementation and structural deformation are most prevalent. A great deal more research is required to establish the regional variation in the ratio; this would have to be executed using cored boreholes which are subsequently pumped. In practical terms, this could be most easily accomplished by drilling cored boreholes at sites at which exploratory production wells are to be constructed. The results of the core analysis could then be compared with the pump test data, and in the course of time, more and more data will be accumulated so that a comprehensive model of the relative importance of fissure and intergranular flow in the formation can be built up.

CHAPTER EIGHT : Correlation with West and East Germany

CHAPTER EIGHT : CORRELATION WITH WEST & EAST GERMANY

8.1. INTRODUCTION

The problem of the relationship between microscopic intergranular permeability, deduced from core analysis, and total transmissivity derived from pumping test analysis, has also been studied in the Permo-Trias in Germany by Hauthal (1967) and by Durbaum, Matthess and Rambow (1969). Their work was similar in conception and execution to the present study, and it may be useful to compare the results of these studies with those obtained in Britain.

It is necessary at this point to digress to consider the present state of knowledge on the problem of correlating the Trias in the British Isles with that on the Continent. This was demonstrated at the 1967 Symposium on the Triassic Rocks of the British Isles, held by the Geological Society of London. The papers presented and the lively discussion of them that ensued were a clear indication that general agreement on such fundamental matters as the position of the upper and lower boundaries of lithostratigraphic subdivisions of the Trias has not yet been achieved. Much of the time was taken up by considering the crucial "Keuper" sequences which do not include much water bearing strata. However, some important points did emerge during the Symposium which are of significance in studies of the ground water hydrology of the British Trias. These may be summarised as follows :-

i. The palynological studies carried out by Warrington (1967) and (1970) indicate that practically the entire sequence of permeable sandstone and pebble beds above the base of the Bunter Pebble Beds is Scythian in age. Parts of the 'Keuper' Building Stones in Central England are Anisian (see Fig. 90 from Warrington (1970)). This means that the principal Triassic aquifers were laid down within the span of a single stage, the earliest of the European Triassic, currently referred to as Palaeo-Triassic.

ii. Although universal agreement is by no means complete, it is widely held that the base of the Trias should be taken at the base of the Bunter Pebble Beds, a plane of marked erosion (see Plate 4B). This naturally places the Lower Mottled Sandstone in the Permian and raises the often discussed possibility that this formation is laterally equivalent to other dune bedded rocks normally referred to the Permian such as the Penrith Sandstone and the Dumfries sands of Scotland. The principal problem here is that of defining the base of the Trias in those areas where Pebble Beds are not developed, as pointed out by Poole (in discussion of Audley-Charles, 1970 a).

Worcestershire (Wills, 1950)	S. Nottinghamshire (Elliott, 1961; base modified)	Cheshire (This paper; tentative)	Central Midlands (modified after Warrington, 1967)	North Sea Sequence (Generalized)	French Sequence (Lorraine, after Ricour, 1962)	German Sequence (Saxony)	Stages		
RHAETIC	RHAETIC	RHAETIC	RHAETIC	RHAETIC	RHAETIC	UPPER KEUPER: RHÄT	RHAETIAN	KEUPER	NEOTRIASSIC
KEUPER MARL GROUP	PARVA FORMATION / TRENT FORMATION	UPPER KEUPER MARL FORMATION	KEUPER MARL GROUP: PARVA FORMATION* / TRENT FORMATION 3	GYPSIFEROUS SILTSTONES AND MUDSTONES	UPPER TRIAS OR KEUPER — UPPER KEUPER: MARNES IRISÉES SUPÉRIEURES / ARGILES DE CHANVILLE	UPPER TRIAS OR KEUPER — MIDDLE KEUPER: STEINMERGEL / ROTE WAND	NORIAN		
	HOLLYGATE [illegible] HILL MEMBER	ARDEN SANDSTONE MEMBER	ARDEN/HOLLYGATE MEMBER	SANDY SILT (SCHILFSANDSTEIN)	MIDDLE KEUPER: MARNES ET DOLOMIE / GRÈS À ROSEAUX	SCHILFSANDSTEIN	CARNIAN		
	EDWALTON FORMATION 2 HARLEQUIN FORMATION	UPPER SALIFEROUS FORMATION	EDWALTON FORMATION* 2 HARLEQUIN FORMATION*	GIPSKEUPER	LOWER KEUPER: MARNES IRISÉES INFÉRIEURES	GIPSKEUPER			
BROMSGROVE OR KEUPER SANDSTONE GROUP	CARLTON FORMATION / RADCLIFFE FORMATION	MIDDLE KEUPER MARL FORMATION	CARLTON FORMATION* / RADCLIFFE FORMATION*	LETTENKOHLE	LETTENKOHLE: DOLOMIE LIMITE / MARNES BARIOLÉES ET DOLOMIE / DOLOMIE INFÉRIEUR	LOWER KEUPER: GRENZDOLOMIT / LETTENKOHLENSANDSTEIN	LADINIAN	MUSCHELKALK	MESOTRIASSIC
	WATERSTONES FORMATION		WATERSTONES FORMATION	DOLOMITIC MUDSTONE	MIDDLE TRIAS — MUSCHELKALK: MUSCHELKALK SUPÉRIEUR	MIDDLE TRIAS — MUSCHELKALK: TONPLATTEN / TROCHITENKALK			
	WOODTHORPE FORMATION	LOWER SALIFEROUS FORMATION	KEUPER SANDSTONE GROUP: BUILDING STONES FORMATION	HALITE	MUSCHELKALK MOYEN	ANHYDRIT GRUPPE	ANISIAN		
?—?		LOWER "KEUPER" MARL FORMATION / WATERSTONES FORMATION		DOLOMITIC MUDSTONES	MUSCHELKALK INFÉRIEUR	WELLENKALK			
MOULDING SAND	UNCERTAIN THICKNESS ABSENT (WARRINGTON, THIS PAPER)	"KEUPER" SANDSTONE GROUP	CONGLOMERATE FORMATION	RÖT (RÖTSALINAR) MAINLY	GRÈS	UPPER BUNTER: RÖT / SOLLING / M[illegible]	[illegible]		PA[illegible]

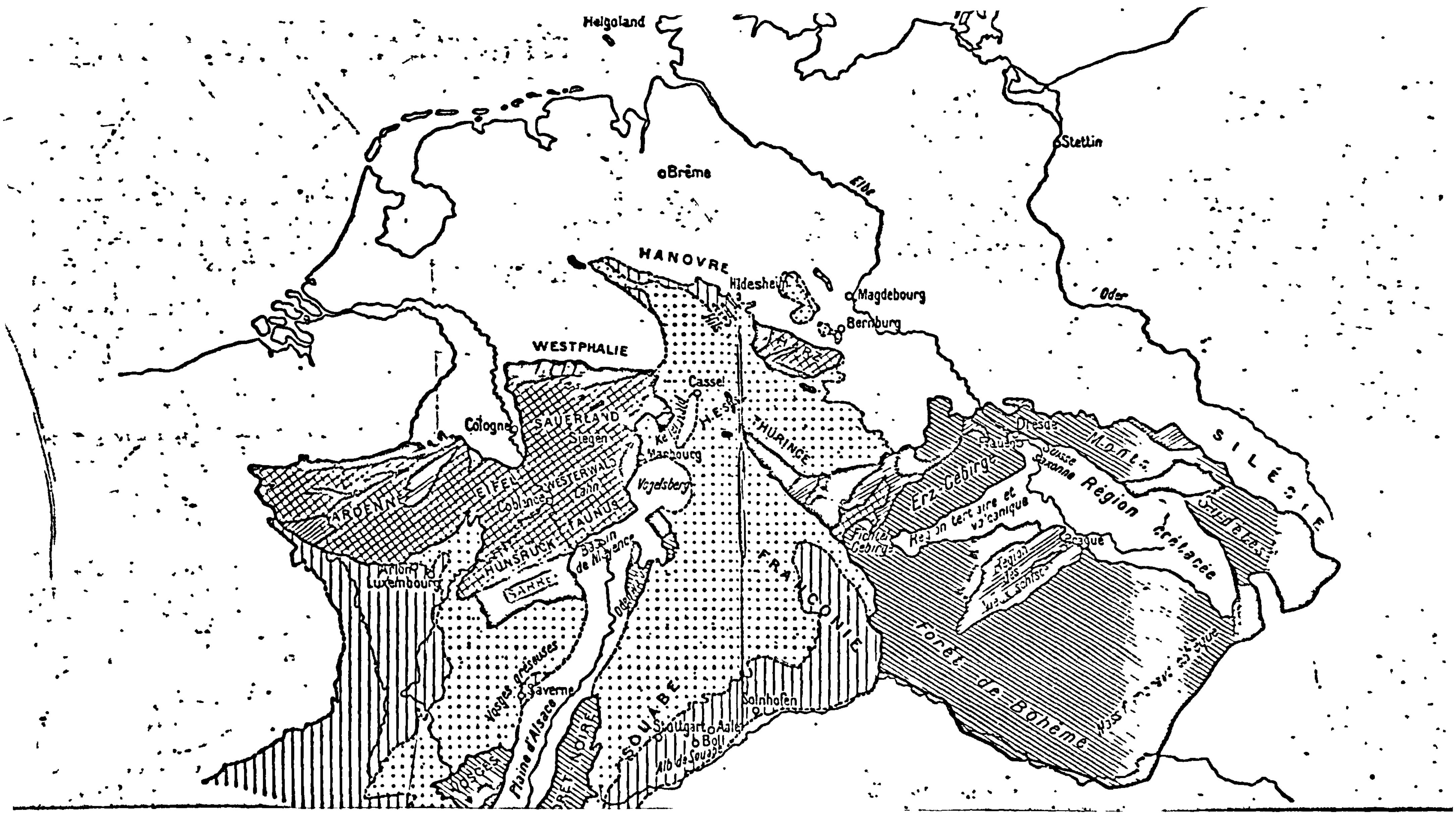
iii. The problem of how the Permian sandstone deposits in the British Isles are related to the sedimentologically similar overlying Triassic rocks was scarcely mentioned. Although strictly the Symposium was concerned with Triassic problems, the question of the location of the base of the Trias must be studied in relation to the underlying formations. In this respect the apparently widespread development of passage beds at this horizon in Northern England and in Ireland, contrasts strongly with the knife-edge junction at the base of the Pebble Beds in the England Midlands. These passage beds were referred to by Audley-Charles (1970b), Manning (in discussion of Audley-Charles, 1970b), and Smith (general discussion). Palynological studies of the St Bees Shales and related passage deposits at equivalent horizons thought to be of similar age are urgently required in order to attempt to establish the relationshi between those Bunter sandstones now known to be late - Scythian in age, and those currently being referred to for convenience as Permian.

iv. It is now considered permissible to use the terms 'Keuper' and 'Bunter' only as facies names. Once the true time relationship of the rocks has been unravelled, new chronostratigraphic names will presumably be given to the various subdivisions. This would best be carried out by the Triassic Working Group of the Mesozoic Era Sub-Committee currently reviewing stratigraphical nomenclature and correlation.

The correlation diagram from Warrington (1970) (Fig.90) indicates how the formations studied by Hauthal (1967) and Durbaum et al (1969) relate to the British sequences. As far as the Author is aware, no similar studies have yet been carried out in France. No doubt they will be in the near future.

8.2. HAUTHAL'S STUDY IN THURINGIA, EAST GERMANY

The Trias occupies a large area in central Germany between the Hercynian crystalline massif of the Black Forest on the west, and the Bohemian massif to the east. Within this wide zone, the type facies of the German Trias is developed, the lower part of which consists mainly of sandstone and conglomerate. This is referred to as "Grès bigarre" by French authors (eg Gignoux,1960) and as Buntsandstein by German authors such as Brinkmann (1926). The outcrop area is shown on the accompanying sketch map (Fig.91) taken from Gignoux (1960) and can be seen to include in the north the major part of the old provinces of Hesse and Thuringia. It is here that the work of Hauthal and Durbaum et al has been carried out.



Helgoland
Brême
Stettin
Elbe
Oder
HANOVRE
Hildesheim
Magdebourg
Bernburg
WESTPHALIE
Cassel
Cologne
SAUERLAND
Siegen
HESSE
THURINGE
Dresde
SILÉSIE
Erz Gebirge
Région
Crétacée
Vogelsberg
EIFEL
WESTERWALD
Coblence
TAUNUS
ARDENNE
HUNSRÜCK
SARRE
Arlon
Luxembourg
FRANCONIE
Fichtel Gebirge
Prague
Forêt de Bohême
Solnhofen
SOUABE
Stuttgart
Aalen
Boll
Alb de Souabe
Saverne
Vosges gréseuses
Plaine d'Alsace

Hauthal's results are based on data from a cored borehole drilled into the Hardegsen, Detfurth and Volpriehausen formations of the Middle Bunter Sandstone at Hy Lauchstadt, about 30 km west of Leipzig in Thuringia. The sequence proved in the borehole was as follows (in metres):

	thickness	dep
Pleistocene loess and sand	5.0	5.
Sandstone and siltstone (Hardegsen Formation)	59.2	64.
Siltstone and mudstone (Detfurth Formation)	14.3	78.
Sandstone (Detfurth and Volpriehausen Formations)	46.5	125.

Laboratory determinations of permeability were carried out on 7 samples of the upper sandstone aquifer (Hardegsen) and on 16 samples of the lower aquifer (Volpriehausen and lower part of Detfurth). These samples were chosen on lithological grounds and the results for each of the aquifers were averaged to produce an arithmetic mean. The values were as follows :

	Mean Value	Range
Hardegsen	$1.3 \times 10^{-7} m.s^{-1}$	$<10^{-9}$ to $6.4 \times 10^{-6} m.s^{-1}$
Volpriehausen and lower Detfurth	$1.2 \times 10^{-7} m.s^{-1}$	$<10^{-9}$ to $1.22 \times 10^{-5} m.s^{-1}$

The field values for permeability were obtained by analysis of both steady and non-steady state pumping data. Comparative data for the upper and lower aquifers were obtained by altering the position of lining tubes. The values obtained using Dupuit, Theis - Jacob and Wiederhold (1965) methods were then also averaged to produce an arithmetic mean value for field permeability. The values were 4.5 x 10^{-6} $m.s^{-1}$ for the upper aquifer (Hardegsen) and 3.2 x 10^{-6} $m.s^{-1}$ for the lower aquifer (Volpriehausen and lower part of Detfurth).

As the in-situ permeability of the aquifers was found to be 20-30 times larger than the intergranular permeability determined on core samples, Hauthal concluded that ground water in the sandstones mainly flows through joints and bedding planes. While this conclusion by itself is not disputed, his work is open to criticism on three counts: firstly, the number of samples he examined is very small and secondly, unless the range of values is very limited, the geometric mean should be used to average permeability data, as this property varies in a logarithmic manner. The use of arithmetic means is very misleading and leads to positive errors in values which in this case cause an over optimistic picture of intergranular permeability to be presented. Finally, his samples were chosen not on a statistical basis but to cover the range of lithology. This leads to obvious errors especially when dealing with small numbers of samples.

Unfortunately no density or porosity data or more detailed lithological information accompanies Herr Hauthal's paper and a letter to him requesting further details brought no reply. According to the known stratigraphy of this part of the Trias in East Germany, it appears that the formations are lithologically similar to the Bunter Sandstone of the Vale of York (Area 6 north of York)) and of North West England (Area 7). It is, therefore, interesting that the permeability data varies over approximately the same range, and one may perhaps conclude that it is likely that T in these parts of the English Trias may also exceed T_p by a factor of 20-30.

8.3. RESULTS FROM HESSE, WEST GERMANY

Similar studies have been made by Durbaum et al (1969) using 4 cored boreholes located in the Triassic basin of northern Hesse. The details of these wells are as follows :-

		thickness	depth
Elgershausen No.1.	Tertiary	94.4	94.4
	Rot (mudstone)	111.6	206.0
	Solling Formation	84.0	290.0
Beberbeck	Tertiary	15.0	15.0
	Solling Formation	22.8	37.8
	Hardegsen Formation	230.2	268.0
	Detfurth Formation	7.0	275.0
Haarhausen No.6.	Solling Formation	55.9	55.9
	Hardegsen Formation	168.6	224.5
	Detfurth Formation	7.0	231.5

		thickness	depth
Altenstädt	Hardegsen Formation	114.55	114.55
	Detfurth Formation	86.9	201.45
	Volpriehausen Formation	7.25	208.70

Samples were taken from the cores at intervals of several metres throughout the formations so that the permeability data was given a good statistical basis. These samples were tested using orthodox petroleum core analysis methods (the same as those employed in this study). From these results laboratory values of transmissivity were calculated by planimetering under a core - log of permeability against depth (using linear scales). These values were compared with those derived from both steady state and non-steady state data obtained during pumping tests on the boreholes, with individual members of the Bunter sequence being separatel[illegible] evaluated by altering the position of lining tubes. The result[illegible] may be summarised as follows :-

Borehole	Formation	T_p Value $m^2.s^{-1}$	T_t value $m^2.s^{-1}$
Elgershausen No.1.	SOLLING	6.4×10^{-5}	$1.8 \times 10^{-}$
Beberbeck	SOLLING + UPPER HARDEGSEN	1.1×10^{-6}	$1.6 \times 10^{-}$
Beberbeck	SOLLING + HARDEGSEN (WHOLE)	1.2×10^{-6}	$2.3 \times 10^{-}$
Haarhausen No.6.	SOLLING + UPPER HARDEGSEN	2.6×10^{-4}	$1.3 \times 10^{-}$
Haarhausen No.6	SOLLING + HARDEGSEN (WHOLE)	5.0×10^{-4}	$2.1 \times 10^{-}$

Borehole	Formation	T_p Value $m^2.s^{-1}$	T_t value $m^2.s^{-1}$
Altenstädt	HARDEGSEN	9.0 x10^{-5}	3.6 x10
Altenstädt	HARDEGSEN + DETFURTH + VOLPRIEHAUSEN	2.5 x10^{-4}	5.5 x10

The formations studied are laterally equivalent to those investigated by Hauthal in Thuringia, and fig.90 shows that they are to be correlated with the upper part of the 'Bunter' sandstone and the lower part of the 'Keuper' sandstone of the English Midlands. Conversion of the k values given by Hauthal to values for primary and total transmissivity allows the following table to be drawn up, comparing results from Hease and Thuringia (units in $m^2.s^{-1}$) :

Formation	HESSE (Durbaum et al (1969))	THURINGIA (Hauthal (1967))
Hardegsen, T_p	9.0 x 10^{-5} *	7.7 x 10^{-6}
Hardegsen, T_t	3.6 x 10^{-4} *	2.7 x 10^{-4}
Detfurth & Volpriehausen T_p	2.5 x 10^{-4} *	5.6 x 10^{-6}
Detfurth & Volpriehausen T_t	5.5 x 10^{-4} *	1.5 x 10^{-4}

* Based on Altenstädt Borehole.

The table shows that although values for Tp in Thuringia are well below those in Hesse, there is a measure of agreement in total transmissivity in the two areas.

Without first hand observation of the Bunter outcrops in Germany, it is difficult to draw firm conclusions on the degree of correlation between the English and German aquifers. The magnitude of the values listed above is similar to those reported here for some British formations. But, whereas the thicknesses of the German units are comparable with those in Britain, the values for primary transmissivity compare with the least permeable aquifers in the British Permo-Trias sequences. The generally very low permeability of the German units is well shown in the diagrams accompanying the paper by Durbaum et al. The results on the Solling sandstone from Elgershausen compare with the Bunter Sandstone of Northern Ireland. Those from Beberbeck are lower than anywhere in Britain, and those from Haarhausen are approximately the same in magnitude as those from the Permian of the Dumfries Basin (Area 9) and those from the Bunter Sandstone north of York (Area 6). When the Altenstädt results are considered, it is found that these are only comparable to the Bunter Sandstone of Area 7.

All the values from Thuringia are lower than anything so far recorded in Britain.

The difference in the properties of the aquifers in the three countries is so great that the values for total transmissivity of the German formations are exceeded by values for primary transmissivity calculated for some of the British units. These values naturally include a fracture permeability component and it is concluded that the German rocks must be insufficiently fractured for their transmissivity to reach moderate values.

8.4. CONCLUSIONS

It appears that the British Permo-Triassic sandstone aquifers are very much more permeable that their German counterparts. Although Durbaum et al (1969) were able to establish that permeability increased towards the margins of the Hesse Basin it seems clear that, in view of the wide departure of transmissivity values, cementation must be much more widespread in the German material. In this respect, the porosity data published by Meisl (1965) are instructive. He has studied the cementation of the Bunter Series in Hesse and in the Schlitz area,for example, the Solling Sandstone was found to have a porosity (presumably total interconnected) of only 2.3 to 6.0 per cent. The very small dimensions of the pore channels of the German sandstones were also demonstrated by Durbaum et al in the same 1969 paper referred to above in which they determined the pore size distribution of three plugs using American Ruska capillary pressure apparatus. The peak in the pore size frequency distribution curve occurred at 10 μ in a lower Hardegsen sandstone plug from Altenstädt, at 25 μ in a Solling Sandstone plug from Haarhausen, and at only 4 μ in an upper Hardegsen plug from Haarhausen. Regrettably, no comparabl studies have been undertaken in UK, although such a project is planned.

Firsthand examination of the German material is obviously the most effective way of discovering what is the principal factor causing the marked differences between the British and the German Permo-Triassic sandstone aquifers.

Finally in this discussion mention should be made of the data which is being accumulated on the reservoir properties and stratigraphy of the Permo-Trias in the North Sea Basin as a result of the continuing offshore exploration for hydrocarbons. The Author has access to information relating to the Bunter of the Hewett gasfield, but unfortunately, at the time of writing, the data remains confidential and cannot be included in this document. It is probable that the answers to some of the discrepancies in the properties of the Permo-Trias reservoir rocks between England and Germany will be found as a result of improved knowledge of facies change in the sequence in the southern North Sea.

CHAPTER NINE : Application of computers in core analysis

CHAPTER NINE : APPLICATION OF COMPUTERS IN CORE ANALYSIS

The obvious necessity in core analysis work to examine very large numbers of samples so that the studies have a high degree of statistical confidence requires that some stages employ automatic data processing systems. In the studies described in this report, a number of short, simple computer programs in Fortran IV language were developed to allow laboratory data to be automatically processed at the Atlas Computer Laboratory of Science Research Council. The Author is indebted to Dr Tim Gover and Mrs. Elizabeth Gill of ACL who assisted with the correction and satisfactory operation of the programs.

All the programs were basically similar. Laboratory data on batches of up to several hundred test plugs were entered on 80 - column preparation sheets at the time the experiments were carried out. The data on these sheets was transferred to punched cards for computer input and for subsequent data banking purposes in IGS. Copies of these purely computational programs accompany this chapter; brief notes on their range of operation are given below. Output was produced on a line printer so that statistical analysis could proceed immediately, but it is envisaged that some alternative form of storage of computed results might be adopted for data banking purposes.

9.1. PORE TEST PROGRAM

This facilitated the calculation of porosity (P), dry bulk density (RB), saturated bulk density (RS) and matrix density (RG) using three input data for each test plug, viz. W, S_1 and S_2 (see Eq(1). p.61). It was found that, in practice, experimental errors could be very rapidly spotted in sequences of results on computer output and it is considered that the use of some form of ADP in routine testing of large numbers of samples besides the saving in time, results in fewer experimental errors going unnoticed.

9.2. PERM TEST PROGRAM

Gas permeability results were computed using this program which solved Eq.5 for k in either cm. sec^{-1} or millidarcy units. The Klinkenberg correction was automatically applied in this program to all results having a value of less than 1000 md, using the simplified correction function Eq.(6). These corrected values were also expressed in both cm.sec^{-1} and millidarcy units. In the form given here, the program has a range of from 10^{-6} to $>$ 20 d, i.e. it can handle the full range of a gas permeameter.

9.3. DARCYTEST PROGRAM

Water permeability test data was calculated using another program which solved Eq.(11), with results again expressed in both cm.$sec.^{-1}$ and millidarcy units.

```
LINE                                 ATLAS -- FORTRAN                    09/03/71        VERSION 7
NUMBER                          SOURCE ROUTINE LISTING                   19.21.59    COUNTER=        9
                                                                                   LABEL FIELD
          I=0
          READ 102,N
      102 FORMAT(I4)
        1 READ 100,W,S1,S2,REF
      100 FORMAT(6X,F7.3,F14.3,F14.3,19X,A8)
          I=I+1
          VP=S1-W
          VB=S1-S2
          VG=W-S2
          P=100*(S1-W)/(S1-S2)
          RB=W/(S1-S2)
          RS=S1/(S1-S2)
          RG=W/(W-S2)
          PRINT 101,VP,VG,P,RB,RS,RG,REF
          IF(I-N)1,9,9
        9 CALL EXIT
      101 FORMAT(4H0VP=,F7.3,4H VG=,F7.3,3H P=,F10.2,4H RB=,F7.3,4H RS=,F7.3
         1,4H RG=,F7.3,10X,A8)
          END
```

PORETEST PROGRAM

ATLAS FORTRAN
SOURCE ROUTINE LISTING

04/03/71 VERSION 7
09.17.05 COUNTER= 9
LABEL FIELD

```
      I=0
      READ 102,N
  102 FORMAT(I4)
    1 READ 100,PQ,PA,D,Q,A,REF
  100 FORMAT(6X,F7.1,F11.2,F8.2,F9.3,F7.3,12X,A8)
      I=I+1
      GD=(36.4/(((PQ+PA)/PA)**2-1.0))*(D*Q/A)
      IF(GD-1000)7,7,8
    7 WD=EXPF(1.1*LOGF(GD)-0.32*2.30258)
      GO TO 80
    8 WD=GD
   80 WC=WD*0.9660E-6
      PRINT 101,GD,WD,WC,REF
      IF(I-N)1,9,9
    9 CALL EXIT
  101 FORMAT(4H0GD=,F10.2,4H WD=,F10.2,4H WC=,F12.6,10X,A8)
      END
```

PERMTEST PROGRAM

ATLAS FORTRAN SOURCE ROUTINE LISTING

07/10/69 11.26.13 VERSION 7 COUNTER= 12

LABEL FIELD

```
      I=0
      READ 103,N
  103 FORMAT(I4)
    7 READ 102,D,C,A,T,REF
  102 FORMAT(13X,F7.2,F8.2,F9.2,F9.1,14X,A8)
    1 READ 100,Q,H
  100 FORMAT(6X,F7.2,4X,F10.2)
      IF(Q)6,7,6
    6 I=I+1
      P=(Q*D*C)/(A*T*H)
      PD=P*1013376.5
      PRINT 101,P,PD,REF
      IF(I-N)1,9,9
    9 CALL EXIT
  101 FORMAT(3H0P=,F14.8,4H PD=,F12.2,10X,A8)
      END
```

DARCYTEST PROGRAM

LINE NUMBER — ATLAS FORTRAN SOURCE ROUTINE LISTING — 25/11/70 10,18,47 — VERSION 7 COUNTER= 19 LABEL FIELD

```
      I=0
      READ 102,N
  102 FORMAT(I4)
    1 READ 100,W,S1,S2,S3,REF
  100 FORMAT(6X,F7.3,F14.3,F14.3,F14.3,5X,A8)
      I=I+1
      VP=S1-W
      VB=S1-S2
      VG=W-S2
      P=100*(S1-W)/(S1-S2)
      RB=W/(S1-S2)
      RS=S1/(S1-S2)
      RG=W/(W-S2)
      S=P*(S1-S3)/(S1-W)
      PRINT 101,VP,VG,P,S,RB,RS,RG,REF
      IF(I-N)1,9,9
    9 CALL EXIT
  101 FORMAT(4HOVP=,F7.3,4H VG=,F7.3,3H P=,F10.2,3H S=,F10.2,4H RB=,
     *F7.2,4H RS=,F7.2,4H RG=,F7.2,10X,A8)
      END
```

VIELDTEST PROGRAM

```
LINE                         ATLAS  FORTRAN                  28/05/70        VERSION 7
NUMBER                  SOURCE ROUTINE LISTING               12.13.52     COUNTER=      10
                                                                       LABEL FIELD

        I=0
        READ 102,N
    102 FORMAT(I4)
      1 READ 100,R1,R2,R3,C,CF,REF
    100 FORMAT(6X,F8.3,F11.3,F13.3,F12.3,F7.3,4X,A8)
        I=I+1
        VG=(C-(0.996*(R3-R1)))*CF
        VB=32.406-(0.996*(R2-R1))
        VP=VB-VG
        P=100.*VP/VB
        PRINT 101,P,REF
        IF(I-N)1,9,9
      9 CALL EXIT
    101 FORMAT(15X,3H P=,F7.3,20X,A8)
        END
```

KOBETEST PROGRAM

9.4. YIELD TEST PROGRAM

Results for the combined porosity and centrifuge specific yield test are calculated using the Yield Test Program.

9.5. KOBE TEST PROGRAM

The Boyles Law Porosimeter formed part of the equipment allocated to the project but it was rejected as a suitable technique for porosity determination at an early stage. This was because of severe mercury contamination problems and poor accuracy when handling friable sandstone plugs (the bulk of the samples were friable). A computer program was however written to handle the laborious calculation: and it is given here for reference purposes.

9.6. CORRELATION PROGRAMS

The correlation of various important parameters determine during core analysis using computers is currently under study. It is considered that certain relationships such as porosity X permeability, porosity X centrifuge specific yield and centifug specific yield X permeability may be of value in such studies as, for example, the quantitative calibration of geophysical well-logs. Except to provide a basis for very general remarks about the physical properties of aquifers, it is not the Author's view that these relationships are of much practical value and that is why no attempt has been made to relate for example, porosity to permeability in the work reported here. So much attention has been drawn to the difficulty of relating parameters such as these that there seems little point in adding to the confusion.

9.7. AUTOMATED INSTRUMENTS FOR CORE ANALYSIS

The need to examine large numbers of samples is particularly onerous where one is attempting to apply core analysis in the ground water field. This is because the technique is chiefly of value in the study of sandstone aquifer behaviour, and these formations are commonly several hundreds of metres thick with the entire thickness very often acting as a discrete aquifer system. Quantitative evaluation of the permeability distribution in such a formation necessitates sampling at closely spaced intervals and therefore the number of samples to be handled from just one fully penetrating cored borehole is likely to run into certainly hundreds, maybe thousands.

It is, therefore, pertinent to consider for a moment how the basic instruments for measuring flow and storage might be automated. Setting aside all considerations of cost, the two accompanying designs have been prepared, the first for a logical gas permeameter instrument, and the second for a logical liquid resaturation porosimeter each of which is briefly explained below. It is emphasised that such designs are only two of a great number of possible instrument systems, and for convenience they are based on the test procedures adopted for the present study.

9.7.1. THE LOGICAL GAS PERMEAMETER(Fig.92)

Drill cores in short lengths are fed into the plug generator which produces right cylinders of average dimensions 28 mm diameter. This would be a numerically controlled machine tool. Owing to slight variations in hardness, the plugs would have slightly variable lengths and diameters and they are therefore calipered either manually or optically. Each plug is then placed in a pressure cell module and batches of several hundred modules are then placed in a remote handling transfer facility. The RHTF passes the plugs in their individual modules into the instrument interface where one at a time they are inserted into a gas stream. Measurement of gas discharge rate, temperature and pressure gradient is recorded digitally. The test data is logged in the computer terminal where it is operated on by a built-in program similar in form to the PERMTEST given above, and permeability data is produced on-line.

9.7.2. THE LOGICAL LIQUID RESATURATION POROSIMETER (Fig.93)

Right cylinders from the plug generator are placed in the porosimetry module which by means of the remote handling

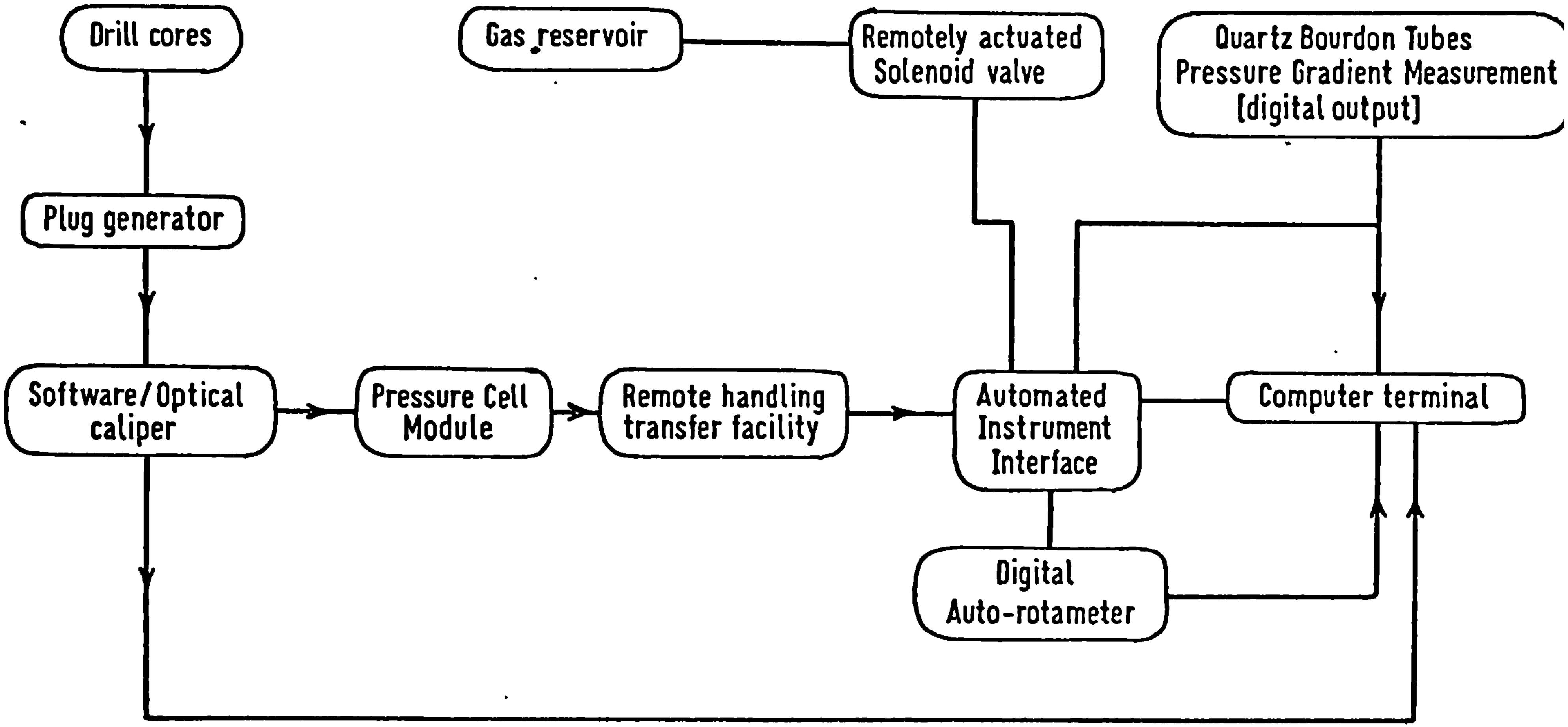


Fig.92 DESIGN FOR A LOGICAL GAS PERMEAMETER INSTRUMENT

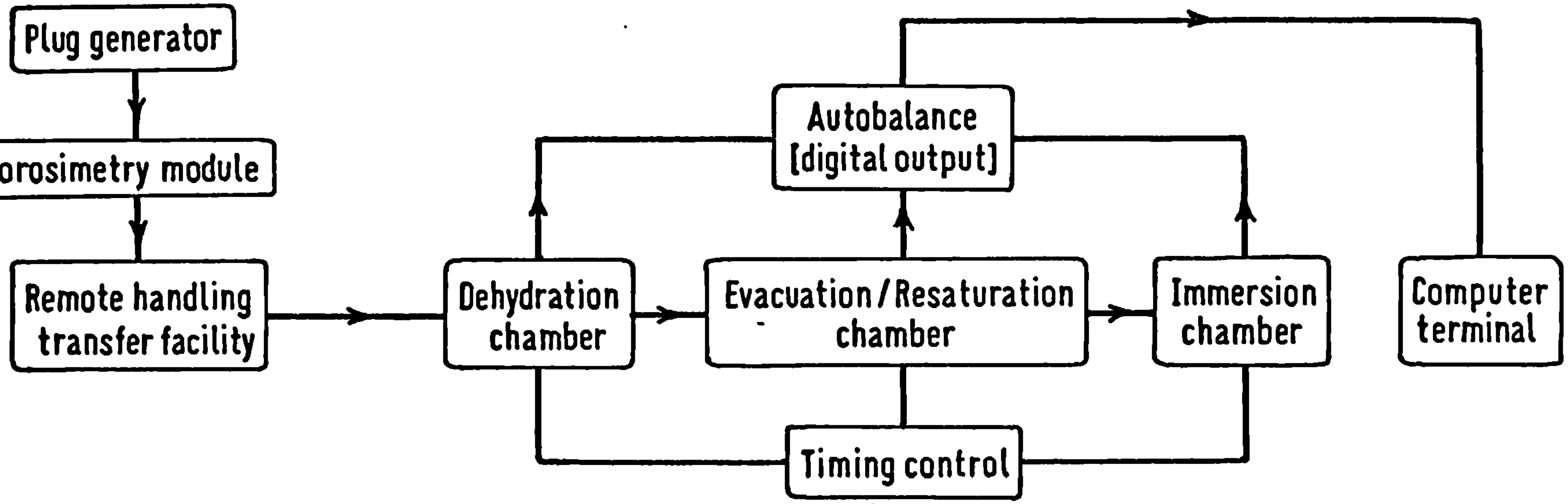


Fig.93 DESIGN FOR A LOGICAL LIQUID RESATURATION POROSIMETER

transfer facility is inserted into a dehydration chamber. After 16 hours at 95°C, the RHTF removes the plugs individually and dry weights are made on the autobalance. At the completion of the cycle, the batch is placed in the second chamber and liquid resaturation under vacuum takes place. Removal and weighing is then accomplished again automatically. Finally, the batch is transferred to the third chamber where immersed weights are obtained. Data from the autobalance are logged in the computer terminal and operated on to produce porosity and density data.

It is only using systems like these that the full value of a cored borehole will be realised. With current drilling costs for coring running at £15 per metre, it seems foolish not to take advantage of the rapidly developing technology of automatic instrumentation. The cost of such instruments is, however, likely to be high with commercial sales very limited. On the other hand, labour costs increase continually and laboratory work such as routine core analysis is essentially labour intensive and monotonous. There is, therefore, a good case for initiating a study of the problems and costs of automated core analysis systems. A thorough consideration of the economics of such systems could then be made, and these compared with the undoubted advantage of being able to quantify parameters such as permeability and saturation almost continously with depth in cored boreholes. The value of such data in building up a comprehensive picture of permeability distribution and in facilitating calibration of geophysical well logs needs no emphasis.

CHAPTER TEN : General conclusions

<u>CHAPTER TEN : GENERAL CONCLUSIONS</u>

The principal objectives of the study were:

i) to investigate to what extent existing methods of core analysis, as used in the petroleum industry, could be applied in the study of sandstone aquifer behaviour.

ii) to develop new core analysis techniques, particularly relevant to hydrogeological research.

iii) to apply any useful data which might be generated by the project to the evaluation of the role of microscopic or intergranular flow in ground water movement through sandstone aquifers, particularly the Permo-Triassic formations in the U.K.

The general conclusion of the study may be summarised as follows :-

1. Orthodox core analysis methods are of value in quantifying certain physical properties of aquifers which are important in studies of ground water movement. The use of these methods naturally depends on the availability of cores of the formation from specially drilled boreholes, but once material is available, the methods are rapid and of an adequate accuracy to allow a firm evaluation of such factors

as intergranular permeability variation and total storage to be made.

2. The drilling of cored boreholes may increase the cost of a hydrogeological exploration programme. However, it is common to drill at least one or two cored boreholes in most projects for stratigraphic control purposes, and in many cases the core material is not used once the geological description has been made and interpreted. Studies of the type described here provide at reasonable cost a great deal more information which would not otherwise be obtained. Moreover the high cost of cored boreholes is better justified if core analysis is carried out.

3. The methods are of less significance in the study of fissured formations. Parallel studies of limestone properties, made by the Author during the course of the project, demonstrate that intergranular movement is negligible in formations such as the Inferior Oolite Limestone, the Chalk, and Coal Measures sandstones. The studies have, however, provided quantitative data on the likely magnitude in these formations of permeability, porosity, density and other physical properties. In particular, the chalk has been found to have extremely low permeability, and moderate to very high porosity. Although these studies have produced essentially negative results, they are nonetheless significant in obtaining a full understanding of the physical structure of these aquifers. Further studies are therefore planned of

such aquifers in order that these properties are measured.

4. The use of core analysis techniques in hydrogeology has some limitations. The first of these is obvious, viz. the methods as they stand, are only applicable to bedrock aquifers which can be cored without too much difficulty. Totally different methods have to be applied to measure the same parameters in unconsolidated sediments. Secondly, bed rock aquifers are commonly several hundred metres thick. In contrast, pay intervals in petroleum reservoirs are often relatively thin and therefore the precise physical property variation within that interval can be investigated in great detail. In theory, the whole thickness of saturated aquifer should be investigated with a comparable degree of thoroughness but clearly this results in the handling of literally thousands of samples. Although the methods are quite rapid, there are limits to the quantities of samples which can be examined both in terms of time and cost. Either sampling intervals have to be extended resulting in overall loss in precision, or much more emphasis will have to be given to the development of automated instruments and computers for aquifer core analysis.

5. In the present study, resort has had to be made to the use of probability in predicting the likely magnitude of important petrophysical parameters. This has been employed

as a first approximation. Future studies it is hoped will be based on larger numbers of samples from smaller stratigraphic intervals so that more emphasis is laid on lithological variation rather than the gross statistical variation.

6. With regard to experimental techniques, it is concluded that the gas permeameter is an efficient instrument with which to measure sandstone permeability over the range 10^{-3} to 10000 md. The liquid resaturation porosimetry system although generally efficient is subject to rather large error at less than 12% porosity; in this region, the Boyle's Law (Kobe) instrument is almost certainly more accurate.

7. A satisfactory laboratory method of simulating gravity drainage in saturated aquifers has been developed. Further research is however urgently required in order to establish by independent means that the mean pore water pressure developed approximates to $\frac{1}{3}$ atmosphere. This would be most easily carried out by the pressure plate method in the laboratory, and by measurement in the field of the saturation of core samples obtained by drilling in the zone of fluctuatio

The field work would require provision of a small mobile core analysis laboratory.

8. The results of the study of air and water permeability correlation indicate that there is a major problem in resaturating many types of porous sandstone with water, using the present evacuation system. The problem might be alleviated if smaller core samples were used. Until such problems are overcome the question of non-Darcy behaviour in the sandstone cannot be fully resolved. It is the writer's opinion, however, that there is no evidence to suggest that any fundamental difference exists between the permeability of the sandstones to air and to water, assuming of course that experimental data are expressed in units of intrinsic permeability. Problems are however likely to arise in cases of sandstone cores cut in muds of the bentonite type. Where coring of aquifers for subsequent analysis is being contemplated, it is essential to pay the same close attention to drilling techniques as that paid by the petroleum industry.

9. Turning now to the detailed conclusions concerning the behaviour of the British Permo-Triassic sandstone aquifers, these may be summarised as follows :-

a) Regional variation in porosity, density and inter-granular permeability in the formation has been documented and quantified in a comprehensive survey for the first time. There are significant differences in these properties in different regions, and in some areas the sandstones are likely to behave as fissured aquifers owing to a negligible intergranular permeability.

b) In the lithological control of physical properties, particle size and cementation are of paramount importance. Laminated bedding in much of the material gives rise to widespread marked permeability anisotropy, which is most prevalent in parts of the Lower and Upper Mottled Sandstone.

c) Porosity and density show regional variation at least as important as the permeability variation.

d) A new parameter, 'primary transmissivity', signified by T_p has been defined in order to describe the relative importance of intergranular and fissure flow in bedrock aquifers. This is distinguished from T_t or total transmissivity normally obtained from the analysis of pump tests. T_p is calculated by multiplying the inter-granular formation permeability value having a probability of 0.50 by either a generalised figure for saturated aquifer thickness, or, in the case of direct correlation with T_t derived from a pumping test, by the actual saturated thickness at the site. T_p is compared with T_t in the form of a ratio. Three cases are clearly possible: i) $T_p = T_t$ ii) $T_p < T_t$ and iii) $T_p = 0$. In the first, fissure flow is zero, all flow taking place at the intergranular level; in the second, part of the flow takes place via intergranular movement and part via discontinuities; in the third, intergranular movement is negligible. At the commencement of the study it is fair to say that case 1 was thought to apply to the Permo-Trias aquifers. However, preliminary results from six widely scattered localities show that case 2 is by far the most likely situation, except perhaps on the outcrop of the Bunter beds in Nottinghamshire, and perhaps at shallow sites elsewhere (as stated by Crook and Howell, 1970). T_p/T_t values have been found to have a considerable range, which is probably logarithmic.

e) Values for T_p are presented for most of the subdivisions studied and it is hoped that more and more correlations between T_p and T_t will be obtained in the near future by conjunctive use of cored boreholes and scientifically controlled pumping tests. The end result would be maps indicating the relative importance of fissure flow in aquifers by means of contoured values of the T_p/T_t index. Clearly, we are a long way from this stage at the present time.

f) The T_p/T_t index is of value in selecting the most effective exploration program for ground water development in a bedrock aquifer. In formations which trial boreholes have demonstrated to have a high T_p, development wells may be drilled at sites chosed on economic and geographic grounds alone. In formations with a low T_p, the same wells would have to be sited where economic, geographic and geologic factors converge owing to the necessity of drilling in well fractured areas. In vie of the present state of development in England, this analysis may be of greatest value in exploring relatively unknown regions abroad.

g) The British Permo-Triassic sandstones are far more permeable than comparable formations in Germany. On the basis of comparing published data, values of T_p for most of the British formations greatly exceed values of T_t on the German Triassic beds, thereby demonstrating that considerable differences of either facies or diagnesis or both must exist.

10. On the whole, the existing stratigraphic classification of the sand stones has been found to be satisfactory during the course of the study. Although it probably has very little validity as far as real time is concerned, it is a good framework within which to operate. There are some obvious misnomers such as Bunter Pebble Beds in Area 5, but in general, it was noted that the various generally accepted sub-divisions were characterised by distinct differences in lithology. An interesting point which emerged from the 1967 debate on the status of the British Trias organised by the Geological Society of London was that, on current knowledge, practically all the economically important Triassic aquifers were laid down during the time span of a single stage, the Scythian.

11. The following recommendations for future research are made :

a) In the field of instrumentation, there is a need for research into the feasibility of automating the basic permeameter and porosimeter systems. It is anticipated that the permeameter instrument could be relatively easily automated.

b) Further investigation is required of the air-water correlation problem referred to above. Owing to the difficult nature of the work and the need for equipment of the highest possible quality, this research should only be undertaken in an environment suitable for measurement of standards.

c) The study of flow of water through bedrock aquifer material at partial saturation would also be worth investigating as a logical development of the work already completed. Techniques for this work could easily be 'borrowed' from the petroleum industry which has wide experimental experience of multiphase fluid flow of porous media, referred to in that literature as "relative permeability".

d) To complete the picture of permeability variation in the British Permo-Trias, cored boreholes are required in areas whereas undue emphasis has had to be given to outcrop material. Important locations are :

i. To the base of the Penrith Sandstone / Brockram formation in the Carlisle district (Area 8) to enable a full evaluation of the Kirklinton, St Bees and Penrith Sandstones to be made.

ii. To the base of the sand facies of the Dumfries sandstone series to the north of Dumfries (Area 9) to evaluate the sandstone at depth and to establish the relationship of the breccias to the sandstone.

iii. To the base of the Bunter Sandstone in the Vale of York in the Thirsk-Northallerton area of the Vale of York (Area 6).

iv. To the base of the Bunter Sandstones in the Hartlepoo - Stockton area (Area 6) of Teesside.

v. In the Devonshire Permo-Trias, where the majority of wells have been drilled using reverse circulation methods and cores have not been available for the present study.

vi. In the various separated Permian basins in the south of Scotland, particularly those of Lochmaben, Thornhi and Mauchline.

12. Finally, it is emphasised that the present study has been primarily a laboratory study ofaquifer properties. Much furthe work will be required to evaluate the relationship between intergranular and fissure flow in sandstone aquifers. In these

studies, it is hoped that use will be made of the new parameter, T_p and the ratio T_p/T_t as described above.

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