FIELD AND LABORATORY INVESTIGATIONS IN THE TRIASSIC SANDSTONE AQUIFER IN THE VALE OF MOWBRAY - ENGLAND

BY

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Abstract.— The results of this preliminary investigation indicate that the Triassic sandstone of the Vale of Mowbray is a good aquifer, worthy further study and development.

The attractive qualities of the sandstone are its friability, granular size, good sorting and the commonly occuring fissures and joints.

Determination of grain size by mechanical analysis and microscopic methods are in close agreement, the aquifer being predominantly fine sand, very uniform with grain size decreasing with depth and to the North. Uniformity and close packing of grains increase with depth, the grains to the south being more angular with a non mosaic type angularity. Petrographic examination of thin sections reveals that the cement between the grains, mainly quartz, decreases to the North and the iron oxides increase with depth.

Porosity measurements give a range between 9 to 25 °/$_0$.

Permeability of unfissured samples measured by a Constant Head Permeameter and a Gas Pressurized one in two directions (parallel and at right angles to bedding) give a range from 0.12×10^{-2} to 0.46×10^{-6} cm/sec. The higher values are parallel to bedding and the low ones at right augles to it, associated with fine partings of marl within the sandstone.

The anisotropy of permeability ranges from 1.1 to 9.37 with most values less than 3.5.

Field evaluation of permeability through pumping tests gives a range from 0.10×10^{-2} to 0.8×10^{-3}, implying a significant contribution from fissures and joints. The coefficient of storage ranges from 0.00054 to 0.00071, indicating confined conditions.

The higher values of permeability are found in the South.

Σύνοψις.— Τὰ ἀποτελέσματα ἐκ τῆς προκαταρκτικῆς ταύτης ἐρεύνης δεικνύουν ὅτι οἱ Τριαδικοὶ ψαμμῖται τῆς κοιλάδος τοῦ Mowbray εἶναι ἕνας καλὸς ὑδροφορεύς, διὰ τὸν ὁποῖον ἀξίζει μία περαιτέρω μελέτη καὶ ἀξιολόγησις.

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Αἱ εὐνοϊκαὶ ἰδιότητες τοῦ ψαμμίτου ἀπὸ ἀπόψεως ὑδροφορίας εἶναι ἡ εὐθρυπτότης, τὸ μεγάλο μέγεθος τῶν κόκκων, ἡ καλὴ διαβάθμισις καὶ αἱ συχνὰ ἀπαντώμεναι ρωγμαὶ καὶ κατατμήσεις.

Ὁ καθορισμὸς τῆς κοκκομετρίας διὰ κοκκομετρικῶν ἀναλύσεων καὶ μικροσκοπικῶν μεθόδων ἔδωσε τὰ αὐτὰ σχεδὸν ἀποτελέσματα. Ὁ ὑδροφορεὺς χαρακτηρίζεται κυρίως ὡς λεπτόκοκκος ἄμμος, πολὺ ὁμοιόμορφος μὲ μέγεθος κόκκων ἐλαττούμενον μετὰ τοῦ βάθους καὶ πρὸς Βορρᾶν τῆς περιοχῆς.

Ἡ ὁμοιομορφία καὶ ἡ συνεκτικότης τῶν κόκκων αὐξάνεται μετὰ τοῦ βάθους. Οἱ κόκκοι εἰς τὸ Νότιον τῆς περιοχῆς εἶναι περισσότερον γωνιώδεις καὶ ὄχι μωσαϊκοῦ τύπου.

Πετρογραφικὴ ἐξέτασις λεπτῶν τομῶν ἀποκαλύπτει ὅτι τὸ συγκολλητικὸν ὑλικὸν μεταξὺ τῶν κόκκων εἶναι κυρίως χαλαζίας, ὅστις ἐλαττοῦται πρὸς τὸ βόρειον τμῆμα τῆς περιοχῆς καὶ τὰ ὀξείδια τοῦ σιδήρου αὐξάνουν μετὰ τοῦ βάθους.

Τὸ πορῶδες κυμαίνεται μεταξὺ 9 καὶ 25 %.

Ἡ διαπερατότης ἄνευ ρωγμῶν δειγμάτων, μετρηθεῖσα δι' ἑνὸς περατομέτρου σταθεροῦ φορτίου ὡς καὶ δι' ἑτέρου, λειτουργοῦντος μὲ βάσιν τὴν δίοδον ὕδατος διὰ χρησιμοποιήσεως ἀέρος ὑπὸ πίεσιν, εἰς δύο κατευθύνσεις (παραλλήλως καὶ καθέτως πρὸς τὴν διάταξιν τῶν στρωμάτων) κυμαίνεται ἀπὸ 0.12×10^{-2} ἕως 0.46×10^{-6} cm/sec. Αἱ ὑψηλότεραι τιμαὶ παρατηροῦνται παραλλήλως πρὸς τὴν διάταξιν τῶν στρωμάτων, αἱ δὲ χαμηλότεραι καθέτως πρὸς αὐτήν, συνδυαζόμεναι πάντοτε μὲ τὰ λεπτὰ στρώματα μάργας ἐντὸς τοῦ ψαμμίτου.

Ἡ ἀνισοτροπία τῆς διαπερατότητος κυμαίνεται ἀπὸ 1.1 μέχρι 9.37 μὲ τὰς περισσοτέρας τιμὰς κάτωθεν τοῦ 3.5.

Ἡ εἰς τὴν ὕπαιθρον ἀξιολόγησις τῆς διαπερατότητος διὰ ἀντλήσεων ἔδωσε τιμὴν κυμαινομένην ἀπὸ $0\ 10 \times 10^{-2}$ μέχρι 0.8×10^{-3}, συνεπαγομένη ἀξιόλογον συμβολὴν ρωγμῶν καὶ κατατμήσεων. Ὁ συντελεστὴς ἐναποθηκεύσεως κυμαίνεται ἀπὸ 0.00054 μέχρι 0.00071 δεικνύων ἀρτεσιανὰς συνθήκας.

Αἱ ὑψηλότεραι τιμαὶ διαπερατότητος εὑρίσκονται εἰς τὸ Νότιον τμῆμα τῆς ἐξετασθείσης περιοχῆς.

1. INTRODUCTION

The usual objectives of exploratory groundwater investigations are to locate and evaluate new sources of grounwater or to increase withrawals from known sources. Such studies require the location and delineation of aquifers, the determination of structural characteristics and lithologies, and the determination of the quality and quantity of water that may be yielded by wells penetrating them. (MEINZER 1932).

The present work gives the results of an investigation concerning some of the hydrogeological aspects of the Triassic sandstone in the Vale of Mowbray, in the North Riding of Yorkshire - England.

The aquifer consists, mainly, of soft red porous sandstones, Triassic in age and up to 1.000 feet in thickness. It is an important formation in engineering geology as a source, firstly of ground water and secontly of material encountered frequently in engineering projects.

Investigations have been made in these sandstones, mainly during the last few years, with the co-operation of the Yorkshire Ouse and Hull River Authority, under which this report is also undertaken.

The need to know the characteristics, and behaviour of the aquifer and its potential as a water source, is important for assessing the future development of the region.

Attention is devoted to the evaluation of the permeation properties of the aquifer in both the field and the lavoratory.

It is concluded that much further work is necessary for a comprehensive knowledge of the aquifer.

2. TOPOGRAPHY - DRAINAGE

The Vale of Mowbray running NNW-SSE is a low lying region, gently undulating with the high ground rising in some places up to 200 feet. The width of this Vale, which is the extension of the Vale of York northward, ranges between 6 and 10 miles.

The higher ground flanks the Vale to the east and west with rising, in some places, of over 1.000 feet. Generally the sharper relief reflects the occurence of Permian and Jurassic rocks to the west and east respectively, whereas the other low lying area owes its relief to the Triassic rocks masked with superficial deposits.

The area is drained by the rivers Swale and Ure and their tributaries (see Fig. 1). The water supplied to these rivers comes mostly from sources outside the Vale. The falls of the rivers crossing the area are very low.

The rainfall in the Vale is quite low with 25″ at Scruton and 27″ at Thirsk. At York, to the south, the long term average rainfall is 25″. On the other hand the rainfall, to the west of the Vale under examination, is much higher reaching 60″ in the upper part of Swaledale. This reflects the higher precipitations over higher ground.

The rivers are subjected to rapid changes in level and during the dry period water is supplied to these, as baseflow, from the aquifers they cross.

3. GEOLOGY

3.1. Indroduction.

The hydrogeological unit under consideration consists of Triassic sandstone and is bounded to the west by Carboniferous and Rermian rocks, and Jurassic rocks to the east. The sandstones have, approximately, NW-SE strike and dip to the NE.

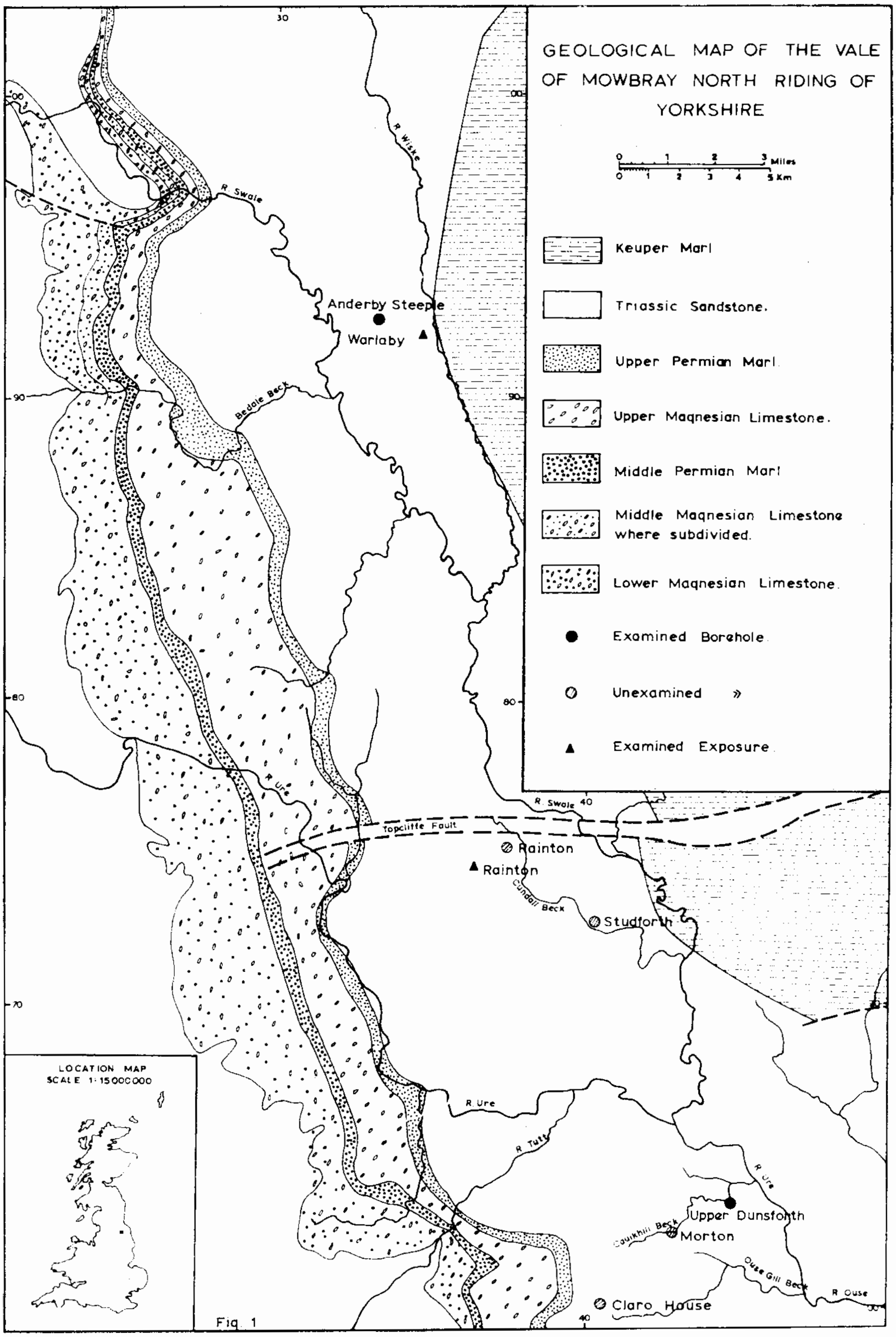

GEOLOGICAL MAP OF THE VALE OF MOWBRAY NORTH RIDING OF YORKSHIRE
0 1 2 3 Miles
0 1 2 3 4 5 Km
Keuper Marl
Triassic Sandstone.
Upper Permian Marl
Upper Magnesian Limestone.
Middle Permian Marl
Middle Magnesian Limestone where subdivided.
Lower Magnesian Limestone.
Examined Borehole
Unexamined »
Examined Exposure
LOCATION MAP
SCALE 1:15000000
30
00
90
80
70
40
R. Swale
R. Wiske
Anderby Steeple
Warlaby
Bedale Beck
R. Ure
Topcliffe Fault
Rainton
Rainton
Cundall Beck
Studforth
R. Tutt
R. Ure
Upper Dunsforth
Coukhill Beck
Morton
Ouse Gill Beck
R. Ouse
Claro House

Fig. 1

In most of the area, the solid rocks are covered by glacial deposits and recent alluvial ones. The Permian rocks follow the Triassic rocks in the structure, dipping gently to the east, but the undrlying Carboniferous ones are mostly faulted and folded.

The structure of the Triassic rocks, because of the superficial cover, was not determinable and the only information available is from boreholes, of which there are only a few in this area. There is no evidence of any folding in the Trias dipping gently to the north - east, over large areas.

The faults encountered in this area are of both N - S and E - W strike.

A stratigrahhic column of the area exhibits the following features. (see fig. 1).

Superficial cover	Post Glacial and recent deposits.	Sands and Gravels Alluvium and river terraces, Warp and Lacustrine clays.
	Glacial deposits	Sand, Gravel, Boulder clay
Jurassic	Oölites	Upper Oölite Middle Oölite Lower Oölite
	Lias	Upper Lias Middle Lias Lower Lias
Triassic	Rhaetic beds	
	Keuper marl	600′
	Sandstones	800′
Permian	Upper marl	50 - 300′
	Upper Magnesian Limestone	30 - 120′
	Middle marl	30 - 150′
	Lower Magnesian Limestone	300 - 800′
	Lower marl and Sands	
Carboniferous	Limestones, Shales and Sandstones	

3. 2. Triassic of the area.

Bunter sandstones, Keuper sandstones and marls, and the Rhaetic shales comprise the Triassic rocks of the area.

The two types of sandstones are separated by a thin Pebble bed. In South Yerkshire the Keuper sandstone is harder and more coarse than the Bunter, but going northwards, the Pebble bed is decreased and no clear contact between these two sandstones can be observed. Accordingly, the sandstones are no differentiated but examined, generally, as Triassic ones.

The Triassic sandstones in the area are thin - bedded, thicker and more massive locally and usually of brick-red colour. They contain marly bands in some places. Boreholes indicate that the approximate thickness of these sandstones is up to 800 feet increasing downdip to 1.000 feet at the coast.

The Keuper marl consists of red and green shales and marls containing several bands of gypsum and some sandstone beds of different horizons. These marls are mostly of a uniform thickness of about 500 feet.

The Rhaetic rocks consist mainly of dark laminated or paperly shales with thin limestone. Generally, their exact relation to the Trias above and to the New Marls below is not clear.

4. HYDROGEOLOGY

4.1. Hytrogeological units.

The Permian limestones, resting between marls, are well bedded and jointed rocks, generally very permeable, providing excellent aquifers. The upper Permian marl, separating the Permian and Triassic rocks, is not actually an effective aquiclude. It is a thin layer with the lithological appearance of fine-grained sandstone so that a flow of water from the Permian limestones to the Triassic sandstones is possible.

The Triassic sandstone is a highly permeable formation, providing one of the best aquifers in Britain.

As will be shown in later sections, high porosities and permeabilities have been recorded in this aquifer.

The only limitation of this aquifer is the presence of the marl bands in the stratigraphic column. It has been found that these layers affect the permeability and consequently the yield from boreholes. It has not been shown whether these marls extend throughout the aquifer dividing it into separate horizons. It is believed that these are thin, discontinuous layers.

In parts the top of the aquifer, below the drift, has been subjected to pre-glacial weathering providing sand.

The covering of the sandstones by the Keuper marl is because of its thickness and lithological nature; an aquiclude and so no flow of water, to or from the Triassic aquifer occurs.

The Rhaetic beds also form an aquiclude.

Some parts of the Jurassic, mainly the sandstones and limestones, are good aquifers but these are separated from the Triassic sandstones by the Keuper marl and the Jurassic shales, the latter being of considerable thickness. Even if the boundaries were not impermeable the eastwards dipping of the Jurassic formations would prevent recharge of the Trias from these rocks.

The superficial deposits, which cover almost the whole area, have many hydrogeological differences. The Boulder clay acts as an impermeable layer preventing infiltration into the sandstones, thus making the aquifer a confined one.

The sands and gravel extend over a large area but their thickness is less than the Boulder clay. Their contribution, either to the infiltration of water into the main aquifer or to their making of a separate aquifer, depends on their grading, sorting, cementation, thickness and the presence of any impermeable material between these and the sandstones.

The alluvium, peat, and river terraces can be permeable, but because of their thickness and location in relation to other formations, their contribution is not usually significant.

5. NOMENCLATURE OF THE SAMPLES TESTED

Many samples were tested in the laboratory in order to measure permeation properties of the Triassic sandstones, among these porosity, permeability and mechanical analysis.

It was thought desirable to number the samples. A sample is specified by a field number, a laboratory number and a letter designating the position according to the stratification of the beds. Samples at right angles to the beds are labelled «S» (Short bedded) and parallel to the beds «L» (long bedded), e.g.

1/27190 L, where 1 is the field number,
27190 the laboralory (departmental) number and L
the position designation.

For mechanical analyses purposes, only locations and depths are given, since the samples are large, hence both «L» and «S» samples are included. Similarly porosity was found to be independent in whether the samble was «L» or «S» and so only depths and locations were specified.

Generally, the samples tested were from two boreholes, Upper Dunsforth and Ainderby Steeple, and two exposures, Rainton and Warlaby.

The locations of the boreholes examined and the two exposures can be seen in the Geological map, Fig. 1.

6. PARTICLE SIZE DISTRIBUTION

6.1. Introduction.

The particle-size distribution is very important but very difficult because it depends on many factors.

In an idealized material composed of spherical grains it would be easy to separate the grains into different sizes.

In actual materials the problem is very complicated.

In the sandstones under investigation the properties of interest are porosity, bulk density, texture etc., where the influencing factors are only the grains and not the crystallite size.

One of the major problems arising in working on sandstones, which are consolidated materials, is the separation of the various grains. Efforts were made in this direction to obtain representative grains of the formation.

6.2. Experimental work.

Eleven (11) of the samples, taken from the boreholes, were examined in the laboratory in order to determine the patricle - size distribution.

The shortage in time did not permit a complete examination, so these results give only an idea of the particle distribution in the sandstones under examination.

During the experimental work the following stages were followed.

6.2.1. Preparation of the samples.

It was realized that the break down of the samples would be one of the major problems. This problem was overcome, as far as possible, by testing only friable samples of the material. The break down was not made by crushing machine but pieces of sandstones pummeled with greaf care and sometimes even divided by hand. Because the samples were not well cemented the process was reasonably easy.

During the crushing of each sample the powder was examined under the microscope in order to see whether grains were broken or whether they were still in agglomerate. The results of this work were quite satisfactory and the powder was more of less representative of the actual grain distribution.

In order to compare the above dry process with granulation in a wet state, material from the sample Upper Dunsforth/21.80 M was broken down after it had been soaked for a few minutes and also after saturation of about 10 hours. The results obtained indicated reasonable similarity. Nevertheless it is believed that the latter process is more satisfactory.

It must be mentioned here that original samples were necessarily subjected to a degree of disturbance, first during the collection by the drilling fluid and later in transportation from the field to the laboratory.

The method employed for the mechanical analysis was dry sieve analysis.

6. 2. 2. Samble size.

The weight of the material which must be used for size analysis depends on the maximum particle size.

Generally, the appropriate weights are as follows:

Maximum sieve range of material	Particle size in microns	Weight of samples in grams
5 — 8	4,000 — 2,000	1,000
8 — 16	2,000 — 1,000	500
16 — 30	1.000 — 500	250
30 — 60	500 — 250	100
60 — 300	250 — 0	50

The weight of the samples tested was 100 grams.

6. 2. 3. Selection of sieves.

In order to obtain detailed distribution curve sieves must be selected covering the entire particle range.

If the material has a wide spectrum of size then every other or every fourth sieve was used. Conversely, if the material has only a small size range then as many sieves as possible are chosen to cover the range.

Generaly, the sieves must be selected in such a way that not more than 30% of the material is retained in any sieve.

The following sieves were used in the experiments.

14, 18, 25, 36, 52, 72, 100, 150, 200, 300 B. S.

The apertures of these sieves, in microns, are respectively:

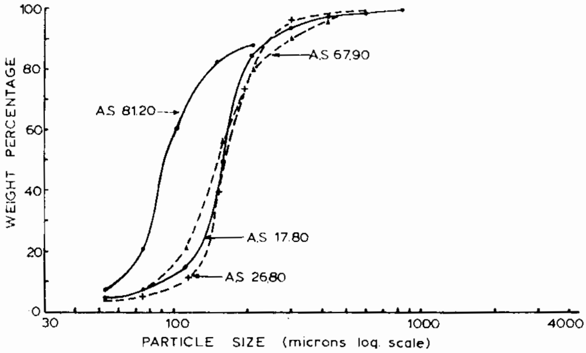
1200, 850, 600, 422, 295, 211, 150, 105, 75, 53

6. 2. 4. Method of sieving.

The sample is weighed and put in the largest size sieve.

The sieves are arranged in a nest, with aperture size decreasing from top to bottom. A fan is placed under the last sieve and a lid fitted. The nest is fastened in the vibrating machine. The timing mechanism is adjusted and finally the apparatus is switched on.

After about 10 minutes the nest is removed. Three sieves of different sizes are selected and the retained material was worked by hand. If after hand shaking for two minutes, less than 0.2% of the retained material passes the sieve then the process is sufficiently complete. If this is not the case the nest is replaced in the machine and vibration is continued for another 10 minutes.



B.S. MESH	APERTURE (microns)	A.S 17.80		A.S 26.80		A.S 67.90		A.S 81.20	
		PERCENTAGES		PERCENTAGES		PERSENTAGES		PERSENTAGES	
		FRACTIONAL	CUMULAT	FRACTIONAL	CUMULAT	FRACTIONAL	CUMULAT.	FRACTIONAL	CUMULAT.
14	1200	–	–	–	–	–	–	–	–
18	850	0.4	99.6	0.3	99.7	0.3	99.7	–	–
25	600	1.2	98.4	0.3	99.4	1.1	98.6	1.5	98.5
36	422	0.8	97.6	0.6	98.8	2.4	96.2	2.0	96.5
52	295	3.9	93.9	3.4	95.4	6.5	89.7	3.8	92.7
72	211	9.1	84.6	18.6	76.8	10.1	79.6	4.8	87.9
100	150	35.3	49.3	46.9(47)	29.8	24.2	55.4	5.7	82.2
150	105	35.2	14.1	19.2	10.6	35.0(35.2)	20.2	21.8(21.9)	60.3
200	75	6.7	7.4	4.7	5.9	12.5	7.7	39.3(39.4	20.9
300	53	2.9	4.5	2.2	3.7	3.3	4.4	13.7	7.2
Passing 300		4.5		3.7		4.4		7.2	
		100.0		99.9		99.8		99.8	
		A.S: Ainderby Steeple							

Fig. 2.

After vibration, the material from each sieve is weighed as well as the material in the receiver. The total weight obtained from these measurements must be within one percent of the original weight.

6.2.5. Presentation of results.

Tables were made showing the percentages of material retained in each sieve. After that, cumulative percentages were calculated and graphs were plotted. (an examble is given in Fig 2).

Residual weights are distributed to the largest fractional percentages.

All the statistical measurememts obtained from the graphs are presented in Table 1, page 404.

6.2.6. Accuracy of results.

The precission of the method depends on the following factors:

a. The nature and grading of the material.
b. Slight differences in procedure between operators.
c. The method of sieving applied (machine or hand).
d. Deviations of sieve apertures from nominal size.

A sieve analysis on dried powder can give quite erroneous results for some materials. For example, clay grains may adhere to each other, and there may be no comparison between dry and wet analyses. A comparison of the results obtained by the two methods on the same material is always advisable. Generally, the choice of method depends upon the state of the sample, the characteristics of the powder and the use of the material.

6.3. Conclusions.

The graphs and statistical measures obtained, exhibit the following features.

Median diameters range from 0.093 to 0.182 mm with smalle values occuring at the greater dephts.

Sorting coefficients range grom 1.17 to 1.43. Values of less than 2.5 indicate a well-sorted sediment, 3 a normally sorted sediment and 4.5 a poorly sorted sediment.

Uniformity coefficients range from 1.61 to 2.80. In general the smaller values occur et greater depths.

Effective sizes range from 0.060 to 0.110 mm, the degree of fineness increasing with depth.

Comparison of samples from the two boreholes indicate that the sandstone in the Ainderby Steeple area is finer and more uniform.

The Triassic sandstones examined are predominately fine sand and highly uniform. This, of course, is not representative of the formation as a whole, because there are lithologic breaks, consisting of clay bands, as it will be discussed below.

The relationship between particle size distribution and other parameters are given in other chapters (see chapters 8 and 9).

The results obtained by the sieving method for the determination of particle size distribution, are compared with thosse obtained by microscopic methods in the next chapter.

7. PETROGRAPHY OF THE SANDSTONES

7.1. Experimental work.

Twenty four thin sections of the sandstone were examined under the microscope to determine the composition, cement, the grains and the grain size distribution, and thus to make a comparison with the results of the mechanical analysis (sieve analysis).

The thin sections were prepared from cylindrical samples, drilled for permeability and porosity tests. Two types of thin sections were prepared from each sample, one parallel and one at right angles to the bedding.

Because of the softness of many of the sandstone samples it was quite difficult to obtain perfect thin sections, some grains being removed in the process. Accordingly, some of the holes are not representative of the material but result from this limitation of preparation.

Although most of the pores are interconnected, there are also sealed (disconnected) pores giving rise to a difference between true and apparent porosity.

After examination of the thin sections a frequency chart was obtained by plotting grain size versus number of grain. In thin sections, where no diagram is given, the mode of the grain size distribution is quoted.

Photomicrographs of some thin sections are given to illustrate textural differences (see Fig. 3 and 4).

The mineralogical composition of the examined thin sections was more or less the same, differing only in the proportion of each mineral and in the grain size and shape.

This composition was as follows :

Quartz : Abundant angular grains widely dispersed throughout the section.

Feldspars : Mainly plagioclase in a similar proportion to the quartz.

Calcite-Ankerite : A few scattered grains.

Phyllosilicates : A few flakes of muscovite and hydrobiotite.

These grains were cemented with abundant quartzite material, usually amorphous, probably derived from chalcedony-opal. This material occured not only in between the grains but also in the form of nests.

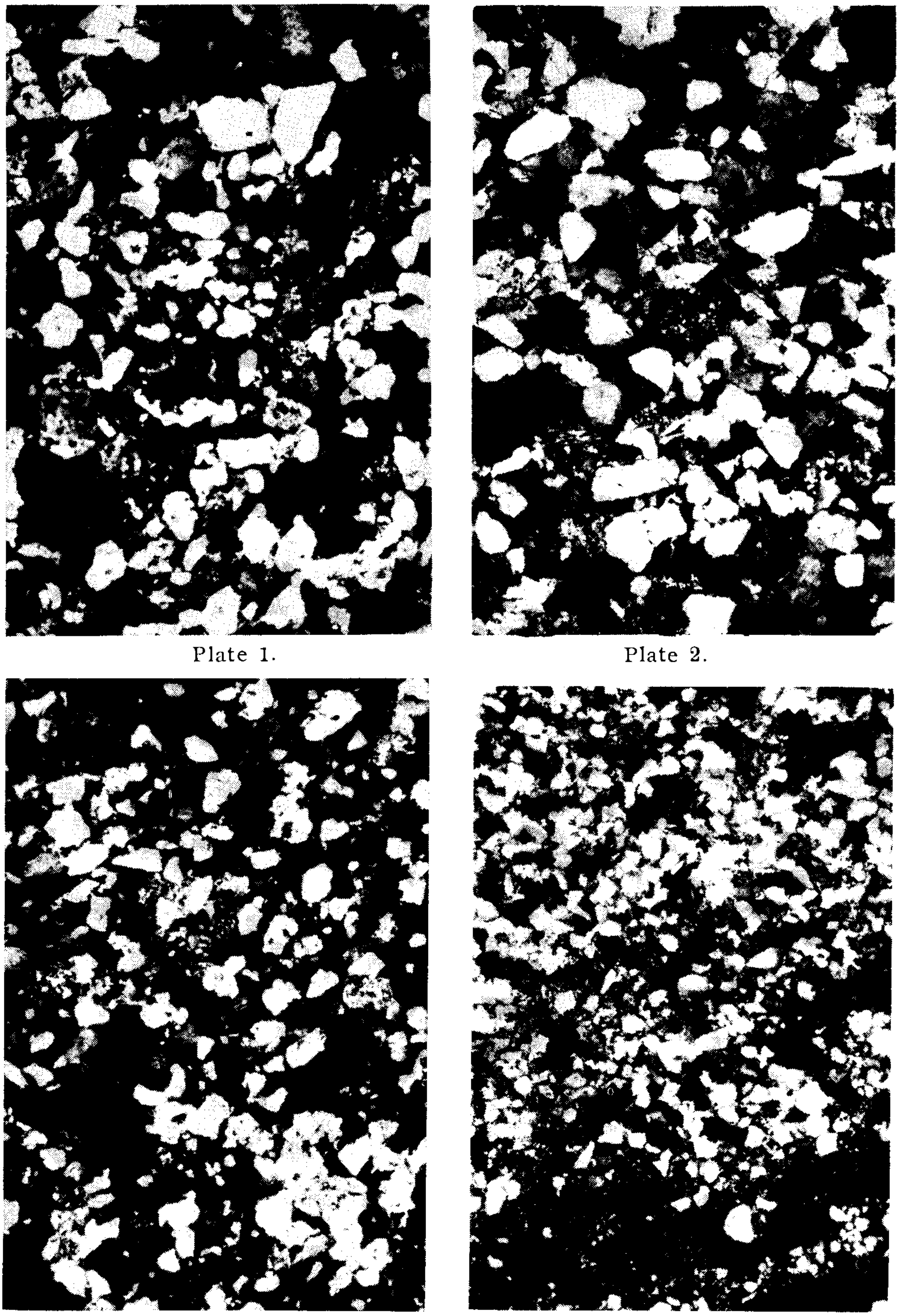


Plate 1.

Plate 2.

Plate 3.

Plate 4.

Fig. 3. Photomicrographs showing textural composition of representative samples in the Upper Dunsforth borehole.

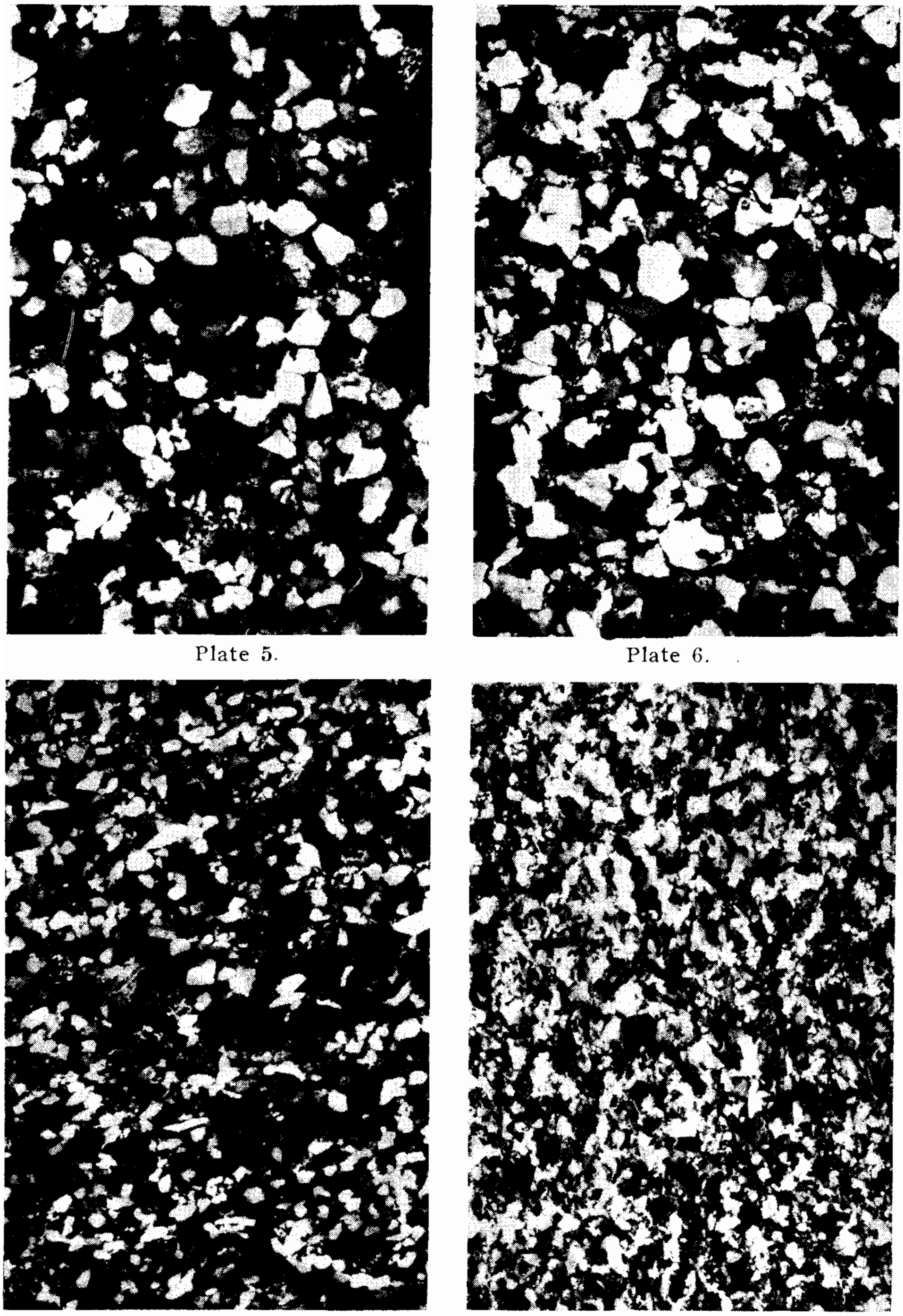


Plate 5. Plate 6.

Plate 7. Plate 8.

Fig. 4. Photomicrographs showing textural composition of representative samples in the Ainderby Steeple borehole.

7.2. Conclusions and comparison of the Results.

Upper Dunsforth.

a. Samples contained equal-sized grains which were angular to slightly rounded.

b. There was abundant cementing material.

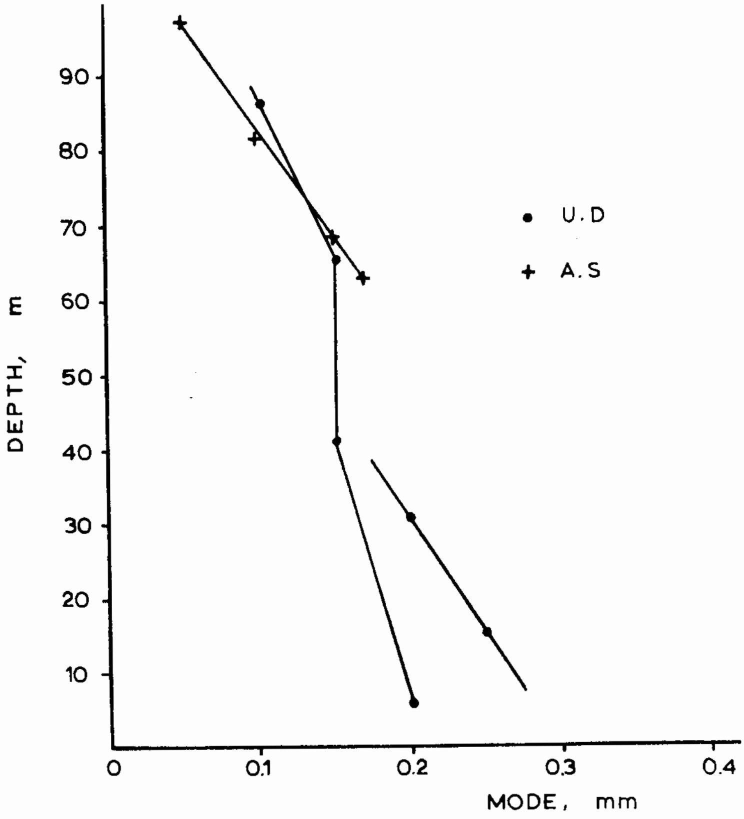


Fig. 5. Variation of grain size mode with depth in borehole.

c. Grain size decreased with depth of borehole.

d. The proportion of clay minerals, calcite and iron oxides increased with decrease in grain size.

Comparing the two methods, sieve analysis and microscopic examination, it is seen that both give similar results for the two boreholes

Ainderby Steeple:

a. The grains were more rounded and uniformly sized than in Upper Dunsforth samples.
b. There was less cementing material.
c. Iron oxides gave rise to a red colour which increased with depth.
d. Crain size decreased with depth. The variation in the modes of the grain size distributions with depth, for the two boreholes, is given in the Fig. 5.
e. The grains are closely packed with little cement.

Comparing and contrasting the two boreholes it can be seen that in the Upper Dunsforth borehole there is more cement and the grains themselves are unequal-sized and angular.

This angularity is not of the mosaic type but the grains are disorderly arranged with large pores and interconnecting channels between them.

It can be inferred, from the general appearance of the sandstones under the microscope and by the results of sieve analysis, that higher values of effective porosity and permeability are to be expected in Upper Dunsforth.

8. POROSITY

8.1. Definition.

All geological formations have pore spaces, no mater how the grains are graded and packed.

The porosity of a material is a measure of the pore spaces, between the grains composing the material. These pore spaces are also called voids, interstices or pores, and are characterized by their shape, size, irregularity and distribution.

The pores can be classified, in terms of size, as capillary, supercapillary or subcapillary. They may also be subdivided into primary pores, created during the geological formation of the rock and secondary pores formed later as fractures, joints or solution openings.

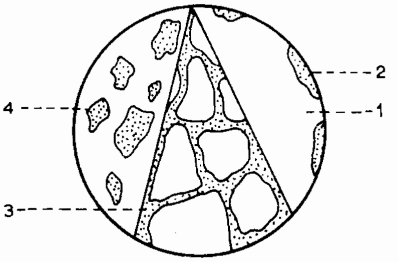
E. W. Washburn recognised the following types of pores: closed, channel pores connecting separate ones, blindalley pores, loop pores, pocked pores, micropores and continuous pores.

A more general classification of the pores is as follows: External pores, which are at the surface of a prepared sample. Open pores which are connected with each other and link to the external voids. Closed pores which are completely closed. These three categories of pores, are shown in Fig. 6.

8.2. Experimental Work.

In the laboratory, 10 samples from each borehole were examined. The samples were of cylindrical form with a length of about 3.5 cm and diameter of 2.5 cm. From the borehole of Ainderby Steeple two samples, from the same depth, were examined because, on superficial examination with the naked eye they appeared different. No difference could be detected on testing.

The method employed for the determination of porosity was that by saturation. A dessicator was cleaned and dried. The samples under examination were dried in an oven at 100° C for about 6 hours, weighed and put in the dessicator. (four samples at a time). After evacuation for about half an hour, water was slowly inserted into the dessicator, without releasing the pressure, until the samples were completely covered. After saturation, for about 15 hours, the samples were weighed, and hence the amount of water filling the pores was found.



1. ROCK SAMPLE
2. OPEN PORES
3. INTER-CONNECTED PORES
4. LOCKED PORES

Fig. 6. Classification of pores.

The bulk volume of the samples was estimated by water displacement and by direct measurement of the sample dimention, without significant difference occuring.

Some samples were tested by the saturation method but without any evacuation. The measured porosity was smaller than with evacuation.

The results are given in Table 2. The porosity varied between 9% and 25% with most values lying in the range 17% to 21%. Visual examination of the tested samples was compared, broadly, with the experimental results. Well cemented samples and those with marl discontinuities were found to have the lower values.

Values of porosity were plotted against sorption (see Fig. 7).

The relation between these two was found to be approximately linear.

A graph of porosity against sorting coefficient (see fig. 8), indicated no relationship between these two parameters, in contrast to theoretical considerations, where porosity is a function of assortment. The greater the range of particle - size the lower should be the porosity, as the small particles occupy the voids between the larger ones.

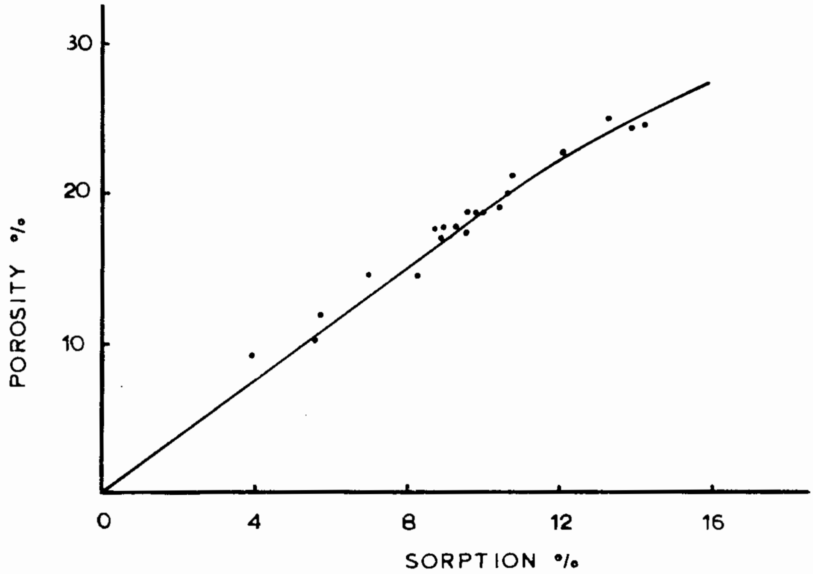


Fig. 7. Effect of density on porosity.

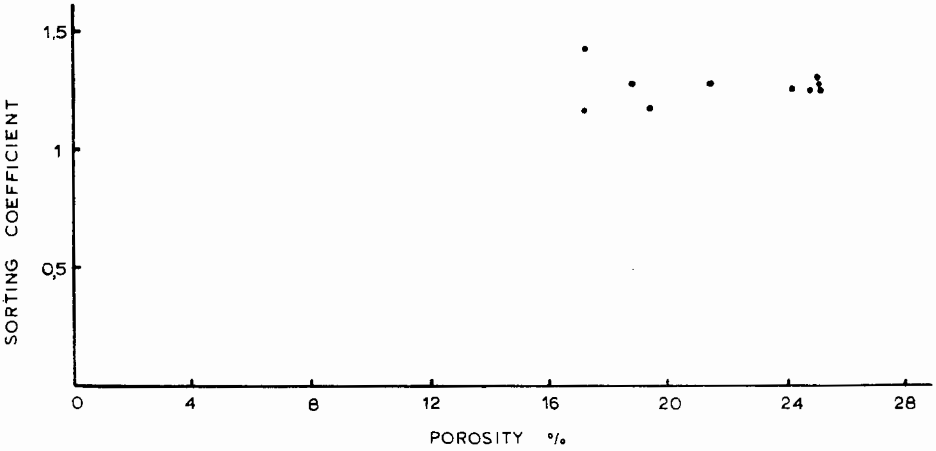


Fig. 8. Relationship between porosity and sorting coefficient.

It is realized that the values plotted are inadequate to obtain the existance of a relation between these two parameters and hence no clear conclusion can be drawn.

Also no relation can be seen between porosity and median particle-size diameter (see Fig. 9). It is quite common for porosity to be independent of particle-size, but again in this case the number of sample points is insufficient to draw significant conclusions.

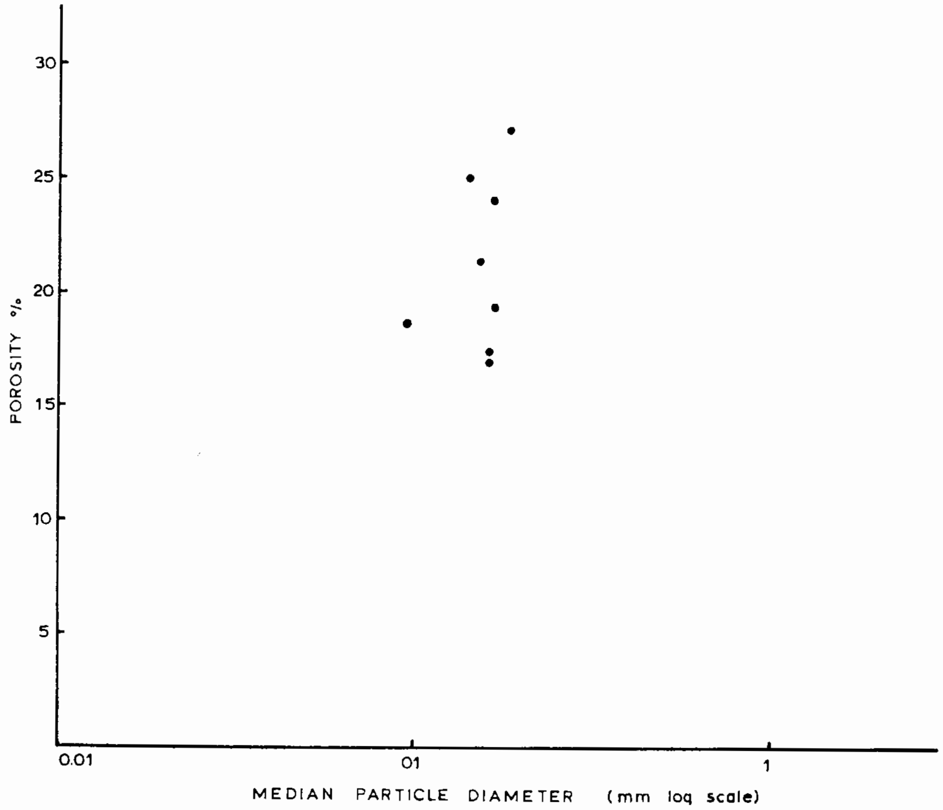


Fig. 9. Relationship between porosity and median particle diameter.

The pore size distribution of the sandstones have not beenn examined. According to some results given by HOWELL and others, the average pore size for Yorkshire samples range from 0.1 - 20 microns.

Conclusions:

a. Tested samples from the two boreholes in the Triassic sandstones gave a range of porosity from 9% to 25%. The total number of tested samples was twenty, covering, approximately, the whole depth of the boreholes.

b. The method employed for the tests was by saturation after evacuation, giving apparent porosity.
c. No significant differences were found from measurements on the same sample.
d. Accuracy is ensured by repeating the measurements on each sample more than once.
e. A difference between common saturation and saturation after evacuation was found. The results of the latter technique were larger and hence the more valuable of the two.
f. Examined thin sections of the material indicated only a few sealed pores and hence a stight difference between apparent and true porosity may be expected.
g. The bulk volume is more accurately determined by mercury displacement rather than water, because of absorption.
i. The number of samples tested was too low to exhibit significantly any relationship between porosity and the parameters of sorting coefficient and particle-size.
k. The ralation between porosity and sorption is approximately linear.
l. Generally, higher values of apparent (effective) porosity were fouud in the Upper Dunsforth borehole samples.

9. PERMEABILITY

9.1. Indroduction.

The permeability of a material is a measure of the ease with which the medium will transmit fluids under a hydropotential gradient (Muskat). Permeability, a dynamic property of the material, depends on the static properties, porosity, grain size distribution, cementation etc. In the field, it is also governed by factors such as fissures, cracks, faults and other openings. These latter factors are the chief cause of variations in permeability in the same geological formation.

The permeability of a rock or soil is found to be, approximately, proportional to the mean grain diameter,

$$k \approx C\,d^2\,[L^2] \qquad (1)$$

where k is the intrinsic permeability, d the mean grain diameter, sometimes called the effective grain diameter, and C a dimensionless constant which depends on the porosity, shape, grain size distribution, packing etc., of the medium.

Permeability, as given by eq. 1, depends only on the medium, and is independent of the nature and properties of the fluid. Hence, the term «intrinsic permeability» has been adopted in order to distinguish permeability from hydraulic conductivity (K).

Intrinsic permeability can be defined by Darcy's law:

$$k = \frac{Q \, . \, v}{g\,(dh/dl)} = - \frac{Q/A \, . \, n}{(d\Phi/dl)} \, [L^2] \qquad (2)$$

where Q/A = rate of flow per unit area
g = acceleration of gravity
v = kinematic viscosity
dh/dl = hydraulic gradient or the unit change in head per unit length of flow
$d\Phi/dl$ = potential gradient.

The U.S. Geological Survey has chosen the square micron $(\mu)^2$ as the unit of intrinsic permeability.

Another unit of this, used mainly in petroleum industry, is the darcy.

The term k is the constant of proportionality in the Darcy's law and replaces the field coefficient of permeability, Pf, hence the inconsistant units gallon, foot and mile (see tables 3 and 4 page 406, 407). The dimentions of K are LT^{-1}.

The hydraulic conductivity depends not only upon the medium but upon the fluid. The nature of pore space, the type of liquid, and the gravitational field, all influence hydraulic conductivity.

Any differences between the hydraulic conductivities in two different places of an aquifer are due to variability of viscosity and or acceleration due to gravity. Hence if intrinsic permeabilities are equal the hydraulic conductivities are related by:

$$K_1 = \frac{v_2 \cdot g_1}{v_1 \cdot g_2} \cdot K_2 \qquad (3)$$

or $K_1 = \frac{v_2}{v_1} \cdot K_2$ because the variation in g is negligible.

In the case of water at the standard temperature of 60^0 F where $v = 1.1296$ centistokes,

k is, numerically, equal to $\frac{4}{3}$ K.

For water at any other temperature these two parameters are related by the equation

$$k\,(\mu)^2 = \frac{4}{3}\,[10^{-12} \cdot m.\,day]\left[\frac{v}{1.1296}\right] \cdot K\,[m.\,day^{-1}] \qquad (4)$$

9.2. Measurement of permeability.

Permeability can be measured either in the field or the laboratory.

9.2.1. Laboratory measurement of permeability.

The methods employed for this measurement can be divided into categories : a. Indirect and b. Direct.

By the indirect methods permeability is estimated via other properties of the specimen, such as porosity, packing and grain size distribution.

On the other hand, direct methods are preferable because measurements are made under actual conditions. The direct methods used in our experiments were as follows:

a. Constant head method

Permeameters designed for measuring permeability, are used for consolidated or unconsolidated samples under low heads. The principle is that water passes through the sample from the bottom and is collected as overflow. The hydraulic conductivity is given from Darcy's law as:

$$K = \frac{V.L}{A.t.h.} \qquad (5)$$

where V/t is the volume of water passed in time t, A the cross sectional area of the sample, h the constant head and L the thickness (parallel to flow) of the sample.

b. Method using Gas Pressurized Permeameter

In this case air pressurizes the water. The hydraulic conductivity is given by the equation

$$\frac{Q}{t.A} = K\frac{\Delta p}{l} \qquad (6)$$

where Q is the volume (ml) of fluid, l is the length (cm's.) of the sample parallel to the flow, t is the time (seconds), Δp the inlet-outlet pressure difference (atmospheres).

To express k in cm's $\times$ sec^{-1}, the pressure must be converted to cm's of water, as follows:

$$1 \text{ bar} = \frac{10^6}{980} = 1022 \text{ cm's of water.}$$

During the experimental work only the hydraulic conductivity was measured since in groundwater studies variations in density and viscosity of the fluid are negligible. Hence, for notational convenience K will be referred to as «Permeability».

Laboratory measurements - Discussion:

In order to have a representative value of permeability for an area under examination, a large number of samples must be examined covering the entire aquifer in extention and depth.

The advantage of the laboratory measurements is that variables can be controlled. They have the disadvantage that it is difficult to obtain undisturbed samples, especially from unconsolidated formation. Repacked samples indroduce many deviations in porosity, grain size and packing.

Consolidated samples give more stable results but in this case samples might not be representative because of weathering effects or they may be disturbed by drilling.

9.3. Experimental work.

As previously stated, the permeability of a medium such as sandstone Pepends on the following factors :

a. The viscosity, b. the flow paths and c. the presence of discontinuities.

Factors a and c can be eliminated from experiments by keeping the viscosity steady and by selecting samples without discontinuities. If this is done, the flow through porous media depends only on the medium itself.

9.3.1. Sampling.

It is well known that sampling is one of the most difficult processes, especially for unconsolidated materials.

During extraction, the sample may be subjected to many alterations causing changes in the density, porosity and even the structure of the various minerals.

For consolidated rocks, reasonably undisturbed samples may be taken from outcrops or even boreholes, if care is taken to avoid excessive pressures and temperatures during drilling.

Factors to be taken into account in sampling are as follows :

a. Samples taken from boreholes are unweathered in contrast to samples from outcrops, fron which cement or other clay minerals may have been washed.
b. Samples covering the aquifer in depth and extention must be tested to give a truly repsesentative value of permeability. Only in this way can the many variables, such as solution, different

cementation, weathering, change in lithology, be controlled and statistically analysed.

c. Stratigraphy and tectonic history must be evaluated in order to isolate the contribution to permeability of factors such as fissures and faults.

During the investigation samples were taken from two exposures of the Triassic sandstones and from two boreholes. The location of the exposures and boreholes is shown on the geological map, Fig. 1.

Forty samples were examined, 6 from the exposures and 34 from the boreholes, covering almost the entire range of depth. The areal coverage of the samples is insufficient to give overall representation of the permeability, so further investigation is recommended.

The samples indicated lateral and vertical variation in the aquifer. Horizons of marls and a few pebbles were found in the stratigraphic column.

In the sandstones, cementation varied. Most of the drill cores consisted of soft and very friable parts, but there were also some well cemented parts.

All samples examined were undisturbed, fresh, unfissured and subjected only to the minimum perturbation. It is considered that representative sampling is only attained if a large number of samples are tested (Howell). Accordingly, sample intervals must be uniformly and closely distributed within the stratigraphic column.

9.3.2. Preparation.

Samples taken from the exposures were cut into cubes of approximate side 8 cm. The cutting was made in the wet state. Cutting in a dry state is preferable because leaching by water is avoided and hence the process is easier and more effective especially when the samples are very friable. A coring machine was used to cut samples from the boreholes into small cylinders of 3.5 cm's in length and 2.5 cm's in diameter (the actual dimentions of the samples tested are given in the tables of permeability measurements).

No difficulties arose in the preparation even for the well cemented semples.

The samples prepared for permeability measurements were of two types, parallel and at right angles to the bedding planes.

9.3.3. Permeability Apparatus.

a. Water Supply.

Tap water was used for the experiments.

Ideally, in order to have reproducible results de-aired water should be used. By creating, in the laboratory, a completely artificial enviroment, which is related in some way to the natural one, both enviroments can be correlated. This is done because it is very difficult to reproduce exactly the many variables encountered in the field.

All the tests were carried out with water at a temperature of about 20°C.

Although this process does not reproduce exactly the field conditions, it is sufficient for a reasonable correlation of permeability. The disadvantage of tap water is that the dissolved air in it can block the flow paths in the sample, reducing the measured permeability of the samples.

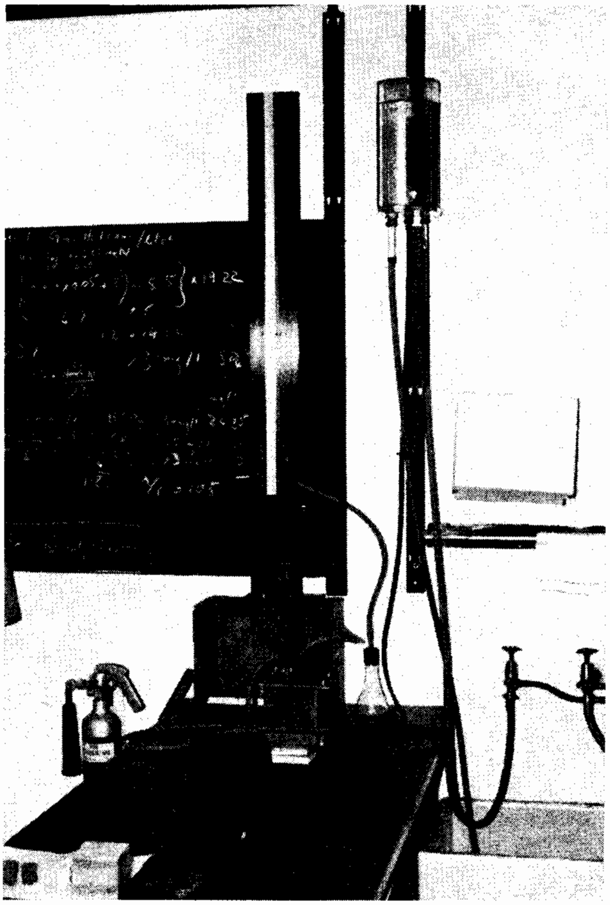


Plate 9: Constant Head Permeaneter.

b. Apparatus used-Test procedure.

Two types of apparatus were used for the experimental work.

1) Constant head Permeameter: This was to obtain the permeability of the cubes. It is a constant head apparatus (see Plate 9).

The head difference applied was 92.3 cm's. The sample was placed in a metal chamber consisting of two pieces controlled by clamps. Rubber was used around the sample to give a tight fit within the chamber.

The sample was enclosed by adjustable metal end pieces.

The samples were partially saturated by soaking in water. After insertion of the sample in the permeameter, a full head was applied and kept constant. Initially, the rate of flow was slow, indicating incomplete saturation. Measurements taken before the flow rate was stabilized were ignored. The time for complete saturation of the samples under full head varied from 15 to 40 hours, a long time. If de-aired water had been used, complete saturation would have been possible much more rapidly, shortening significantly the duration of the work.

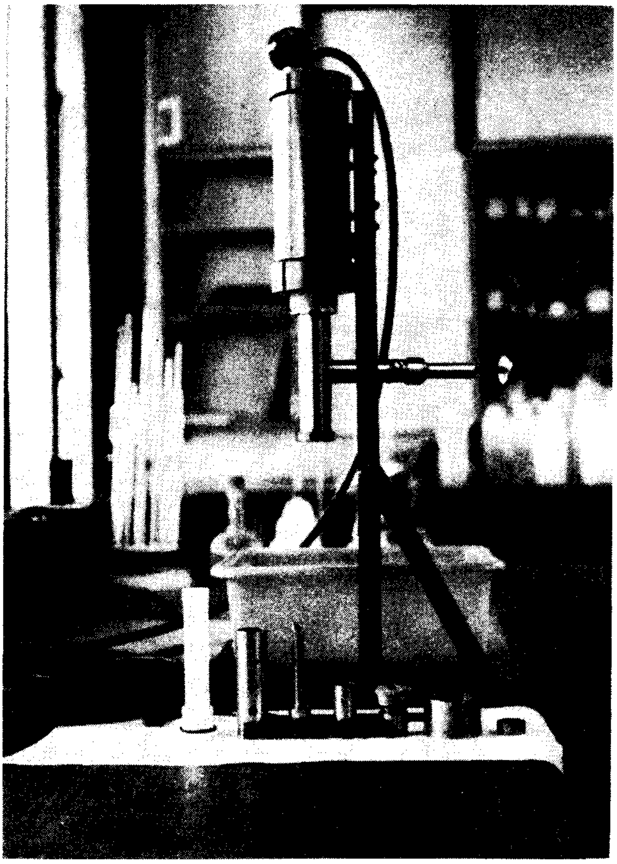


Plate 10. Gas Pressurized Permeameter (G.P.P.)

The tests were carried out at a temperature of 20°C. Water was

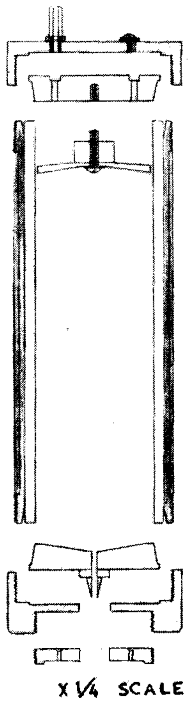


Plate 10a. G.P.P.
Water Reservoir

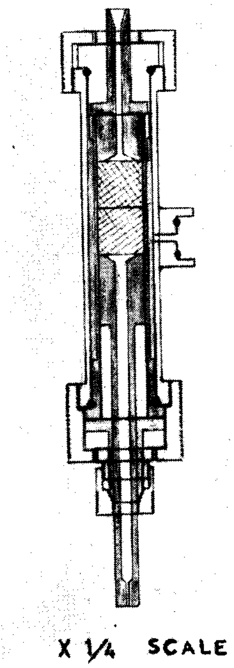


Plate 10b. G.P.P.
Permeability cell.

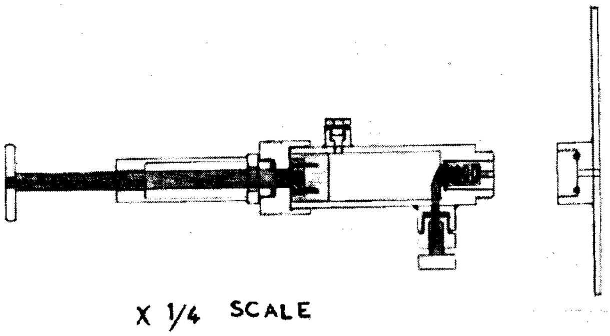


Plate 10c. G.P P. — Oil Pump.

supplied to the samples from the bottom. In one sample the flow was reversed without producing a significant difference.

For samples with low permeability, flow rate through the sample is low using this procedure (small constant head) and hence the falling head permeameter had to be used.

2) Gas Pressuarized Permeameter : Testing samples by the constant head permeameter thought to be reliable, is slow for evaluating parameters, such as permeability where a large number of samples must be tested.

In order to increase productivity a fast, simple and quite accurate permeameter was designed and constructed for the work. This consisted of three parts : Water reservoir, Permeability cell and Oil Pump (see Plates 10a, 10b, 10c).

The permeability was measured by passing water through the sample under the action of compressed air.

The permeameter was designed to give pressure of 11 bars, but the pressure applied during the experiments was kept constant at 1.5 bars·

The diameter of the samples was 2.5 cm's, a little less than the diameter of the tube. In order to attain a good fit, the samples were taped. It was not necessary to have a very close fit between the sample and the tube because the oil pressure held it in place. The tank was almost totally filled in order to take as nany measurements and to achieve a steady flow.

It was found that measurements at the beginning and at the end of the tests were not reliable.

As a check, results from this permeameter were correlated with those from the constant head permeameter. To do this, cores were drilled from the cubes used for the constant head permeameter and placed in the pressure premeameter. Permeabilities taken from both permeameters corellated well.

The procedure for resting a sample by the pressure permeameter was quite laborious because of the need to refill the oil container two to three times during an experiment, hence holding air in. To facilitate this a more suitable adjusting screw could be incorporated for pressurizing the oil.

Despite this limitation the equipment proved very usefull and accurate, cutting operating time from a few minutes to some hours, depending on the sample.

9. 3. 4. Calculation of results.

Equations for the calculation of permeability have given in the section 9. 1.

It has been shown that under the conditions of the experiment, the flow should be laminar and so Darcy's law applies. The results were normally expressed with an exponent.

9.3.5. Permeability test results.

The results from all the samples are presented in table 5. The highest steady values were generally chosen as the representative permeability. Some sample results were not recorded because no water came through the sample in the time of observation, indicating that the permeability of these samples exceeded $0.1X10^{-6}$ cm/sec. This sometimes occured in both directions, indicating that some samples were impermeable parallel and at right angles to the bedding. If such samples form distinct extensive horizons, these will divide the aquifer, affecting its yield.

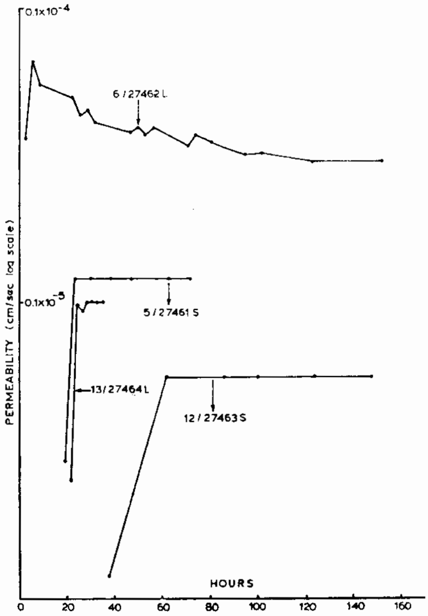


Fig. 10. Variation of permeability with time.

The variation of permeability with time, for the cubic samples, is given in graphs (see an example in Fig. 10).

The abrupt change of permeability in the initial part of the graphs is because the time of saturation has been included in the calculations. During saturation the water slowly dissolves the entrapped air and frees the flow paths until a constant flow is attained.

As it can be seen from these graphs there was no significant variation in permeability during the test period. Slight variations were observed in some samples where the flow was parallel to the bedding, perhaps because of favourable reorientation of the particles along this plane. For example the permeability of sample 6/27462 L decreases slightly. A more likely explanation of this phenomenon lies in the use of tap water in which air bubbles might occur or bacteria may grow.

The higher the permeabilities the shorter the time required for constant flow.

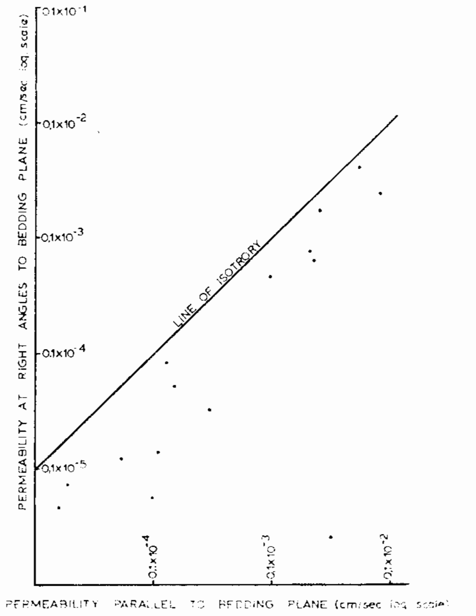


Fig. 11.
Anisotropy of permeability.

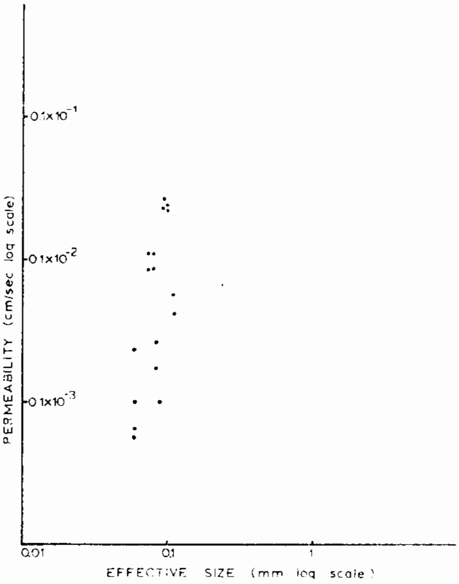


Fig. 12.
Relationship between permeability and effective size.

The flow reversed for sample 16/27466 L. No significant change can be seen.

To examine the anisotopy in the rock, a graph was plotted of the parallel and at right angles values of permeability (see fig. 11).

It can be seen that all points are below the line of isotropy, so the permeability parallel to the bedding planes is higher than at right angles. The degree of anisotropy is not high, the points lying close to the line of isotropy.

These variations in the lithology through the stratigraphic column can be seen in the thin sections and the cores available.

The anisotropy of the samples expresed as,

$$A = \frac{\text{K parallel}}{\text{K at right angles}} \qquad (6)$$

ranges from 1.1 to 9.37, most values being less than 3.5, (also one very high value was recorded). Generally anisotropy was low where there were no marl banks. Muskat suggested that such anisotropy was due to the tendency of the pore spaces to develop a prefered orientation during sedimentation.

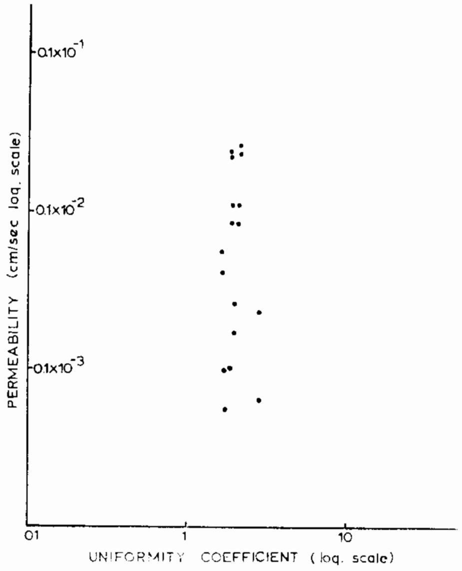


Fig. 13. Relationship between permeability and uniformity coefficient.

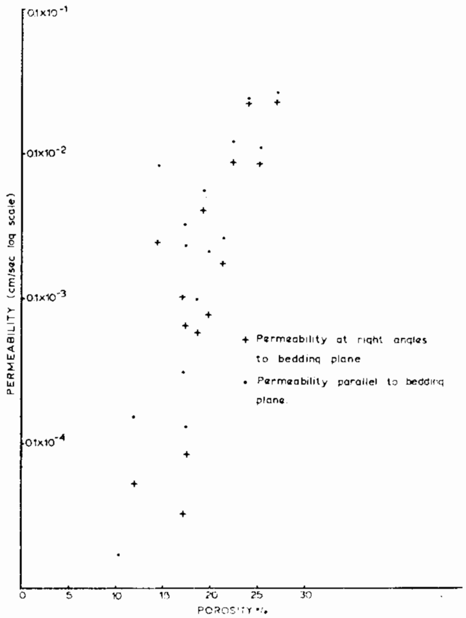


Fig. 14. Relationship between porosity and permeability.

Permeability was found to increase slightly as the effective size and the uniformity coefficient increased (see Fig's 12 and 13).

In Fig. 14 the permeability parallel and at right angles to the bedding plane is correlated with the porosity of the rock. A relation between permeability and porosity can be seen, the larger values of permeability corresponding to higher values of porosity, but the correlation is not good enough to fit a quantitative relation.

Howell and others in an account of the permeation properties in the Lankashire and Yorkshire regions found quite different properties and concluded that these differences were because of the deposition of sandstones in different sedimentary basins (see Fig. 15, I.G.S Tectonic map, 1966). Hence prediction in new areas by extrapolation is not reliable.

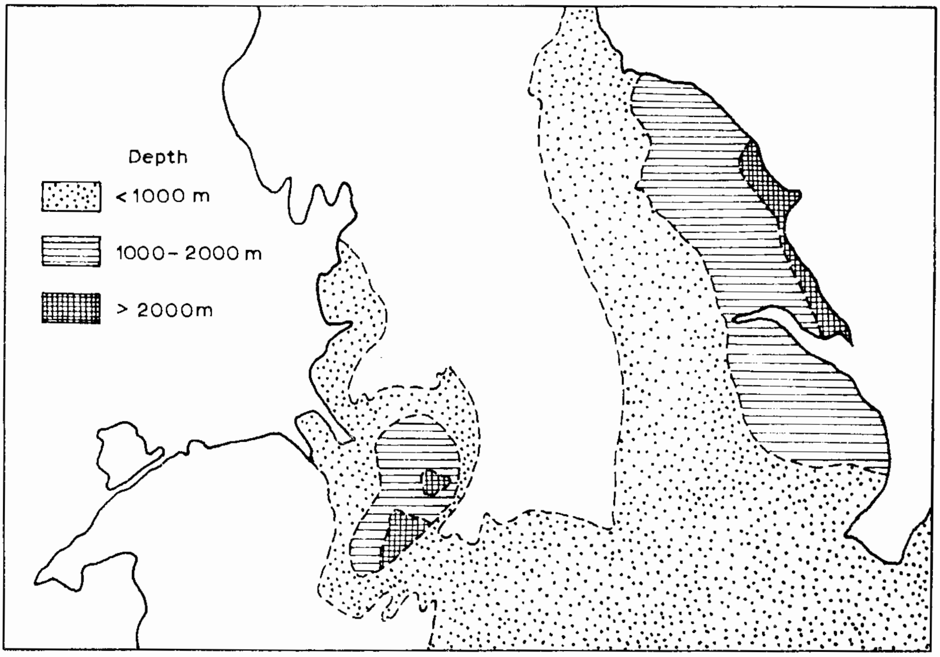


Fig. 15. Sketch map illustrating depth of Bunter sandstone basins in Lankashire and Yorkshire (after tectonic map of Great Britain).

9.3.6. Interpretation of the results.

a. Both horizontal and vertical permeability have been determined and hence the anisotropy.

b. The permeameters used were the classical constant head and a new Gas pressurized one. The samples were more or less representative of the aquifer, particularly those taken from the boreholes.

c. A difference between field and laboratory results can be expected because of the influence of fissures, faults etc.

9.8. Conclusions.

a. New terms and definitions have been used for some parameters according to those accepted recently by the U. S. Geological Survey.

b. Forty samples were tested in the laboratory. Of these samples 34 were from two boreholes and the rest from two exposures.

c. The apparatus used for testing the samples comprised a constant head permeameter and a Gas Pressurized permeameter constructed in the Department of Earth Sciences for this project.

d. The two permeameters used gave similar results. This encourages further use of the second permeameter which was very fast, although some modifications would be desirable.

e. The samples tested were of two types, parallel and at right angles to bedding.

f. No significant variation of permeability with time was found.

g. The values of permeability ranged from 0.12×10^{-2} to 0.46×10^{-6} cm/sec, for both types of samples. However, values can be expected to reach up to 0.1×10^{-8} cm/sec in the less permeable samples which were not tested for sufficient time. Most of the results are between 0.2×10^{-2} and 0.1×10^{-5} cm/sec. Horizontal permeabilities range from 0.12×10^{-2} to 0.16×10^{-5} cm/sec and those at right angles from 0.22×10^{-6} to 0.46×10^{-6} cm/sec, for the measured permeabilities.

h. Permeabilities parallel to the bedding planes were greater than those at right angles to the bedding. The anisotropy of the samples ranges from 1.1 to 9.37 with most values less than 3.5. The fine marl bands meant that the permeability was very low at right angles to the sandstones. Higher values were recorded in the North of the aquifer.

i. The large range of permeability is due to many factors, cementation, the nature of particle sorting etc. but the anisotropy of individual samples is because of the presence of thin marl bands.

j. No significant change in permeability was found on reversal of flow.

k. An upward trend of permeability to the South was observed. This agreed with the porosity, and mechanical analyses and with the microscopic examination.

l. Permeability decreased with depth in both boreholes, because as was shown earlier, the cement and iron oxides around the grains, increased with depth, and the grains became smaller, more uniform and more tightly packed.

m. There is a slight increase of permeability with effective size and uniformity of the samples.

n. There is a relation between porosiry and permeability; higher values of permeability corresponding to mere porous samples, but the correlation is not good enough to obtain one parameter from measurements of another.

10. GROUND WATER - AQUIFER TESTS

All the equations of ground water flow and the methods used are well known. It was considered necessary to give only the case of Leaky confined aquifer and partial penetration as directly faced in our problem.

10.1. Unsteady radial flow - Leaky confined aquifer with vertical movement.

In a confined aquifer the confining beds are not absolutely impermeable and they have some finite permeability.

In order to derive the previous equations for the confined aquifers, the confining beds were assumed impermeable and no vertical flow components existed.

The following equations explain the nonsteady radial flow from an infinite aquifer whose confining beds leak water from or to the aquifer.

Huntush and Jacob (1955) gave the formula for this case as,

$$s = \frac{Q}{4\pi T} L(u, v)\,[L] \qquad (7)$$

where L (u, v) is the Leakance function of u and v,

$$u = \frac{r}{2}\sqrt{\frac{K'}{B'T}}\ [\text{dimensionless}] \qquad (8)$$

and $$u = r^2 S/4Tt \quad [\text{dimensionless}] \qquad (9)$$

In equation (8) K′ is the vertical hydraulic conductivity of the confining bed, b′ is the thickness of the confining bed and T is the transmissivity of the aquifer.

The coefficient of storage is given by the equation

$$S = 4T\,\frac{t/r^2}{1/u}\ \text{dimensionless} \qquad (10)$$

and $$\frac{K'}{b'} = 4T\,\frac{v^2}{r^2} = \frac{S\left(\frac{v^2}{u}\right)}{t}\,[T^{-1}]. \qquad (11)$$

In order to obtain these perameter values of !L (u, v) were plotted versus 1/u. Two families of type curves have been prepared by Cooper, in one of them u is the parameter and in the other v^2/u is the parameter.

The u type curves correspond to a plot of s versus t at some constant distance r, and is plotted as t/r^2 (horizontal). The v^2/u type curves correspond to a plot of s versus t/r^2 at some constant t.

By plotting s versus t/r^2 and superposing, a match point is found and the values obtained are substituted in equations (7) and (10).

Also values of u or v^2/u by substituting in equation (11) give the value of K'. When $K' \rightarrow 0$ then $v \rightarrow 0$ and L (u, v) approaches W (u), hence equation (7) becomes exactly the Theis equation.

Hantush also derived some modifications of this method where the storage in the confining bed or beds is taken into account and also where constant drawdown is taken into accoun too.

10.2. Partially Penetrating Wells.

If the pumping well does not fully penetrate and perforate the total thickness of the aquifer, distorted drawdown curves occur which vary according to the vertical condition under consideration.

Jacob suggested a technique in the arrangement of the observation wells in the case of partially penetrating well, mainly applicable to thin unconfined aquifers.

Some other suggestions for the case of a confined aquifer are as follows: a) Observations must be taken at a distance from the pumped well where the distortions are minor. This distance is approximatelly equal to $2b\sqrt{Kh/Kv}$. b) If the bedding in the horizontal direction is very strong and the measurements of drawdown are taken close to the pumped well, then it is assumed that the aquifer ends at the bottom of the well.

Muskat, Kozeny and Jacob have found formulae for this adjustment of observed drawdowns in some cases of partial penetration.

In the case where $Qp = Q$ then $(\Delta h)p > \Delta h$ and when $(\Delta h)p = \Delta h$ then $Qp < Q$ where the symbols Q, Δh, Qp and (Δh)p are the discharges and drawdowns of a fully and partially penetrating well, respectively.

In Todd the equations for a partially penetrating well for both confined and unconfined aquifer are given. Hence for a confined aquifer, where a well penetrates the upper part of it,

$$D = \frac{Qp}{4\pi K}\left[\frac{2}{hs}\ln\frac{hs}{2rw} + \frac{0.20}{b}\right] \qquad (12)$$

where Qp = discharge of the well,
hs = depth of the aquifer penetrated by the well,
b = saturated thickness of the aquifer,

2rw = well radius,
K = hydraulic conductivity.

This equation is valid when $1.3\,hs \leqslant b$ and $hs/2rw \geqslant 5$.

For an unconfined aquifer the drawdown is given by,

$$D = \frac{Qp}{4\pi K}\left[\frac{2}{hs}\ln\frac{\pi hs}{2rw} + \frac{0.20}{H}\right] \qquad (13)$$

where H is the saturated trickness of the aquifer and the other symbols as in equ. (12).

10.3. Field Evaluation of the Aquifer - Pumping Tests.

As stated in the previous sections, permeability may be influenced by the viscosity of the fluid, the effective porosity and the discontinuities.

Up to now we have been dealt with porosity and permeability.

In order to complete the study, results from small - scale pumping tests are needed.

Full - scale tests determine the overall character of the aquifer by estimating the permeability under field conditions. It was considered necessary to examine pumping test data from the two boreholes, in order to compare and contrast with the laboratory results. The coefficient of storage and Transmissivity have been evaluated from pumping test data from the two boreholes.

The tested samples were taken not from the main boreholes but from the observation wells 0_1 and 0_5 for Upper Dunsforth and Ainderby Steeple, respectively. The diameter of the observation wells was 15.24 cm.

The two boreholes did not penetrate the full depth of the aquifer and both have been drilled through a cover by Boulder clay. The specifications of the boreholes are shown in table 6, page 409.

10.4. Comparison of the Results.

The hydraulic parameters have been estimated by taking into account partial penetration and leakage. (See Fig. 16, for the Leaky confined aquifer case).

Assuming the same leakage for both boreholes, (as this has been estimated for the Ainderby Steeple site). the values of K and S are as follows :

Upper Dunsforth :	$K = 0.00101$ cm. sec.$^{-1}$	$S = 0.00054$
Ainderby Steeple :	$K = 0.00080$ cm. sec.$^{-1}$	$S = 0.00071$

If leakage does not occur in the Upper Dunsforth site then the values of the parameters are those found in the partial penetration case. Also, the effects of well loss have to be taken into account.

The computed coefficients of storage are in the range associated with artesian conditions. For confined aquifers, although rigid limits cannot be established, the storage coefficients range from about 0.0001 to 0.001. For water table conditions the coefficients range from about 0.05 to 0.30.

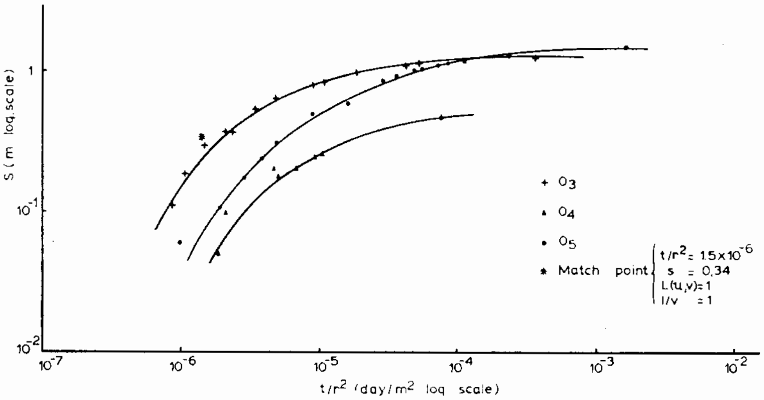


Fig. 16. Drawdown curves in the Ainderby Steeple borehole (Leaky confined aquifer case).

The pumping tests were long - term ones and hence it is expected that the recorded values of the coefficient of storage will correspond to the true values. In short - term tests and where the vertical permeability is small, it is likely that artesian coefficients of storage will be recorded under water table conditions.

10.5. Conclusions.

a. An account of the various techniques and methods used for the solution of various problems in the aquifers has been given. Comments on the reliability and application of these methods have also been presented. All the equations for the various methods have been given in the S. I. system of units.

b. The effects of partial penetration have been estimated for both boreholes and the values taken are as follows:

Upper Dunsforth : $K = 0.00090$ cm. sec^{-1}
Ainderby Steeple : $K = 0.00072$ cm. sec^{-1}

c. The effect of leakage from the superficial cover to the aquifer has been estimated for the Ainderby Steeple case. Leakage is also possible in the Upper Dunsforth site. The values of K and S for the aquifer, if we take into account the effects of leakage, are as follows:

$$K = 0.00114 \text{ cm. sec}^{-1}, \quad S = 0.00099$$

d. Taking the estimated effects of partial penetrarion and the same leakage for both boreholes, the values of the parameters K and S are as follows:

Upper Dunsforth : $K = 0.00101$ cm. sec^{-1}, $S = 0.00054$
Ainderby Steeple : $K = 0.00080$ cm. sec^{-1}, $S = 0.00071$

e. The values of K are smaller in the Ainderby Steeple site because of the lithology of the aquifer.
These results are in a close agreement with the results obtained from the examination of the thin sections, the mechanical analysis of the samples and the effective porosity measurements.

f. It is believed that the aquifer in both sites of the boreholes is in a confined condition influenced by leakage from the superficial cover.

g. The coefficient of storage is found to increase to the North.

h. During the pumping of the aquifer a recharge is indicated which is propably due to the rivers or any other source bordering the aquifer.

i. The overall picture of the aquifer indicates no large differences.

j. The values of the parameters estimated, indicate highly permeable strata, the aquifer being a good source for water supplies.

11. CORRELATION BETWEEN FIELD AND LABORATORY DATA

As it has been mentioned, the overall permeability of an aquifer is the resultant of the pores of the medium, vertical and lateral variations in the lithology and cracks in the form of joints, fissures, faults and bedding planes.

Examining the aquifer by laboratory and field methods, the contributions of each of the above factors to the overall picture of the aquifer was evaluated.

The estimated values of permeability in the laboratory range from 0.12×10^{-2} to 0.46×10^{-6} cm. sec^{-1} (with some not recorded values, reaching 0.1×10^{-8} cm. sec^{-1}) and those estimated by pumping tests are in the range of 0.12×10^{-2} to 0.8×10^{-3}.

The pumping test values of permeability are in reasonable agreement with the long-bedded laboratory values. This implies that the contribution of long-bedded flow to the yield of the well, through the interconnected pores of the sandstone, is of importance. Where the anisotropy is nearly unity, then the contribution from both directions must be considered.

Generally there is a difference between short-long bedded laboratory values and those found from the boreholes, the difference increasing to the North. On the other hand the estimated field values are similar in both sites. The explanation of this is a combination of the following:

a. Fissures, joints, faults and bedding planes contribute greatly to the overall permeability of the aquifer.
b. These discontinuities appear to be uniform throughout the whole area of the aquifer with only slight variations.
c. The lithological variations in the aquifer, both vertically and horizontally, seem not to consist of distinct extensive layers and therefore the aquifer is not separated into many isolated layers.

The Triassic sandstones are generally characterized by large yields and correspondingly low drawdowns, this being a resultant of the pores and the discontinuities.

12. FUTURE WORK

During the present investigation of the Triassic sandstones in the Vale of Mowbray, field and laboratory data from two boreholes and two exposures have been evaluated.

The data evaluated are insufficient to properly correlate the two kinds of data, and to specify completely the behavior of the aquifer.

The overall picture of the aquifer can be found by extention of this work to samples and data from all the boreholes and exposures. For representative results the frequency of samples must be as high as possible.

Detailed permeability and porosity measurements must be made in conjuction with microscopic examination, mechanical analysis, taking full account of the geology.

The permeameters used are quite satisfactory but for testing large numbers of samples, a more advanced air pressurized equipment is recommended. In other establishments air set ups, utilizing rock triaxial cells, have been used.

De-aired water is recommended for future permeability tests in the laboratory.

Small scalle «in situ» test determinations of permeability must be related with laboratory and pumping test data.

Other properties of the rock mass and rock material must be found such as compressive strength, deformation modulus etc.

A comparison between geophysical and hydrogeological data on the aquifer may be of some value.

The effect of superficial cover on the main aquifer needs to be evaluated.

A Geochemical investigation of the ground water would be useful.

A detailed study of the ground water levels will give information on decline and determine the optimum yield for which overdraw will be avoided.

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TABLE 1

Statistical measures in samples from boreholes.

Borehole	Depth (m)	Median diameter		Sorting Coefficient So	Effective Size		Uniformity Coefficient
		(Microns)	(mm)		(Microns)	(mm)	
Upper Dunsforth	15.30	182	0.182	1.26	94	0.094	2.07
»	21.80[1]	146	0.146	1.28	80	0.080	2.02
»	21.80[2]	137	0.137	1.30	77	0.077	1.94
»	21.80[3]	134	0.134	1.26	77	0.077	1.88
»	30.60	165	0.165	1.26	100	0.100	1.80
»	40.00	160	0.160	1.43	60	0.060	2.80
»	66.20	150	0.150	1.36	74	0.074	2.27
Ainderby Steeple	17.80	160	0.160	1.17	90	0.090	1.85
»	26.80	165	0.165	1.18	110	0.110	1.61
»	67.90	150	0.150	1.28	84	0.084	1.99
»	81.20	93	0.093	1.28	60	0 060	1.71

1. Sample in dry state. — 2. Sample immersed for a few minutes. — 3. Sample immersed for about 10 hours.

TABLE 2

Porosity in samples by saturation method

Borehole	Depth (m)	Initial weight (dry) (grams)	Weight after evacuation and saturation (grams)	Sorption (°/₀)	Porosity after evacuation (°/₀)
Upper Dunsforth	5.80	31.435	35.228	12.06	22.50
»	15.30	28.432	38.480	14.23	24.66
»	21.80	30.303	34.322	13.26	25.03
»	30.60	29.423	33.530	13.95	24 08
»	37.26	36.130	38.648	6.96	14.70
»	40.00	30.833	33.748	9.45	17.42
»	43.10	29.083	32.470	8.20	14.50
»	45.00	31.892	35.300	10 68	19.90
»	56.90	34.312	37.330	8.76	17.50
»	89.80	33.842	36.811	8.77	17.30
Ainderby Steeple	17.80	31.764	34.590	8.89	17.12
»	26 80	32.082	35.425	10.42	19.29
»	32.00	31.955	34.895	9.20	17.80
»	37 00	39.472	41.338	4.72	10.30
»	67.90	31.721	35.139	10.77	21.35
»	68.50	34.700	37.490	8.90	17.70
»	80.10	36.420	38.480	5.65	11.90
»	81.20[1]	31.856	35.042	10 00	18.69
»	81.20[2]	30.369	33.370	9.65	18.67
»	97.60	40.192	41.788	3.97	9.23

1. At right angles to bedding plane. — 2. Parallel to bedding plane.

TABLE 3

Relation of units

[Equivalent values shown in same horizontal lines, † indicates abandoned term].

A. Hydraulic conductivity

Hydraulic conductivity (K)		† Field coefffcient of permeability (P_t)
Feet per day (ft day^{-1})	Meters per day (m day^{-1})	† Gallons per day per square foot (gal day^{-1} ft^{-2})
One	0. 305	7. 48
3. 28	One	24. 5
. 134	. 041	One

B. Transmissivity (T)

Square feet per day (ft^2 day^{-1})	Square meters per day (m^2 day^{-1})	† Gallons per day per foot (gal day^{-1} ft^{-1})
One	0. 0929	7. 48
10. 76	One	80. 5
. 134	. 0124	One

C. Permeability

Intrinsic permeability $k = -\frac{q\nu}{d\varphi/dl}$ $[(\mu m)^2 = 10^{-8}\ cm^2]$	$Darcy = -\frac{q\mu}{dp/dl + \rho g\, dz/dl}$ $[0.987 \times 10^{-8}\ cm^2]$	† Coefficient of permeability $P \text{ or } P_m = -\frac{q \text{ (at } 60^\circ F)}{dh/dl}$ † [gal day^{-1} ft^{-2} at 60° F]
One	1. 01	18. 4
0. 987	One	18. 2
. 054	. 055	One

TABLE 4

Conversion factors for hydraulic units of measure

[Equivalent values shown in same horizontal lines]

Cubic feet per second (ft^3 sec^{-1})	Acre-feet per day (acre-ft day^{-1})	Acre-feet per year (acre-ft yr^{-1})	Gallons per minute (gal min^{-1})	Gallons per day (gal day^{-1})	Cubic feet per day (ft^3 day^{-1})	Cubic meters per day (m^3 day^{-1})	Square mile-inch per year (mi^2-in yr^{-1})
One	1.9835	7.2397×10^{2}	4.4883×10^{2}	6.4632×10^{5}	8.6400×10^{4}	2.4466×10^{3}	1.3574×10^{1}
5.0417×10^{-1}	One	3.6500×10^{2}	2.2629×10^{2}	3.2585×10^{5}	4.3560×10^{4}	1.2335×10^{3}	6 8438
1.3813×10^{-3}	2.7397×10^{-3}	One	6.1996×10^{-1}	8.9274×10^{2}	1.1934×10^{2}	3.3794	1.8750×10^{-2}
2.2280×10^{-3}	4.4192×10^{-3}	1.6130	One	1.4400×10^{3}	1.9250×10^{2}	5.4510	3.0244×10^{-2}
1.5472×10^{-6}	3.0689×10^{-6}	1.1201×10^{-3}	6.9444×10^{-4}	One	1.3368×10^{-1}	3.7854×10^{-3}	2.1003×10^{-5}
1.1574×10^{-5}	2.2957×10^{-5}	8.3793×10^{-3}	5.1948×10^{-3}	7.4805	One	2.8317×10^{-2}	1.5711×10^{-4}
4.0873×10^{-4}	8.1071×10^{-4}	2.9591×10^{-1}	1.8345×10^{-1}	2.6417×10^{2}	3.5314×10^{1}	One	5.5483×10^{-3}
7 3668×10^{-2}	1.4612×10^{-1}	5.3333×10^{1}	3.3065×10^{1}	4.7613×10^{4}	6.3649×10^{3}	1.8024×10^{2}	One

TABLE 5

Permeability values for the samples tested

Sample	K (cm. sec^{-1}) (At right angles)	K (cm. sec^{-1}) (Parallel)	Sample
1/27216 S	0.86×10^{-3}	0.12×10^{-2}	2/27217 L
73/27375 S	0.23×10^{-2}	$0\ 26 \times 10^{-2}$	74/27376 L
65/27377 S	0.85×10^{-3}	0.11×10^{-2}	66/27378 L
41/27302 S	0.22×10^{-2}	0.24×10^{-2}	42/27303 L
43/27304 S	0.64×10^{-4}	0.23×10^{-3}	44/27305 L
3/27218 S	0.24×10^{-3}	0.83×10^{-3}	4/27219 L
57/27318 S	0.76×10^{-4}	0.21×10^{-3}	58/27319 L
11/27226 S	0.84×10^{-5}	0.13×10^{-4}	12/27227 L
33/27294 S	0.26×10^{-6}	0.32×10^{-3}	34/27295 L
1/27379 S	0.10×10^{-3}	(Damaged)	2/27380 L
5/27383 S	0.41×10^{-3}	0.56×10^{-3}	6/27384 L
11/27389 S	Not recorded	0.17×10^{-5}	12/27390 L
21/27449 S	0.17×10^{-3}	0.26×10^{-3}	22/27450 L
23/27451 S	0.32×10^{-5}	0.30×10^{-4}	24/27452 L
25/27453 S	0.51×10^{-5}	0.15×10^{-4}	26/27454 L
27/27455 S	$0\ 56 \times 10^{-4}$	0.98×10^{-4}	28/27456 L
31/27459 S	Not recorded	Not recorded	32/27460 L
5/27461 S (cube)	0.12×10^{-5}	$0.54 \times 10^{\ 5}$	6/27462 L (cube)
12/27463 S (cube)	0.56×10^{-6}	0.10×10^{-5}	13/27464 L (cube)
15/27465 S (cube)	0.72×10^{-6}	0.19×10^{-5}	16/27466 L (cube)
5/27461 S (cylinder)	0.14×10^{-5}	0.11×10^{-4}	6/27462 L (cylinder)
15/27465 S (cylinder)	$0.46 \times 10^{\ 6}$	0.16×10^{-5}	16/27466 L (cylinder)

TABLE 6

Specification of Boreholes

Borehole	Depth (m)	Diameter (cm)	Obser-vations	Distance of the observations from the pumped well (m)	Drift cover (Boulder clay) (m)	Change of discharge rate (Times)	Depth of penetration of aquifer (m)	Approximate depth of the aquifer (m)
Upper Dunsforth	91.44	45.7	2	01 = 34.2 02 = 296	12.0	3	79 44	167.64
Ainderby Steeple	91.44	25.4	5	01 = 47.7 02 = 81.9 03 = 56.0 04 = 122.7 05 = 26.6	13.5	1	77.94	182.88

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