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Report No. 22

OIL IN GLAUCONITIC SANDSTONE AT LAKES ENTRANCE, VICTORIA

BY

R. F. THYER and L. C. NOAKES

Issued under the Authority of Senator the Hon. W. H. Spooner,
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LIST OF REPORTS

1. Preliminary Report on the Geophysical Survey of the Collie Coal Basin.—N. G. Chamberlain, 1948.
2. Observations on the Stratigraphy and Palaeontology of Devonian, Western Portion of Kimberley Division, Western Australia.—C. Teichert, 1949.
3. Preliminary Report on Geology and Coal Resources of Oaklands-Coorabin Coalfield New South Wales.—E. K. Sturmfels, 1950.
4. Geology of the Nerrima Dome, Kimberley Division, Western Australia.—G. J. Guppy, J. O. Cuthbert and A. W. Lindner, 1950.
5. Observations of terrestrialmagnetism at Heard, Kerguelen, and Macquarie Islands, 1947-48. (Carried out in co-operation with the Australian National Research Expedition, 1947-8.).—N. G. Chamberlain, 1952.
6. Geology of New Occidental, New Cobar and Chesney Mines, Cobar, New South Wales.—C. J. Sullivan, 1951.
7. Mount Chalmers Gold and Copper Mine, Queensland.—N. H. Fisher and H. B. Owen, 1952.
8. The Ashford Coal Province, New South Wales.—H. B. Owen, G. M. Burton and L. W. Williams, 1955.
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11. The Nelson Bore, Victoria; Micropalaeontology and Stratigraphical Succession.—I. Crespin, 1955.
12. Stratigraphy and Micropalaeontology of the Tertiary Marine Rocks between Adelaide and Aldinga, South Australia.—I. Crespin, 1955.
13. Geology of Dampier Peninsula, Western Australia.—R. O. Brunnschweiler (in press).
14. A Provisional Isogonic Map of Australia and New Guinea, showing Predicted Values for the period 1955-65.—F. W. Wood and I. B. Everingham, 1953.
15. Progress Report on the Stratigraphy and Structure of the Carnarvon Basin, Western Australia.—M. A. Condon, 1955.
16. Seismic Reflection Survey at Roma, Queensland.—J. C. Dooley.
17. Mount Philp Iron Deposit, Queensland.—E. K. Carter and J. H. Brooks (in press).
18. Petrology and Petrography of Limestones from the Fitzroy Basin, Western Australia.—J. E. Glover (in press).
19. Heard Island Magnetic Report.
20. Micropalaeontological Investigations in the Bureau of Mineral Resources, 1927-52.—I. Crespin.
21. Macquarie Island Magnetic Report.
22. Oil in Glauconitic Sandstone at Lakes Entrance, Victoria.—R. F. Thyer and L. C. Noakes, 1955.
23. Seismic Survey, Darriman, Victoria.—M. G. Garrett.
24. Sedimentary Control of Uranium Deposition in Northern Territory.—M. A. Condon and B. P. Walpole, 1955.

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Minister: SENATOR THE HON. W. H. SPOONER

Secretary: H. G. RAGGATT

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FOREWORD

The two papers which make up this Report were prepared as Reports (now Records) in 1944 and 1945, when Lakes Entrance was one of the few areas in Australia with a known oil potential. The papers were given a limited circulation at this time.

The revived interest in oil search in that area, as well as in many others throughout Australia and New Guinea, suggested the advisability of giving the papers a wider circulation. One deals entirely, and the other largely, with fundamental physical properties of oil-bearing rocks and with techniques developed for measuring those properties, and the papers have, therefore, a wider bearing than the geographical part of the title would indicate. It is hoped that the information thus made available may be of interest to those prospecting for oil in the Lakes Entrance area and elsewhere in Australia and New Guinea.

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INTRODUCTION

In 1942 the Commonwealth Government arranged to sink a vertical shaft to a depth of approximately 1200 feet to the oil-bearing glauconitic sandstone at Lakes Entrance, so that horizontal drill holes could be drilled in the sandstone for the production of oil. When the shaft reached a depth of 1117 feet it was desired for engineering and other purposes to test the micaceous marls and the glauconitic sandstone below the bottom of the shaft. It was decided to put down a diamond drill hole and to use the cores for the necessary testing. The drill hole passed through 80 feet of micaceous marls and 1 foot 10 inches of glauconitic marls, and penetrated 19 feet 2½ inches of glauconitic sandstone, without reaching the bottom of the sandstone. An index chemical (glucose) was added to the drilling water when the sandstone was being drilled.

This report deals mainly with the examination of the cores of glauconitic sandstone obtained from the drill hole. Most of the laboratory investigations on the cores were carried out at Canberra and included examination under ultra-violet light, some petrological work, and determinations of porosity and oil and water saturations. In addition, experiments were carried out at Lakes Entrance to determine the quantity of gas yielded by the Pilot and Imray Bores; and determinations of the glucose content of the samples of water extracted from six cores were made by Mr. W. R. Jewell of the Victorian State Laboratories, Melbourne. Experiments were made in Canberra to establish the dehydration characteristics of the glauconitic sandstone.

An attempt has been made to correlate much of the available data on the Lakes Entrance field which has a bearing on the Lakes Entrance oil project, and to provide a summary of the occurrence and distribution of oil in the glauconitic sandstone. From all this information it has been possible to make a tentative calculation of the probable oil content of that portion of the reservoir to which the data are applicable.

Finally the report includes a critical examination of the factors influencing the recovery of oil from the glauconitic sandstone by horizontal oil wells, and an estimate of the percentage of oil which might be recovered from a given area at Lakes Entrance.

DESCRIPTION OF THE SHAFT BORE

Drilling Procedure

The diamond drill hole, which will be referred to in this report as the Shaft Bore, was drilled from the bottom of the Lakes Entrance Oil Shaft. The object of the drill hole was firstly to provide solid cores of the rock underlying the shaft as a guide to sinking operations, and secondly to provide complete cores from the glauconitic sandstone from which reliable data on the occurrence and distribution of oil could be obtained.

An initial attempt to drill the hole from the collar of the shaft failed and the bore was finally drilled from the bottom of the shaft at a depth of 1117 feet below the shaft collar. A total of 101 feet was drilled, consisting of 80 feet of fine sandy micaceous marl containing four hard bands of limestone, followed by 1 foot 10 inches of sandy glauconitic marl and 19 feet 2½ inches of glauconitic sandstone. Core recovery from the micaceous marls was very low despite the care exercised in drilling, but the recovery rose to 82 percent in the glauconitic sandstone.

The glauconitic sandstone was cored in sections approximately 2 feet long, and most of the core wqs recovered in continuous lengths with small losses at the base of each section. The cores were 3 inches in diameter in the micaceous marls, but only 1⅛ inches in the glauconitic sandstone, because the bore had to be cased from the collar to the sandy glauconitic marl.

Water was circulated during drilling and an index chemical was introduced during the coring of the glauconitic sandstone, so that it would be possible to determine whether any of the drilling fluid entered the cores and if so to what extent. The index chemical used was glucose. It was introduced in a solution containing 62.5 lb. per 1,000 gallons of water. Mercuric chloride was added to the solution in the proportion of 1/50,000 to inhibit fermentation of the glucose. Most of the cores were dipped in merthiolate solution, strength 1/10,000, as a further precaution against fermentation.

Owing to the lack of space at the bottom of the shaft, the solution was mixed in 40 gallon drums at the No. 5 plat, about 200 feet above the drilling platform, and fed to the drill by gravity. The returned solution could not be used again and was allowed to drain into the bottom of the shaft, from which it was pumped to the surface. Samples of the solution were collected from each drum and combined to provide a representative sample of the drilling fluid used. The water from the solution was drawn from a garland in the shaft, and a sample was taken for analysis.

Treatment of Cores

The glauconitic sandstone was cored with AX core barrel fitted with an inner tube in which the core was retained. The drilling fluid circulated through the annular space surrounding the inner tube and thus minimised flushing of the core. Cores were withdrawn from the core barrel at the bottom of the shaft, placed in cylindrical metal containers[1] and carried to the surface. After preliminary examination and measurement of the cores they were wrapped in waxed paper and sealed in the containers.

The containers of three of the cores which showed noticeable traces of oil were soldered immediately and were not opened until the cores were required for examination in Canberra. The remainder of the containers, which were sealed with insulation tape, had to be opened on two occasions, once at Lakes Entrance and once at Melbourne, to allow inspection of the cores by the Lakes Entrance Executive Committee and by consulting engineers.

All the cores were exposed in Canberra when each section was cut into 3-inch lengths and placed in air-tight jars. Most of the cores were subjected to further exposure when the 3-inch sections were cut into discs $\frac{1}{4}$ inch thick for examination under ultra-violet light. Estimates have been made of the total length of time for which each core was exposed to the air after withdrawal from the core barrel, and these are indicated on the columnar sections, plate 2. The three cores in soldered containers suffered a maximum exposure of only 30 minutes, but the remainder of the cores were exposed for approximately

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1 The containers were approximately $1\frac{1}{2}$" in diameter and 2' to 2'6" long so that $1\frac{1}{8}$" cores, wrapped in waxed paper, fitted tightly into them.

50 minutes. The effect of this exposure on the liquid content of the cores will be discussed in a later section.

EXAMINATION OF CORES

Preliminary examination for Oil and Gas

When first examined at Lakes Entrance most of the cores showed patches of oil on their surface. The position and extent of each patch was noted because the oil appeared to indicate the position of oil-bearing sandstone. The amount of oil observed was usually sufficient to form a dark brown film on the surface of the cores. Oil was not observed dripping from any core, but where the oil film was thickest, drops of oil could be wiped from it with the fingers. On the whole there was little evidence of gas in the glauconitic sandstone. An intermittent stream of gas bubbles rose through the water in the bore hole during drilling, but less gas was encountered in the glauconitic sandstone than in the overlying micaceous marls, where definite surges occurred on two occasions and where the stream of gas bubbles was almost continuous. Occasionally small bubbles of gas were observed emerging through patches of oil on the surface of the cores, but no bubbles were observed emerging from non-oil-bearing sections. However, these bubbles were observed some minutes after the cores had been removed from the core barrel, and up to ¾ hour after the rock had actually been cut, so that they are no indication of the amount of gas originally held in the cores.

Examination under Ultra-Violet Light

Introduction

The fluorescent properties of crude and refined oils under ultra-violet light are well known and have been used in America and Germany in the examination of drill cores. This method provides a simple and effective means of detecting very small quantities of oil, which might otherwise be overlooked, and is particularly effective in establishing the distribution of oil in a drill core in which the oil content is low and irregular.

The presence of oil in the glauconitic sandstone could not be reliably detected under ordinary light because of the dark green colour of the rock and because the oil possibly occurs in a finely divided state. Cores from the Shaft Bore, Lake Entrance, were first examined under ultra-violet light at the suggestion of Mr. P.B. Nye, and the method proved so effective that a technique was developed by which the distribution of oil could be plotted to scale on a longitudinal section of each core.

The cores were examined under two types of ultra-violet lamp: the "Mineralight" lamp and the "Mercra" lamp. The "Mineralight" equipment consists essentially of a coiled quartz tube in which a cold electric discharge through mercury vapour takes place. Electric power may be obtained either from batteries or from the 240 volt A.C. main supply with suitable transformer. The lamp is fitted with a filter constructed from a type of glass known as "Red Purple Corex A No. 986". The ultra-violet light emitted mostly corresponds to a wave length of 2537 Å.

The "Mercra" lamp provides a source of near ultra-violet light and no appreciable amount is emitted below a wave length of about 3100 Å. The equipment consists of a mercury vapour lamp enclosed in a dark glass envelope, which absorbs most of the visible light. The lamp which was used is rated at 80 watts and, in association with a choke coil, operates from the 240 volt A. C. main supply.

Crude and refined oils fluoresce under both lights but the fluorescence is distinctly brighter under the "Mercra" lamp, which was therefore used throughout the investigation. Under this lamp, portions of the core which contain oil show a yellow fluorescence which varies in intensity from a bright golden yellow to a pale yellow-brown, the intensity being apparently dependent upon the proportion of the rock surface actually covered with oil and on the thickness of the oil films.

Various tests were carried out to ensure that this fluorescence was actually produced by crude oil in the core and not by any of the other substances which could be present, such as glucose solution, mercuric chloride and merthiolate. Each of these substances was tested under ultra-violet light and showed no fluorescence. Next, a few fragments of fluorescent and apparently oil-bearing core were placed in a test tube stoppered with cotton wool. Neither tube nor stopper showed any fluorescence under ultra-violet light. The test tube was heated for a few minutes, and then cooled, and both tube and stopper bore a condensate which gave a bluish-white fluorescence typical of oil distillates. The fragments of core were also examined after heating and found to have lost all fluorescence under ultra-violet light. A further experiment was carried out using "Shellite" solvent to remove oil from a portion of fluorescent core, and after drying at low temperature, the core no longer showed fluorescence. Finally a portion of the core showing no fluorescence was impregnated with Lakes Entrance oil and the resulting fluorescence was identical with that found elsewhere in the cores.

Procedure

When ultra-violet light examinations were initiated, some of the cores from the Shaft Bore had been withdrawn from the sealed tins and cut into short sections (approximately 3" long), and each section was sealed in a 4 oz. airtight jar. Other cores remained intact in the sealed metal containers. The examination under ultra-violet light was carried out in a dark room and care was taken that each core, or section of a core, should be exposed to the air as little as possible.

In the first series of tests the external surfaces of the cores were examined and the distribution and intensity of fluorescence plotted on a columnar section of half natural size.

During this examination it was found that the patches of oil originally observed on the surface of the cores could no longer be discerned under ordinary light. The ultra-violet light showed that oil had been absorbed by the waxed paper in which the cores were wrapped. However, it was found that the patches of oil on the surface of the cores were visible under ultra-violet light. The complete surface of the core was portrayed in three columnar sections which were obtained by placing the core in a core holder in which it was held horizontally and could be rotated about the horizontal axis. The core was viewed from above and the distribution and relative intensity of the fluorescence sketched on to the columnar section. The core was then rotated 120^{o} in an anti-clockwise direction to the second position, examined, and similarly rotated to obtain the third position. The top and bottom of each core were also examined and the fluorescence noted.

The resulting core diagram provided a clear picture of the distribution of oil on the surface of the cores. However, subsequent examinations, using an improved method, showed that these diagrams, although they indicated the principal oil-bearing zones, did not present a true picture of the original distribution of oil in the rock because, in many cores, oil which had welled out of portions of a core during drilling and recovery had either gravitated down the surface of the core, or had been spread by the core catcher over a larger area than it originally occupied. The distribution of oil on the surface could also be affected during handling or by movement within the sealed metal containers.

In the procedure finally adopted, each core or portion of core was cut into thin discs, each about $\frac{1}{4}$ inch thick, by means of a specially constructed core cutter. To facilitate the orientation of these discs a heavy pencil line was drawn longitudinally on the surface of the core before it was cut. Each disc cut from the core could then be placed on a sheet of paper in correct orientation. The suite of discs so obtained was examined under ultra-violet light, and the fluorescent areas showing on each were plotted on a sheet bearing a series of circles representing cross-sections of core at half natural size. Both obverse and reverse sides were examined to provide two series of diagrams from which the distribution of oil in the core could be clearly established.

The diagrams showed that the oil content of the sandstone varied widely. Some sections of the cores showed no trace of oil; some carried isolated patches of oil; others showed definite oil zones in which the oil-bearing portions could be traced with definite vertical continuity through a number of adjacent discs.

For the purpose of portrayal, the sandstone was classified into the following five grades, based on the proportion of the rock which showed fluorescence:

(1) Oil-bearing patches covering 75% or more of the core in cross section and vertically continuous;

(2) Oil-bearing patches covering 50 to 75% of the core in cross section and vertically continuous;

(3) Sections of core carrying numerous small oil-bearing patches with no vertical continuity;

(4) Sections of core carrying a few oil-bearing patches;

(5) Core carrying no oil in cross sections.

From these diagrams, columnar sections of cores 20 to 28 inclusive were prepared; sandstones of various grades as established by ultra-violet light were projected on to a section representing a vertical plane passing through the centre of the core. These sections are shown on plate 2. A generalised columnar section of the 192 ft. of glauconitic sandstone penetrated by the bore, and showing the distribution of oil, was then prepared from the individual columnar sections and is shown on plate 1.

DISTRIBUTION OF OIL

Oil-bearing Zones in the Shaft Bore

The various core diagrams show that oil is distributed irregularly over the whole 188½ inches of core recovered and that an aggregate of only 67¾ inches, or 36 percent, of the core has no discernible trace of oil. By using the classification shown above, but combining grades 3 and 4, the following aggregate thicknesses are obtained.

	Total thickness	% of total core recovered
Grade 1	22 inches	11.7
Grade 2	16¾ "	8.9
Grade 3 and 4	82 "	43.4
Grade 5	67¾ "	36
	188½ inches	100.0

In the sandstone of grade 1 an aggregate of only 10 inches is almost entirely oil-bearing and it is probable that most of the oil produced can be attributed to these 10 inches. However, it is believed that some oil may be produced from grade 2 sandstone although the yield would probably be small and the recovery relatively low. It is assumed therefore that oil is produced from sandstone of grades 1 and 2, but not from the other grades. On this basis the aggregate thickness of sandstone from which oil might be produced is 38¾ inches, distributed in five well defined zones (Nos. 1 to 5) shown on plate 1 and in the following table.

Zone	Limits of zone depth below top of Glauconitic Sandstone	Aggregate thickness of sandstone from which oil might be produced	% of total thickness of oil producing sandstone
1	1' 8" - 3' 8"	11.0 ø	28.0
2	7' 7¼"- 9' 0½"	12.0 θ	30.2
3	11'11" -12' 7"	8.0	20.2
4	13' 7½"-13'10"	2.5	6.3
5	18' 8½"-19' 2½"	6.0	15.3
		39.5	100.0

Zones 4 and 5 are minor ones consisting almost entirely of grade 2 sandstone and, although they may possibly yield some oil, appear too thin and isolated to warrant inclusion in the calculation of total oil content. This is supported by the close parallel, discussed below, between oil zones in the Pilot and Shaft bores which suggests that zones 4 and 5 extend into the Pilot bore, where, however, bailing tests have shown that their yield is insignificent. The probable effective thickness of producing sandstone is therefore considered to be 31 inches, comprising zones 1, 2, and 3, measuring 11 inches, 12 inches, and 8 inches respectively.

Comparison of Shaft and Pilot Bore Logs

The productive zones as defined by the Pilot Bore log are shown in plate 1 and are listed below for comparison with the zones considered capable of production in the Shaft Bore.

Pilot Bore Productive Zones	Shaft Bore Zones considered capable of production.	Zone Numbers
0' - 4'0"	1' 8" - 3' 8"	1
8'3" - 12'0"	7' 7¼"- 9' 0½"	2
	11'11" -12' 7"	3
14'4" - 15'6"	13' 7½"-13'10"	4
16'7" - 18'7"	18' 8½"-19' 2½"	5

Only two productive zones (the upper two shown in the table above) were originally established from the Pilot Bore log, but reconsideration of the production data, in the light of information provided by the Shaft Bore,

ø Including 1" not recovered but included because it occurs in the centre of Zone 2.

θ Excluding ¼" of grade 1 sandstone included in the 38¾" of grades 1 and 2 sandstone.

indicates that the second zone from the top in the Pilot Bore includes both zones 2 and 3 from the Shaft Bore, and that there are probably two very minor oil-producing zones in the lower section of the Pilot Bore, which correspond approximately with zones 4 and 5 of the Shaft Bore. The evidence for the existence of zones 4 and 5 can be seen in the production graph accompanying a report on the Pilot Bore by L.C. Noakes (1945). On the graph, which shows the average production of dry oil, emulsion, and water per core section, the rate of decline of dry oil produced from the sandstone above the base of core section 8 decreases markedly after section 9 had been cored, and indicates a possible small producing zone (zone 4). Production actually increased slightly after section 11 had been cored, and indicates a possible zone 5. However, the combined production from zones 4 and 5 is only a small fraction of the total production from the Pilot Bore.

The above table shows that, allowing for errors in measurement in the two bores, the productive zones[x] are comparable within geological limits. For this reason, there is justification for using information gained from production tests at the Pilot Bore to aid in interpreting the log of the Shaft Bore, where oil was produced but no bailing tests could be carried out. Since the bailing tests from the Pilot Bore indicate that no significant oil-producing zone exists between 12 feet and 23 feet below the top of the sandstone, production of oil from zones 4 and 5 in the Shaft Bore, which occur between 12' 7" and 19'2½" below the top of the sandstone, may be regarded as insignificant. It is considered, therefore, that in the upper 19 feet of glauconitic sandstone in the vicinity of the Lakes Entrance shaft the productive oil zones are restricted to the top 13 feet.

General Distribution of Oil in the Glauconitic Sandstone

In general, the distribution of the oil-bearing sandstone as indicated by ultra-violet light is most irregular. Examination of the discs indicates that none of the core consists entirely of oil-bearing sandstone. An aggregate thickness of approximately 10 inches of core is almost entirely composed of oil-

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x Productive zones refers to zones established by bailing tests in the Pilot Bore and zones considered capable of production in the Shaft Bore.

bearing sandstone; but even this portion contains small patches of barren rock, and in the grade 2 sandstone, the oil-bearing portions apparently occur in patches which constitute about half the rock. Furthermore, a complete gradation may be seen in the cores from barren sandstone, through sandstone carrying a varying number of oil-bearing patches, to rock almost entirely composed of oil-bearing sandstone with only small patches of barren rock

The oil-bearing zones established in the Pilot and Shaft Bores occur on approximately the same horizons within the sandstone; this strongly suggests horizontal continuity over at least 100 feet, and probably over a considerably wider interval. This is substantiated to some extent by evidence provided by the logs of other bores on the field. Table 1 shows the distribution of oil as recorded in the logs of eight bores situated at distances up to 6800 feet from the Lakes Entrance Shaft, and the relative position of each bore is indicated by bearing and distance from the Shaft itself. However, considerable caution is necessary in interpreting and correlating older bore logs because many were not prepared under technical supervision, and because the positions of oil zones were not determined by critical bailing tests. An additional possible source of error lies in the logging of the top of the glauconitic sandstone. In some bores the sandy glauconitic marl overlying the sandstone appears to have confused drillers and may have given rise to errors ranging up to several feet in the logging of the top of the formation.

Of the bores listed in Table 1, Nos. 8 and 10 Government bores were reliably logged, but no details have been found regarding the supervision of the remaining six. However, the logs show fairly close agreement and appear to establish at least two oil-bearing sections. The upper section lies at the top of the sandstone and ranges from 9 to 14 feet in thickness; the lower section is commonly situated at or below 24 feet from the top of the sandstone and apparently varies considerably in thickness.

It may therefore be concluded that, over a large area, the glauconitic sandstone contains oil-bearing zones in its upper 13 feet. A relatively barren section lies between 13 and 24 feet; but at, or below, 24 feet an additional oil zone may be expected. The Pilot, Shaft, and Imray bores have not penetrated the glauconitic sandstone far enough to test the lower oil zones, but they have established the details of the distribution of oil in the upper section. Unfortunately, most of the other bore logs provide insufficient data for detailed comparisons with the Pilot Bore, but progressive bailing tests during the drilling of No. 8 Government bore established an oil distribution strikingly similar to that established in the Pilot and Shaft Bores, 6800 feet away. The zones established by these three bores are shown in the following table:

Major Oil Zones Established by Pilot, Shaft and No. 8 Government Bores.

Pilot Bore.	Shaft Bore.	No. 8 Government Bore.
0' -4' 0"	1' 8" - 3' 8"	0' - 2'
8' 3" -12' 0"	7' 7¼"-12' 7"	5' - 9' 3"
Not penetrated	Not penetrated	37' - 40'

Sources of Error

In applying the results of the examination under ultra-violet light to the calculation of oil content of the glauconitic sandstone due consideration must be given to the errors that may be involved.

In the first place, core recovery from the 19' 0½"✝ of glauconitic sandstone drilled amounted to only 82.5%, or 15'8½", so that the cores provide no record of 3' 4" of the formation. This loss is unfortunate, but on analysis it is not as serious as the figures suggest. The length and position of the sections from which no core was obtained are as follows:

Section.	Core No.	Depth below top of Glauconitic Sandstone	Loss in inches.
1	20	2" - 1' 8"	18
2	21	4' 2" - 4' 2½"	½
3	22	6' 2½" - 6' 5"	2½
4	23	8' 5" - 8' 6"	1
5	24	10' 6" - 10' 7"	1
6	25	12' 7" - 13' 6"	11
7	26	15' 6" - 15' 9"	3
8	27	17' 9" - 18' 0"	3

There is no reason to believe that any of these sections were lost because they consisted of, or included, incompetent strata which failed to core. Section 1 was lost because core 20 did not break off when the core barrel was raised, but remained standing in the hole. Recovery of the core was attempted but only the basal 6 inches survived the process. A similar accident occurred with core 21, but a "core lifter" was fashioned from a cylindrical tin and all the core was recovered.

✝ Excluding the uppermost 2 inches of hard glauconitic sandstone, recovered at the base of core 19, but not included in the investigations.

Section 6, from the base of core 25, was also lost by accident. The core barrel was blocked to take 2 feet of core, but 2 feet 11 inches of formation were drilled. The first 2 feet were recovered and the remaining 11 inches were ground away. The remainder of the lost sections Nos. 2, 3, 4, 5, 7 and 8 represent minor losses at the base of cores, incurred during the process of dry blocking and breaking the cores before withdrawing the core barrel.

Therefore it may be assumed that those sections of core that were lost are essentially similar to those recovered, and do not represent or include any unrecorded phases of the glauconitic sandstone.

A further analysis of the losses shows that Nos. 2, 3, 5, 7, and 8 occur in unproductive sandstone, bounded above and below by rock which is barren or which carries only traces of oil. Section 4, consisting of 1 inch at the base of core 23, lies in the centre of an oil-bearing zone and has been included in the productive sandstone of zone 2. Any significant loss of oil-bearing sandstone is, therefore, limited to sections 1 and 6.

Section 1 consists of the upper 18 inches of core 20 and probably includes some sandstone capable of producing oil since the basal 6 inches recovered consists of productive sandstone from zone 1 (see plate 2). However, it is probable that the sandstone at the top of core 20 is unproductive since the 2 inches of glauconitic sandstone recovered at the base of core 19 showed no trace of oil. Section 6, consisting of 11 inches at the base of core 25, almost certainly includes some productive sandstone forming the base of zone 3, but no allowance for this has been made in determining the thickness of the zone. The total loss in core from sections 1 and 6 amounts to 29 inches, but unfortunately there is no reliable basis for estimating how much of this was productive, and it is therefore not practicable to apply a correction to the figure of 31 inches established for the aggregate thickness of productive sandstone. The calculation of total oil content will, therefore, be based on the measured 31 inches of sandstone, all of which has been examined and tested for oil, and not on an estimated total figure involving assumptions in both thickness and oil content of sections not recovered. Because of this, the figures for oil content will tend to be low rather than high.

A second source of error lies in applying data obtained from the Shaft Bore to a wide area of glauconitic sandstone. The thickness of the individual oil zones and the aggregate thickness of productive sandstone in the uppermost 13 feet of the formation may vary considerably from place to place and results obtained from any one hole may not necessarily represent the average for the area as a whole.

The Pilot Bore is the only other drill hole in which an attempt was made to determine accurately, through saturation tests on drill cores, the aggregate thickness of productive sandstone, but this bore is only 100 feet from the Shaft Bore and the order of accuracy of the determinations was not high, owing to the fragmental nature of the cores recovered. However, the figure obtained from the Pilot Bore, 24 to 30 inches, is not markedly different from the minimum 31 inches established at the Shaft Bore. Another possibly significant feature is that the daily oil yield from the Pilot Bore is almost the same as that from Imray Bore, situated 600 feet to the west. This suggests that the reservoir characteristics at the two bores are comparable.

For the purpose of calculation of oil content it will be assumed that the aggregate thickness of productive sandstone in the upper 13 feet of the formation is approximately 31 inches. A true average figure for the area involved cannot be obtained from the data available and therefore any calculations based on a thickness of 31 inches may involve an error in thickness whose magnitude is not known, but which is probably not greater than 40 percent.

THE GLAUCONITIC SANDSTONE

General

The unbroken cores recovered from the Shaft Bore provide a much clearer picture of the glauconitic sandstone than did the fragmentary material recovered from the Pilot Bore. An examination of the Pilot Bore cores obtained with a Baker core barrel suggested that the glauconitic sandstone was not a homogeneous formation but contained at least three types of sandstone, varying in grain size and texture. It was also considered that these types graded one into another with no clear lines of demarkation.

In general, the cores from the Shaft Bore confirm these earlier observations, although the variations within the sandstone are not dependent upon changes in grain size - at least not to the extent originally postulated. In macroscopic examination, cores from the Shaft Bore consist mainly of fine-grained calcareous glauconitic sandstone. The rock is fairly tough and generally reacts slightly with dilute hydrochloric acid. Two variations from this normal type can be detected:

1. More highly calcareous rock which is distinctly tougher than the remainder of the sandstone, presumably owing to the higher percentage of calcium carbonate in the matrix, and which occurs in bands or lenses up to three or four inches thick.

2. A somewhat softer and more friable sandstone which occurs in numerous irregular bands and patches but which differs little in appearance from the normal glauconitic sandstone. These variations do not commonly occur in clearly discernible bands, but tend to grade one into the other. Some of the harder bands are clearly defined, but as a rule the more friable material can only be detected by scratching the rock with a knife. The more friable sandstone may also appear darker in colour but, in some cores at least, this is due to the presence of oil.

In some of the Pilot Bore cores there appeared to be evidence of numerous thin partings in the glauconitic sandstone, but cores from the Shaft Bore show no evidence of any consistent partings in the rock. Most cores of the sandstone were recovered in unbroken lengths, but others were recovered in two or three pieces which appeared to have parted along horizontal planes which may be bedding planes. With the exception of these and of one small fracture at the base of core 22 (which may have been caused by drilling), there is no evidence in the cores of faulting, jointing, or cracking in the glauconitic sandstone.

Petrology

A petrological study of glauconitic sandstone has been made by Dr. F. L. Stillwell (1944), who examined samples of sandstone from No. 10 Bore, Lakes Entrance. From his description, the specimens examined appear comparable with the normal type of glauconitic sandstone found in the Shaft Bore. In the report on his investigations Stillwell described the mineral assemblage as follows:

> "The thin sections revealed that the specimens from the different horizons were closely similar in mineral composition and texture, but varied slightly in the proportion of the various constituents. They consist of numerous smooth surfaced oval and sub-angular grains of glauconite dispersed through a fine-grained felspathic sandstone which consists of quartz, orthoclase, oligoclase and abundant biotite with minor amounts of muscovite, iron ore, leucoxene, tourmaline, zircon and apatite, and in places calcite, cemented by a greenish to greenish-yellow isotropic substance, presumably a glauconitic mud."

Stillwell's study showed that glauconite constitutes a significant proportion of the rock - the glauconitic mud alone constitutes over 50 percent in some specimens. Much of the glauconite was altered before or during lithification to limonite and ferruginous clay, and normal green glauconite and altered brown glauconite occur in about equal proportions.

Cores from the Shaft Bore provide additional data on the petrology of the sandstone, since, by means of the ultra-violet lamp, oil-bearing and non-oil-bearing portions of the rock can be isolated and examined. A complete petrological and petrographical study of these cores has not been attempted, but as much as possible has been done in the available time, and the results suggest a logical explanation for the distribution of oil within the sandstone. Many fragments of oil-bearing and non-oil-bearing sandstone were compared under the microscope and other samples were ground to allow a closer comparison of the mineral assemblage to be made.

Comparison of pieces of oil-bearing sandstone with barren rock shows no apparent difference in mineral content or grain size. In one or two pieces of oil-bearing rock there may have been a slight concentration of larger grains, but detailed grain-size tests would be necessary to confirm this.

But, under the microscope there is a marked difference in appearance between oil-bearing and barren sandstone. Oil-bearing sandstone possesses a relatively open, even spongy texture, whereas barren sandstone - the normal type described above - appears tightly cemented and shows comparatively few openings. The explanation appears to lie in the relative amounts of matrix in the two rock types. The same mineral assemblage is present and the grain size is approximately the same in both, but whereas one rock is tightly cemented the other has many open pore spaces. This may explain why oil-bearing sandstone is more friable than the barren rock.

The principal cementing materials in the glauconitic sandstone are glauconitic mud and calcium carbonate. As a rule both rock types show some reaction with dilute hydrochloric acid and there appears to be no signigicant variation in carbonate content between oil-bearing and barren rock. On the other hand, the amount of glauconitic mud present in oil-bearing sandstone appears to be lower than in barren rock and on this account some fragments of productive sandstone appear lighter in colour under the microscope. The composition of this so-called glauconitic mud is not known but it is presumed to consist mainly of glauconite in various stages of alteration, and fine clay material.

From appearances alone one would expect the oil-bearing sandstone to possess a distinctly higher porosity and permeability than the barren rock. No permeability tests have yet been made on these cores, but porosity tests on selected samples show no significant variation between the two rock types. This presented a definite anomaly before the possibility that planar water was present in the glauconitic mud was taken into account. Planar water and its significance in porosity determination are discussed in a later section.

Origin of the Oil Zones

The general distribution of oil in the glauconitic sandstone indicates that the more open-textured type of sandstone, which now carries oil, is consistently found on certain horizons, and this in turn suggests that the principal factor controlling its formation was a depositional one.

One suggestion is that the production or supply of glauconitic mud during the deposition of the sandstone was not constant, but varied with time and place. The result was a sandstone in which the degree of cementation varied with the supply of fine clayey material to form the matrix. Where glauconitic mud was relatively plentiful, a clayey matrix formed in the rock and swelled with planar water and gave rise to a tightly bonded glauconitic sandstone of very low permeability. This has been termed the normal type of glauconitic sandstone and now carries no trace of oil. Where the supply of glauconitic mud was irregularly distributed the resulting sandstone was not entirely cemented, but included patches of rock with relatively little matrix, in which traces or patches of oil may now be found. Finally, where the supply of glauconitic mud was relatively low, beds, lenses, or large patches of poorly cemented sandstone were formed; and these on account of their relatively high permeability and actual proosity ultimately became the principal reservoirs for oil.

It is difficult to determine the factors controlling the distribution of glauconitic mud since little is known about its constituents and even less about the diagenesis of the sandstone itself. In some shelf sediments bearing glauconite, Galliher (1939) cites "a gradual change in facies from biotite-rich sands fairly near shore to mixed glauconite-mica silty sand further off shore and a little deeper, thence progressively to glauconitic muds at a depth of about 100 fathoms". The glauconitic sandstone at Lakes Entrance was apparently deposited off shore as a silty sand in an anaerobic or reducing environment which allowed the glauconite to form. Under these conditions numerous factors could control the supply and distribution of colloidal and silty material, but further conjecture can serve no purpose until these factors are better understood and the constituents and properties of the glauconitic mud are better known.

If the above deductions are correct it follows that the glauconitic sandstone as a whole is not an oil reservoir, but that it contains oil in a series of thin stratigraphical traps. The horizontal extent of any one of these beds or lenses has not been determined, but their form, lithology, and distribution suggest that they occur as a series of irregular lenses on fairly definite horizons within the formation.

SOURCE OF THE OIL

The source of the oil found in the glauconitic sandstone is not known, but migration from unknown source beds lying to the south has been suggested. However, the migration theory is difficult to envisage if the stratigraphical traps within the sandstone are disconnected and separated by rock of such low permeability. An alternative hypothesis, in which the oil is assumed to be of local origin, is therefore suggested.

The work of the Commonwealth Palaeontologist, Miss Irene Crespin, indicates that the beds with the highest fossil content in the Tertiary sequence below the Balcombian stage at Lakes Entrance are the upper micaceous marls and the glauconitic sandstone, both of which are included in the Janjukian Stage. The upper marls contain numerous foraminifera and mollusca with some bryozoa. The glauconitic sandstone contains large mollusca, abundant fish remains in the form of coprolites and fish scales, and foraminifera referable to species found in the marls. Between the glauconitic sandstone and the upper marls are 150 to 200 feet of fine sandy micaceous marls in which organic remains are scarce.

Traces of oil have been found in the upper marls, but migration of oil from these beds through the barren sandy marls to the glauconitic sandstone below appears unlikely. On the other hand, there seems no reason why oil should not have originated in the glauconitic sandstone. The eventual concentration of most of this oil in a series of major and minor stratigraphical traps within the sandstone could be brought about by the gradual compaction of the rock - a process during which oil would accumulate in the sections of the sandstone with a relatively high permeability. It would be difficult or impossible for oil, once collected in an isolated lens of more permeable sandstone, to migrate outwards into rock of low permeability and the oil would thus remain trapped.

THE SATURATION TESTS

Introduction

The apparatus used and technique employed were the same as for the tests on core samples from the Pilot Bore and, as they have been described fully in the report (Thyer, 1945a) on those tests, the description will not be repeated here.

The method is one of extraction in which a sample of known weight is held in an extraction thimble in a suitable solvent at approximately 100°C, and its water content is evaporated, condensed, and collected in a graduated tube, while at the same time the solvent flows through the sample in the thimble, dissolving and removing the oil. When the extraction is complete (usually after 10 hours) the thimble is removed, dried at 90°C, and weighed. The total loss of weight is equal to the combined weights of the water collected and the oil lost. The experiment is completed by determining the pore volume of the dried sample by the method previously described (Thyer, 1945a) and the water and oil contents are then expressed as percentage saturations, i.e. the percentage of the volume of the pores filled respectively with water and oil.

That portion of the pore volume not filled with water or oil is filled with gas but the experiment does not give any indication of the nature of this gas.

The porosities determined from the measurements of pore volumes were generally comparable with those determined previously on samples from Bore No. 10 (Thyer, 1944) and the Pilot Bore (Thyer, 1945a) and ranged from 35 to 45 percent. The quantity of liquid extracted from the specimens was sufficient to fill from 70 to 99 percent of the pore spaces.

Before proceeding to a general discussion of the results, however, it is proposed to examine critically the relation which the quantities of water, oil and gas found experimentally bear to the quantities of these fluids that were present in the samples when they were in place in the reservoir. It is proposed also to examine critically the relation that the porosities, as determined from the pore volumes of dry samples, bear to the porosities of the sandstone in situ.

The Water

There are three main reasons why the quantity of water extracted from the samples might differ from the quantity that was present in them before the glauconitic sandstone was drilled, namely -

1. Drilling water may have entered the core samples during drilling.
2. The samples may have lost water through evaporation.
3. The decrease in fluid pressure in the cores after drilling may have caused a change in the amount of water in the cores.

Effect of Drilling Water

The cores from which the samples were taken were obtained by means of a diamond drill in which water circulated during drilling operations; and there was a possibility that drilling water might have entered the cores or flushed out some of their fluid content. In order to determine the extent if any, to which drilling water entered the cores, an indicator chemical, glucose, was added to the drilling water and six pieces of core were later analysed to see if they contained any glucose. A small quantity of mercuric chloride was added to the glucose solution to inhibit fermentation. The strength of the glucose solution used was 0.625 percent by weight of glucose and the sensitivity of the analytical method used was such that if 1 percent of the pore spaces of the cores analysed had been filled by drilling water then the glucose in the cores could have been detected. The analysis was done by Mr. W. R. Jewell, Research Chemist of the Victorian State Laboratories. Six pieces of core each 3 inches in length were submitted for test, but in only two could any glucose be detected and then only in traces. The traces were less than 1 mg., indicating that at the most 1 percent of the water content of the cores was drilling water containing 0.625 percent glucose. The cores submitted for analysis were not examined under ultra-violet light to determine whether or not they contained oil, but their selection was based on the original logging of the cores in which sections carrying patches of oil were noted. It is believed that the samples selected for glucose analysis included some that contained oil and that they were more or less representative of the whole range of saturations.

From the results of the analyses it has been concluded that drilling water has not significantly contaminated or flushed cores and that the water extracted from the samples does not include any drill water.

Effect of evaporation

It is certain that during the time that the cores were exposed to the air a small part of their water content evaporated - the amount depending on the time of exposure and on atmospheric conditions.

The cores were first exposed when they were taken from the core barrel prior to being wrapped in waxed paper and sealed in air-tight containers. The loss during this time would be small. Some of the cores were later temporarily removed from their containers for examination at Lakes Entrance, Melbourne and

Canberra. The total time of the above exposures was probably less than 30 minutes. The cores were later removed from their containers, cut into 3-inch lengths and sealed in air-tight jars, and finally most of the 3-inch lengths were cut into discs about ¼ inch thick and examined under ultra-violet light.

The total time of exposure for each sample has been estimated, and the maximum was of the order of 60 minutes. It is evident that the loss of water through evaporation would be greatest during the time that the 3-inch core sections were cut into thin discs and exposed for examination.

In order to determine the extent of this loss a test was made on three samples each comprising about four discs of glauconitic sandstone which had been saturated by soaking them in water. The discs were placed on watch glasses and exposed to the air. They were weighed at half-hourly intervals to a total of 5 hours, and it was found that they lost water at a relatively uniform rate equal to approximately 2 percent of their initial moisture content per half hour.

It is believed, however, that the loss of water by evaporation during the time of exposure was greater than the results of this test would seem to indicate.

This belief is supported by the saturation results on those samples which contained no oil. It is assumed that, in situ, such samples were completely saturated with water. Testing showed that those samples which had been exposed for the longest time had the lowest water saturations, thus suggesting that the difference from 100 percent was principally due to loss of water through evaporation. This difference ranged from 1 to 10 percent and corresponded to almost twice the loss that would have been expected from the results of the test described above. During the test, however, the discs of sandstone remained on the watch glasses, whereas during examination under ultra-violet light, they were laid on paper and absorption by the paper may have accounted for additional loss.

<u>Effect of Decrease in Fluid Pressure</u>

It was shown in an earlier report (Thyer, 1945B) that the fluid pressure in the glauconitic sandstone intersected by the Pilot and Imray Bores is of the order of 600 lb per square inch, and it will be shown later in this report that there is evidence that under reservoir conditions the oil has some gas dissolved in it.

It is evident therefore that when the pressure of the fluids in the core is reduced by drilling from 600 lb per square inch to atmospheric-

(a) the fluids will expand and some may be forced from the cores;

(b) gas may come out of solution and force liquids from the cores.

It is believed that no free gas exists in the reservoir and that there has been no significant loss of water or oil through expansion because the expansion coefficients of liquids are small. On the other hand there is fairly definite evidence that gas has come out of solution from the oil and forced liquids from the cores. The fact that the liquid produced from the oil zones in the neighbouring Pilot and Imray Bores is over 90 percent oil is taken as evidence that the liquid forced out of the cores by relief of pressure will also be over 90 percent oil. It has been estimated that the amount of water lost by the cores owing to the decrease in fluid pressure from 600 lb per square inch to atmospheric would represent less than 1 percent water saturation.

Conclusions on Water Lost by Cores

It may be concluded from the above that the quantity of water in the samples is less than was present in the samples when they were in place in the glauconitic sandstone, the loss being principally due to evaporation. However, another factor which must be considered is whether or not the water collected during extraction at 100°C contains any appreciable quantity of water of crystallisation or water from any source other than from the interstitial spaces. This will be discussed in the next section.

Source of Water Extracted

It is believed that the water collected during extraction at 100°C was predominantly free water, i.e. not chemically combined in any of the minerals in the sandstone; but some of it may possibly have been water of crystallisation of one or more hydrated minerals in the sandstone.

It was shown earlier in this report that the glauconitic sandstone contains a few hydrated minerals of which glauconite, ferruginous clay (derived from alteration of glauconite), and other alumino-silicates which may constitute part of the glauconitic mud, form a significant proportion of the rock. It is proposed therefore to discuss the dehydration properties of glauconite and clay.

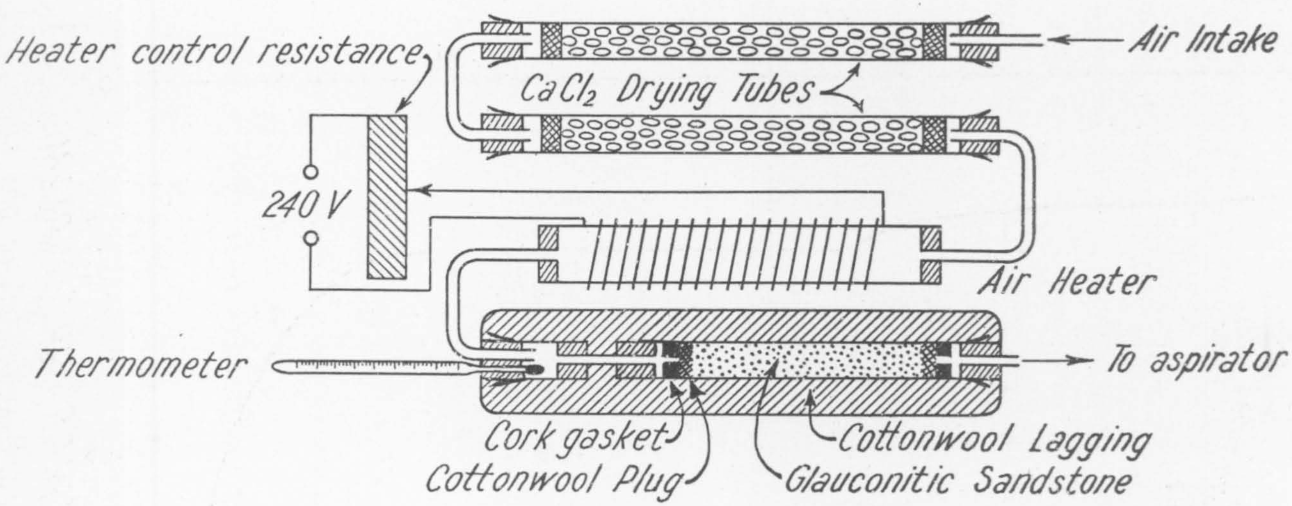
Dehydration of glauconite - According to Ross (1926) and Takahashi (1939) who have published dehydration curves for this mineral, dehydration begins at about 70°C, but between this temperature and 100°C, the temperature to which the samples were subjected in the extraction apparatus, the weight lost by their sample was less than 0.5 percent. However, much of the Lakes Entrance glauconite has undergone alteration and it is not certain that dehydration of the altered glauconite would begin at a temperature as low as 70°C. In addition it was possible that the sandstone contained minerals other than glauconite which lost water of crystallisation at low temperatures.

It was decided therefore to carry out tests to determine the way in which the glauconitic sandstone as a whole lost water at various temperatures.

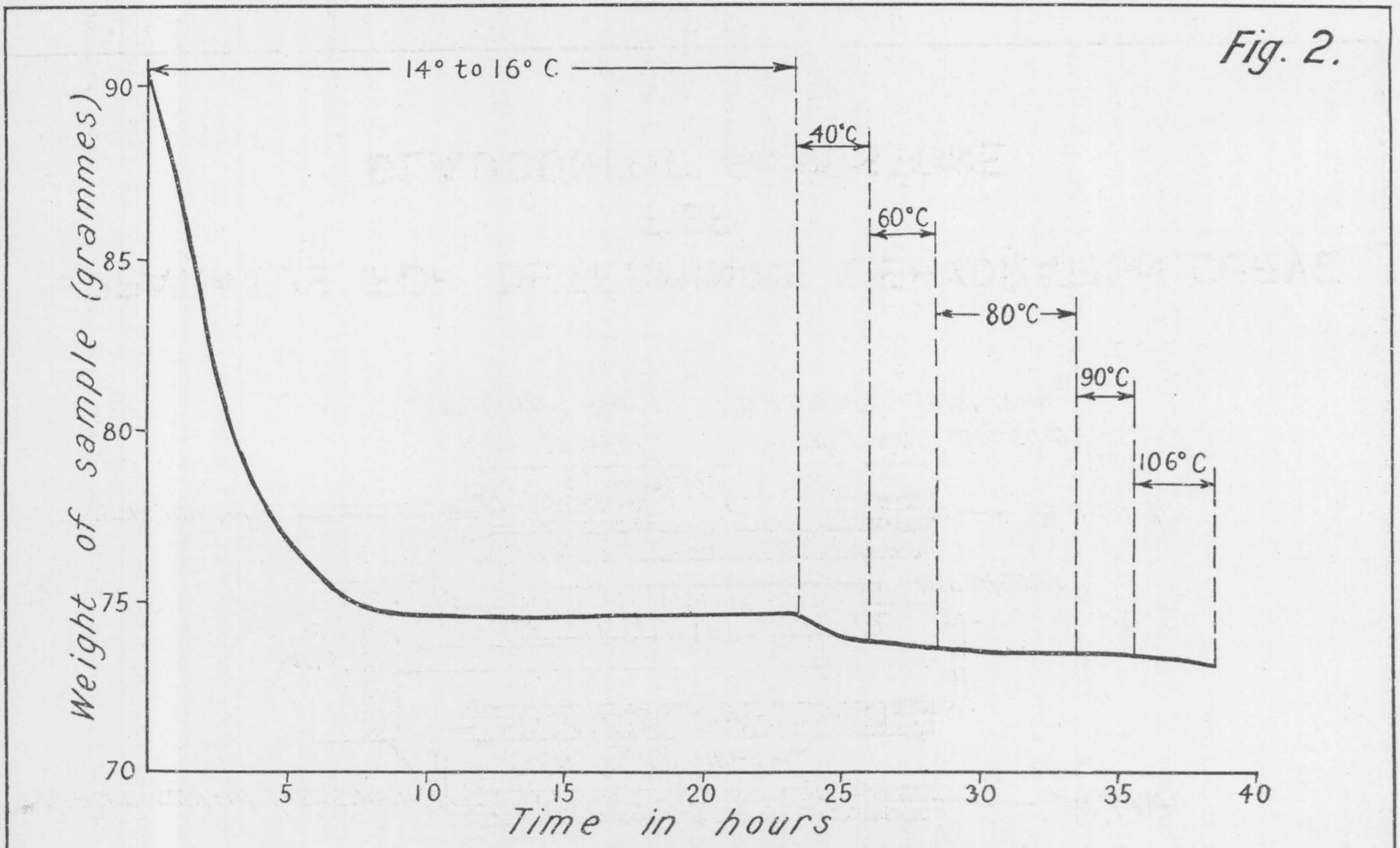
A sample of glauconitic sandstone known as a result of examination under ultra-violet light to be free from oil was ground until the larger pieces were the size of wheat grains. The sample was then carefully packed into a glass tube about 20 cm long and 2 cm in diameter and the ends sealed with plugs of cotton wool held in place by cork gaskets. Dry air was passed through the sample, and sample and holder were weighed from time to time as the experiment progressed. The temperature of the air was regulated by passing it through a heater placed in the circuit between the sample tube and the initial drying tubes (containing $CaCl_2$).

The temperature of the air flowing through the sample was read by a thermometer placed in a special compartment immediately preceding the sample tube, which was lagged with cotton wool. A sketch of the apparatus is shown in figure 1 and the results of the test are shown in the form of a curve (figure 2) giving the weight of the sample at various times and the temperatures to which the sample was subjected. It will be seen that the sample lost 15.9gm of water over the first 8 hours drying at room temperature (14 to 16°C) the weight remaining constant thereafter during a further 12 hours drying at this temperature. The temperature was then raised to 40°C. for 4 hours; during this time the sample lost a further 0.6 gm, and further small losses of weight occurred as the temperature was raised by successive steps to 106°C. Drying was maintained for several hours at 106°C.

Fig. 1



APPARATUS FOR DETERMINING DEHYDRATION CURVE
FOR
GLAUCONITIC SANDSTONE



DEHYDRATION CURVE
FOR NORMAL GLAUCONITIC SANDSTONE
From Lakes Entrance, Victoria.

Upon completion of the drying test the porosity of the larger fragments was determined. The total loss in water amounted to 17.2 gm, which represents an initial water saturation of 68 percent. The volume of the water lost between $40^{\circ}C$ and $106^{\circ}C$ was 1.33 cc, which is equal to about 5 percent of the total pore volume of the sample.

It is believed that the correct interpretation of the results is that none, or at the most a very small part, of the water lost was water of crystallisation; there was certainly no sudden change in the water-loss characteristics at and above $70^{\circ}C$ at which temperature glauconite is said to begin dehydration. It is concluded therefore that none of the water collected in the oil extraction apparatus at $100^{\circ}C$ is water of crystallisation.

Dehydration of Clays and Related Minerals. Clays and related minerals (alumino-silicates) are essentially colloidal, i.e. their behaviour is determined by the state of division of the particles and the surface reactions of the smallest grains. In crystal structure the alumino-silicates can be classed in three simple structural groups, namely fibre structure, micaceous structure, and framework structure. Clays contain all three types, but, in the smallest size particles, micaceous types predominate and are likely to determine the behaviour of the mixture. Kelly, Jenny and Brown (1936) have studied the way in which soil colloids and minerals retain water and have explained their results in terms of crystal structure. They may hold water as

(i) crystal water,
(ii) broken-bond water,
(iii) planar water.

Crystal water or water of crystallisation is incorporated in the crystal structure; is very tightly bonded and usually required high temperatures (e.g. $500^{\circ}C$ for kaolinite) to drive off.

Water attached to clay minerals which may be driven off below 350° to $400^{\circ}C$ is usually bound to the surface of the sheets or framework structures and is therefore classed as adsorbed water. The nature of the surface determines the strength of the bonding and the temperature at which adsorbed water will be driven off.

The broken-bonded water is that which is attached to broken areas of framework structures and edges and rims of micaceous crystallites and requires temperatures of the order of 300°C to remove it.

Planar water is not rigidly bonded to the clay minerals but is held by weak electrostatic forces on the tops and bottoms of the flat plates of micaceous crystals (crystallites). Water held in this fashion may be evaporated almost as readily as free water. It is the adsorption of planar water which causes swelling in clays when wet. When clay is dry the crystallites are bound closely together, but when water is added, molecules of water migrate between adjacent crystallites and force them apart.

That clay or at least some mineral or minerals capable of swelling when wet exist in the glauconitic sandstone and particularly in the cementing material is supported by the following facts.

i. Stillwell states that much of the glauconite has been altered during deposition to limonite and ferruginous clay. This statement refers specifically to the observations made on the grains of glauconite in the sandstone, but such alteration almost certainly is present in the glauconite content of the glauconitic mud.

ii. The removal by powdered glauconitic sandstone of the colouring matter from solutions of Lakes Entrance oil in petrol and also of the colouring matter from coloured petrol suggests the presence of clays or related minerals which are strongly adsorbent. According to R.E. Grim (1939) "it is well-known that almost all clays with a high ability for removing the colour from oil are composed of members of the montmorillonite group or certain types of illite." Members of these two groups are composed of micaceous crystallites and are capable of taking up large amounts of planar water.

iii. The rapid decrease of permeability in glauconitic sandstone containing much glauconitic mud with increasing moisture content suggests the presence in the cement of material that swells on wetting.

This was demonstrated by permeability tests on samples of glauconitic sandstone from Bore No. 10 at various moisture contents. Two different types of glauconitic sandstone were tested. The first type - a coarse-grained sandstone from the lower section of the cores with little cementing mud - showed little decrease in permeability with added moisture. The second type - a fine-grained sandstone containing up to 50 percent glauconitic mud - showed a relatively large decrease in permeability with added moisture. This fact has been used elsewhere (Thyer, 1945b) to explain why large sections of glauconitic sandstone exposed in the Pilot Bore do not yield water, although they are known to be saturated with water at a reservoir pressure of approximately 600 lb/square inch. It was assumed that the swelling of clay-like grains in the glauconitic mud has reduced the permeability to zero.

iv. The fact that the average compressive strength of wet glauconitic sandstone is only half that of dry could be explained by the presence in the glauconitic mud of clayey particles containing planar water which reduces the internal resistance to shear.

Conclusions. It is concluded therefore that there are, in the glauconitic sandstone, clay-like minerals capable of taking up planar water. It seems probable that a significant proportion of the water extracted from the samples may be planar water adsorbed by the surfaces of crystallites. It is not possible, however, without further and very detailed work to determine what percentage oc clay-like minerals is present in the sandstone. Further, there is no way in which the relative amount of planar water in a sample can be determined.

The Oil

When the cores were withdrawn from the core barrel, patches of oil were observed on certain sections of them, but after they had been wrapped in waxed paper in sealed containers for some time, these patches were no longer visible in ordinary light although they fluoresced. The waxed paper appears to have absorbed this surface oil, as is evident from oily stains on the paper, but it is not likely that this absorption removed any significant portion of the oil from inside the cores.

The quantity of oil extracted from the samples was determined by the difference between the total loss of weight and the weight of water collected, the maximum for any sample being 0.68 gm. In samples which, as a result of examination under ultra-violet light, were known to have no oil in them, the maximum difference between the loss of weight and the weight of water collected was 0.03 gm. In the average sample 0.03 gm would be equivalent to an oil saturation of approcimately 0.5 percent, which can be regarded as the uncertainty in any single determination.

The oil found experimentally is called residual oil and the saturation based on this quantity is called residual saturation.

The quantity of oil in a sample may differ from the quantity present in the rock in situ for the following reasons -

1. Oil may be flushed from the cores by drilling water.

ii. Oil may be lost through evaporation and by absorption of wrapping paper.

iii. Decrease in fluid pressure in the cores subsequent to drilling may have resulted in a loss of fluid contents.

The glucose tests described in the preceding section indicated that none of the drilling water entered the cores, so that loss of oil by flushing is regarded as negligible. The loss through evaporation is also considered negligible because Lakes Entrance oil has a low vapour pressure at ordinary temperature. As already stated, it is believed that no significant loss has occurred through absorption of the wrapping paper.

On the other hand it is reasonably certain that oil has been forced from the cores by gas coming out of solution from the oil as the pressure dropped from reservoir pressure to atmospheric. As the oil/gas ratios determined for the Imray and Pilot bores and described in a later section of this report are sufficiently low to permit of an assumption that all the gas would be in solution under reservoir conditions, it has been concluded that the volume of the oil lost by relief of pressure is equal to the volume of the gas which has replaced it.

The Gas

The gas saturation of the cores has been expressed as the percentage of the voids not filled with oil or water. The composition of this gas was not determined during the experiments but it is reasonably certain that it comprises two main components, namely air and methane. The air has entered the samples to replace water that has been lost through evaporation, and the volume of air in any sample will be equal to the volume of water which the sample has lost from this cause. It is assumed that the methane has come out of solution from the oil in the samples.

At the time that the saturation tests were made there was no direct evidence that gas was produced with the oil from any of the bores in the Lakes Entrance Area. However, it was realised that the quantity of gas might have been very small and might have escaped detection. In the cores from the Shaft Bore small gas-bubbles emerged from some of the oil patches shortly after the cores had been removed from the core barrel. This is accepted as evidence that the oil in situ has a certain amount of gas dissolved in it. In order to check the results of these observations it was decided to make measurements on the Pilot and Imray Bores to determine whether gas was being produced, and, if so, in what quantities.

Tests for the Production of Gas

Procedure. The Pilot and Imray bores are cased with unbroken strings of casings from the surface to the top of the glauconitic sandstone into which the casing is cemented. It was believed, therefore, that if, at each bore, the top of the casing could be tightly sealed it would be possible to measure the rate of flow of gas. It was realised that there was a strong possibility that the joints in the casing might not be gas-tight, especially near the surface, and a substantial leakage might occur through them. However, it was believed that even if such leaks occurred it would be possible to get sufficient data to determine whether or not gas was being produced with the oil, although quantitative measurements might not be accurate. The bore casing was sealed with a tapered wooden plug hammered firmly into place, and the seals completed with plastic clay and finally gasket cement. An outlet tube in the wooden plug was connected by rubber tubing to a flow-meter graduated from 0 to 1 cc/sec. It was found that the flow-rate increased steadily as the pressure inside the casing built up, but the pressure build-up was accelerated by artifically increasing the pressure in the casing until a pressure was reached at which the flow-rate was constant over several hours. During the test, records were kept of barometric pressure and air temperature. The flow-meter was then removed and the outlet tube coupled to a water manometer. If the casing had been completely sealed the pressure read on the manometer would have continued to increase as gas and fluid entered the sealed casing. However, it was found that the "sealed-up" pressure did not continue to rise above a certain limiting pressure, thus indicating that gas was leaking through the casing.

Results. At the Imray Bore the flow rate was found to be constant at 0.98 cc/sec. with a pressure drop of 7.75 inches of water across the flow-meter. The "sealed-up" pressure was only 8.7 inches of water above atmospheric indicating that the leakage through the casing was considerable. Assuming that the leak through the casing was non-turbulent, i.e. that the rate of leak was proportional to the pressure differential, it has been calculated that, for the pressures and rate of flow given above, the amount of gas flowing out of the casing at atmospheric pressure would be 9.9cc/sec. From the known rate of production of oil and water it was calculated that the liquid rising in the casing would be displacing gas at the rate of 0.18cc/sec. and therefore the amount of gas produced would be 9.72cc/sec. The rate of oil production at the time of the test was 0.14cc/sec., and the gas/oil ratio therefore, equals $\frac{9.72}{.14} = 70$cc/cc. There was evidence, however, that the rate of production of gas, and presumably oil and water, was not constant during the time over which the test was made. The gas/oil ratio, as given above, is therefore subject to a very large possible error. Nevertheless the fact that the flow-meter showed a discharge of gas at least five times as great as the rate at which gas would be displaced by liquid rising in the casing is definite evidence that gas of at least this amount was being produced from the formation exposed in the Imray bore.

At the Pilot Bore the flow-meter showed a steady gas discharge rate of 0.75cc/sec. with a pressure drop of 5.9 inches of water across the flow-meter. This rate was constant within narrow limits (0.72 to 0.78) during the twelve hours over which the test was made. The "sealed-up" pressure continued to rise until the manometer stood at a pressure 24 inches of water above atmospheric, when the plastic clay seal broke. However, the rate of pressure build-up had been noted at various pressures and it was possible to estimate the value to which the "sealed-up" pressure would have risen had the seal remained intact. It was estimated that this pressure would have been approximately 25 inches of water above atmospheric. The large difference between the pressure at which the flow-meter discharge was constant and the "sealed-up" pressure indicated that the leakage through the casing in the Pilot Bore must have been small in comparison to the discharge rate of the flow-meter. Calculations show that the total discharge of gas from the bore at atmospheric pressure would be 0.96 cc/sec. At the time the tests were made the total liquid production was at a rate of 48 pints per day, i.e. 0.316cc/sec., of which oil was equal to 0.19cc/sec. It is seen, therefore, that the flow-meter showed a discharge of more than double the rate at which liquids were entering the casing, thus providing definite evidence that some gas was being produced from the formation exposed. The gas/oil ratio found experimentally was approximately 4.0cc/cc.

<u>Conclusions</u>. The tests provide ample evidence that gas is produced with the liquids from the glauconitic sandstone. No samples of the gas were taken, but it is believed that the gas produced is substantially methane. (A sample of gas was obtained subsequently from the Shaft Bore and on analysis by the Victorian Mines Department showed 98.8 percent methane, 0.8 percent nitrogen, 0.2 percent CO_2 and 0.2 percent oxygen.) The only gas which has been known to occur in appreciable quantities in the glauconitic sandstone or formations adjacent to it has been proved by analysis to contain approcimately 90 percent methane. However, there is very little direct evidence on which to base a claim that the methane is in solution in the oil. The main reasons on which such a claim could be based are -

i. Methane is very much more soluble in oil than in water.

ii. Small bubbles of gas were observed emerging from those portions of the core which were covered by oil when the core was first removed from the core barrel, but no bubbles were noticed, and gas was evidently not present, in those sections of the core which contained no oil.

iii. The saturation determinations for those cores which contain no oil indicate that the formations from which these cores were cut are completely saturated with water in situ, and that no free gas is present in them. On the other hand the saturation determinations on those cores which contain oil showed that a significant proportion of their pore spaces contained gas.

The low gas/oil ratios found for the Pilot and Imray Bores suggest that if this gas is methane it must have been completely in solution in the oil under the existing conditions of reservoir temperature and pressure. The saturation results of cores containing oil are consistent with the theory that gas is in solution in the oil and that the act of coring reduces the pressure in the cores to atmospheric, thus allowing gas to come out of solution and force liquid from the cores.

Porosity

Petrological examination of glauconitic sandstone from Lakes Entrance by Drs. Stillwell (1944) and Edwards (1945) has not fully explained the reason for the exceptionally high porosities which have been measured.

Microscopic examination by Stillwell of thin sections of sandstone showed that many of the glauconite grains exhibited shrinkage cracks which in some grains constituted 30 to 40 percent of their volume. The shrinkage probably occurred during lithification, and, according to Stillwell, it is doubtless a factor contributing to the high porosity of the rocks, but he concluded that the shrinkage cracks observed in the sections would account for porosities of only about 10 to 15 percent, whereas the average porosity of the samples he examined was 36 percent.

Edwards considered that, as there are no obvious cavities in the rock sufficiently large to account for porosity of the order measured, "the pore spaces can only be accounted for as due to incomplete compaction allowing the existence of sub-microscopic openings along grain boundaries and in the glauconitic mud cement". Edwards has concluded, however, that "it may be doubted whether the measured porosity is the true porosity of the rock in its natural state because even air-drying of the rock may cause shrinking of the natural cement thus increasing the porosity of the rock considerably."

The correctness of Edwards' conclusion would appear to depend on his definition of porosity. If he considers the spaces occupied by adsorbed planar water in grains of clay or similar minerals as being part of the solid structure of those grains and not as interstitial spaces contributing to the total porosity of the rock, then the swelling of the grains would cause a reduction in porosity. If such a reduction is accepted there is no need to define two porosities for each sample; one which might be defined as the <u>absolute</u> porosity and incorporates the spaces occupied by planar water, and the other which will be called the <u>actual</u>[X] porosity, which is based on the interstitial spaces remaining when the colloidal grains, expanded by the addition of planar water, are considered as solid particles.

In attempting to apply the results of experiments such as those by Dunlap (1938), Leverett and Lewis (1941), van Wingen (1938) and others on the flow of oil-gas-water mixtures through a permeable medium such as the glauconitic sandstone, the spaces occupied by planar water in the grains could not be considered as interstitial spaces through which fluids could flow, but as part of the solid structure of the rock. The porosity of the glauconitic sandstone corresponding to the porosity of the samples used by the above experimenters would therefore be the actual porosity as defined above.

For the same reason, when applying deductions such as those concerning the residual oil saturation found in cores from formations[ø], it will be necessary to consider the expanded grains as solid particles and to consider that the planar water is not part of the fluid content of the pores.

It is concluded therefore that the porosities measured experimentally and given in Table II are <u>absolute</u> porosities, but that when reservoir behaviour is considered the reservoir porosity will have to be considered as lower than the absolute and equal to the <u>actual</u> porosity as defined above.

The absolute porosities of the samples tested were of the order of 35 to 45 percent, and a comparison of the porosities of oil-bearing and oil-free samples shows that there is no difference is absolute porosity between them.

X The term "effective porosity" is not used because it has a different meaning, viz, the porosity based on interconnected voids in the sample and excluding voids completely sealed and therefore not capable of holding reservoir fluids or exercising an influence on fluid flow through the rock.

ø Experimental evidence from the study of residual water and oil saturations of numerous drill cores from producing formations in the United States has shown that the residual oil saturation of such cores is seldom, if ever, less than 15 percent.

A direct comparison was made between the absolute porosities of of oil-bearing and oil-free fragments taken from the core between 1201 feet 4½ inches and 1201 feet 10½ inches which, under examination by ultra-violet light, showed oil confined to small patches throughout the core. By careful splitting, it was possible to isolate two samples, one of oil-free glauconitic sandstone and the other of glauconitic sandstone containing oil. The absolute porosities were found to be 37.5 and 38.2 percent respectively.

On the other hand microscopic examination suggests that the <u>actual</u> porosities of oil-bearing and barren sandstone may differ because the oil-bearing samples have a more open texture and a lower glauconitic mud content than is evident in barren samples.

It follows that the oil-bearing portions contain less clay or clay-like particles than the barren portions, with a result that there are fewer grains to swell when wet. The oil-bearing portions have therefore a greater <u>actual</u> porosity and a greater permeability under reservoir conditions than have the barren portions.

TABLE I.

DISTRIBUTION OF OIL IN GLAUCONITIC SANDSTONE AS INDICATED BY BORE LOGS.[x]

Bore	Direction from Oil Shaft	Distance from Oil Shaft. Feet	Thickness of Glauconitic Sandstone	Depth below top of Glauconitic Sandstone at which oil observed	Remarks from Bore Logs.
No. 10 Gov	N.E.	1120	45	Top dry 4' - 13' 7" 22'11" - 25'11" 32' 5" - 36' 6"	Oil observed in cores.
No. 1 Oil Search	E.N.E.	4200	42	11' - 12' 6" 24' - 26' 6" 29' - 30'	Oil observed in cores.
Fosters	S.E.	600	31+	11' 6" 24'10"	"Good oil showing" on coring; core saturated.
No. 3 Pt. Addis	S.S.E.	1650	39	Top 25' 39'	
No. 4 Pt. Addis	W.	2440	38	Top 10' 6" 11' 6" 25' 0" 29' 6"	Oil showings.
No. 8 Gov.	W.N.W.	6800	40	0' - 2' 5' - 9' 3" 37' - 40'	Approximate limits established by bailing.
Midwest No. 2.	N.W.	1320	28	1' 4' to 14' 6"	-"Good Oil". - Still producing oil. -"Splendid oil".
South Australian Oil Co. No. 7	N.N.W.	725	32+	Top 20' - 31' 31' - 32'	-"Strong oil". -Oil. -"Rich oil".

x The information is drawn from records published by the Mines Department of Victoria, and from records compiled by Mineral Resources Survey.

TABLE II.

SHAFT BORE.

RESULTS OF SATURATION TESTS

Sample	Porosity (Absolute) Per cent	Saturation (Per cent) Oil	Water	Total	Apparent Density.	Grain Density
1200' 7" - 1200' 9"	47.6	8.6	72.5	81.1	1.53	2.93
1200' 9" - 1200' 10"	49.6	5.6	82	87.6	1.49	2.95
1200' 11" - 1201'	42.6	4.3	85	89.3	1.69	2.94
1201' 3¾"- 1201' 4½"	37.8	4.1	79	83.1	1.82	2.94
[a]1201' 4½"- 1201' 10½"	37.5	-	-	-	1.84	2.94
[b]1201' 5¾"- 1201' 8¼"	38.2	4.9	70	74.9	1.79	2.90
1201' 10½"- 1202' 1½"	44.4	3.5[c]	84.5	88	1.58	2.84
1202' 5" - 1202' 6"	44.5	5.0	82.5	87.5	1.59	2.86
1202' 7" - 1202' 10"	44.6	0	90	90	1.59	2.87
1203' 6½"- 1203' 7½"	39.7	1.3	92	93.3	1.74	2.90
1203' 8½"- 1203' 9½"	35.7	0	98	98	1.90	2.94
1204' 6¾"- 1204' 7¾"	47.8	0	91.5	91.5	1.59	3.05
1204' 7¾"- 1204' 8¾"	47	0	98	98	1.60	3.03
1205' 9" - 1205' 11¼"	43.3	0	92	92	1.64	2.89
1206' 5" - 1206' 6"	40.9	2.5	92	94.5	1.68	2.85
1207' - 1207' 1"	39.5	5.5	86	91.5	1.75	2.90
1207' 4" - 1207' 5"	36.2	7.1	81	88.1	1.81	2.84
1207' 5" - 1207' 6"	35.2 (39.4)	5.7 (5.1)	90 (80)	95.7 (85.1)	1.79	2.76 (2.90)≠
1207' 6" - 1207' 7"	44.4	11.6	72	83.6	1.65	2.97
1207' 7" - 1207' 8"	42.7	5.6	81	86.6	1.65	2.88
1208' 11" - 1209' 1"	39 .6	0	98.5	98.5	1.77	2.94
1209' 9½"- 1209' 10½"	36.5	0	99	99	1.80	2.84
1210' 9¾"- 1210' 10¾"	35.4	4.5	71	75.5	1.91	2.95
1210' 10¾"- 1210' 11¾"	37.2 (34)	9.9 (10.8)	63.5 (69)	73.4 (79.8)	1.91	3.05 (2.90)≠
[b]1211' 1" - 1211' 4"	39.3	6.0	80	86	1.74	2.86
1212' 5" - 1212' 6½"	41.4	4.0	80.5	84.5	1.69	2.88
1212' 6½"- 1212' 8"	41.2	12.2	73	85.2	1.65	2.80
1213' 11" - 1214' 1¼"	40.8	3.6[c]	89	92.6	1.67	2.83
1215' 3" - 1215' 4"	27.4	0	99	99	2.11	2.90
1216' 1" - 1216' 1¾"	42.8	1.6	92	93.6	1.69	2.96
1216' 1¾"- 1216' 2½"	41.8 (45)	0	97.5 (89)	97.5 (89)	1.60	2.74 (2.90)≠
1216' 2½"- 1216' 3½"	43	0	94	94	1.62	2.86
1217' 8" - 1217' 9"	36	5.2	90	95.2	1.84	2.87
1217' 9" - 1217' 10"	39.8	2.8	79	81.8	1.82	3.02

(a) Selected non-oily fragments.
(b) Selected oily fragments.
(c) Doubtful oil - no coloration of solvent noted.
≠ Values in brackets are based on grain density of 2.90.

Results

In the early stages of the investigation selection of samples was based on the distribution of oily patches observed on the surface of the cores when they were removed from the core barrel, but, as the examination under ultra-violet light proceeded, it became evident that the position of these patches was not a reliable indication of the occurrence of oil-bearing sandstone. As a result the selection of the samples in the later stages of the investigation was based on the results of the examination under ultra-violet light, and only those cores an appreciable portion of whose surfaces fluoresced were tested. Most of the samples which had oil in them were selected in this way.

The average size of the samples was equivalent to 1 inch of core length and the average weight was 27 gm. From most of those samples in Table II with core lengths greater than $1\frac{1}{2}$ inches, a portion representative of the whole length was selected and tested. In the few cores which were recovered as fragments, the selection was biased in favour of oily fragments, but, where the results of such tests have been used in the calculation of the average saturation of the oil zones, allowance has been made for this non-representative selection.

The samples were broken into pieces the size of small peas to facilitate the extraction of oil and water, and the average time required for extraction was approximately 11 hours. The results of the tests are shown in Table II, which includes the oil and water saturations of 33 samples representing a stratigraphical thickness of $45\frac{1}{4}$ inches out of a total of $230\frac{1}{2}$ inches of glauconitic sandstone intersected by the Shaft Bore. Of the $185\frac{1}{4}$ inches of sandstone not tested no core was obtained for 40 inches, and the ultra-violet light examination showed that the remainder contained so little oil that saturation determinations were not considered necessary.

Of the 33 samples tested, 10 contained no oil and 23 contained oil, but two of them may be doubtful determinations. The 10 samples which contained no oil represent a stratigraphical thickness of 14 inches, and their water saturations ranged between 90 and 99 percent and averaged 95.5 percent. The average was somewhat higher (96.5%) for those samples that were not cut into discs for exposure to ultra-violet light, but those which were cut and exposed average about 93.5 percent. It is assumed that if no loss of water by evaporation had occurred, the water saturation of the 10 samples would have been 100 percent, from which it follows that this loss varied between 1 and 10 percent and was greatest in those exposed for the greatest length of time.

The 23 samples which contained oil (including the two doubtful ones) represent a stratigraphical thickness of 31¼ inches. If the two doubtful ones are excluded the thickness is 26 inches. Their oil saturations ranged between 1.3 and 12.2 percent. Ten samples ranged between 1.3 and 4.5 percent (including the two doubtful ones), nine between 4.5 and 7.5 percent and four above 7.5 percent. The average of the 23 samples was 5.4 percent. Their water saturations ranged between 63.5 and 92.0 percent and averaged about 81 percent. Their total liquid saturations (water plus oil) averaged 86.4 percent. The difference between average total saturation and 100 percent is the average gas saturation, namely 13.6 percent. The gas is considered to be partly air which had replaced evaporated water and partly methane which was in solution in the oil when the samples were in situ. When the fluid pressure was decreased from reservoir pressure to atmospheric during drilling, the methane came out of solution and forced oil and a small amount of water from the cores. The average air saturation is estimated at approximately 6 percent and the average methane saturation is consequently 7.6 percent. It is assumed that the pore volume occupied by the latter was formerly occupied mainly if not wholly by oil, and it is concluded that the average oil saturation in the rocks in situ would be 5.4 plus 7.6 or 13 percent. It is admitted that this conclusion is based on assumptions which may be somewhat faulty through lack of direct evidence or misinterpretation of such evidence as there is. It is believed however that the conclusion is substantially correct and that it provides a satisfactory basis for determining the fluid content of the reservoir rocks in situ.

The preliminary examination under ultra-violet light revealed that even in the oil-bearing samples, only a portion of the sandstone contained oil. In six samples, the oil-bearing portion was more than 95 percent of the total but in others it ranged from 30 to 80 percent. Calculations based on the assumption that the latter samples contained non-oily portions with a water and gas saturation of 95 and 5 percent respectively, and that all the oil and the remainder of the gas was confined to the oily patches, gave oil saturations ranging up to 16.7 percent (six were above 11 percent) and averaging 9.4 percent, and water and gas saturations averaging 67 and 23.6 percent respectively. These values more nearly represent the true saturations of the oily portions of the glauconitic sandstone than the values tabulated in Table II, but those in the table represent the average saturation of the samples as a whole, i.e. including any portions which are oil-free, and therefore they have been used in estimating the total quantity of oil which is present in the oil zones.

In order to determine satisfactory averages for oil, water and gas saturations for use in the calculation of oil content of the individual oil zones, the following procedure was adopted.

i. The measured or residual oil, water, and gas saturations of those samples whose grain densities were notably different from 2.90 were adjusted. The grain density varies between narrow limits throughout the glauconitic sandstone and tends to follow a fairly uniform distribution. Values substantially different from those of adjacent samples are regarded with suspicion and probably indicate errors in determining the grain volume during porosity tests. In such samples the grain volume has been recalculated from its weight assuming a grain density of 2.90 (which is regarded as an average grain density), and the pore volume and saturations of the original samples recalculated.

ii. It was assumed that the samples had lost water before testing and a loss has been allotted to each sample. The loss was due principally to evaporation, and the factors considered in arriving at the loss from this cause were the time the samples were exposed to the air and the average water saturations of those samples which had no oil in them. In addition the samples probably lost a small quantity of water owing to gas coming out of solution from the oil during drilling and forcing oil and a small quantity of water from the pores. The total loss has been expressed as the percentage of the pores filled with the air which has replaced the water lost and ranges from 5 to 8 percent.

iii. In those samples which comprised fragmented core from which the selection of pieces for testing had been biased in favour of oily pieces, the saturations determined experimentally were adjusted by assuming that the original sample comprised 80 percent oil-bearing rock, the remaining 20 percent having water and gas saturations of 95 and 5 percent respectively.

iv. Oil, water, and gas saturations, porosities, and water losses were allotted to those portions of the oil zones for which no determinations of the above were made. This allotment was based on the grade of sample as determined by the ultra-violet light examination (i.e. grade 1 or 2) and on the average saturations, porosities, and water losses of all samples of the respective grades.

v. The samples were divided into their respective zones and, after values had been allotted in accordance with iv. above, average values, weighted in accordance with the length of the samples, were calculated to ascertain the average saturation, porosity, and water loss for 1 inch of core from each of zones 1, 2 and 3. These saturation values and averages are set out in Table III.

The saturations of the rocks in situ have been arrived at by assuming -

a. The pores filled with gas, which is not air replacing lost water, were filled with oil when the samples were in place in the reservoir.

b. The total oil saturation is the measured or residual saturation plus the gas saturation in accordance with (a) above.

c. The original water saturation is equal to the sum of the measured water saturation and the water loss.

d. The original gas saturation was zero.

The average oil and water saturations in situ arrived at for zones 1, 2 and 3 as shown in Table III are: oil 14.8, 13.0 and 16.0 percent, and water 85.2, 87.0 and 84.0 percent.

Discussion of Results

A vast amount of experimental work on the oil saturations of cores from producing formations in the United States has shown that the residual oil saturation is seldom if ever below 15 percent in cores from producing formations; and hence it might be claimed that none of the glauconitic sandstone in the cores tested represents producing formations.

Oil is certainly being produced by the sandstone exposed in the Shaft Bore, and it is possible, although most unlikely, that the sandstone from which it is coming is included in the sections which did not core. However, the close parallel between the oil zones as determined by the ultra-violet light examination in the Shaft Bore with those determined by bailing tests in the neighbouring Pilot Bore is regarded as sufficient evidence that oil is being produced from sandstone represented in the samples.

It is believed that the explanation is that the actual porosities of the reservoir rocks in situ are lower than the porosities determined experimentally, and in consequence the residual oil saturations are higher than given in Table II, and in some samples they may in fact exceed 15 percent.

Another fact which appears to be contrary to the results of experiments and to considerations of production evidence in the United States is that a sandstone with such high water and low oil saturations should produce liquid which contains more than 90 percent of oil.

It is believed that the explanation for the high percentage of oil in the liquid yiedled is to be sought partly in the theory advanced earlier in this report, that a substantial proportion of the water extracted from the samples was planar water from clay-like minerals in the matrix of the rock. Consequently the actual water saturations would be lower and oil saturations higher than those determined experimentally. Although there appears to be no means of determining the amount of planar water by direct experiment, it was shown earlier that there is ample indirect evidence of its existence, or at least of the existence of clay-like minerals in the glauconitic sandstone. It is proposed therefore to show in what way the saturations of a sample are affected by making certain assumptions regarding the amount of planar water present in it. A differentiation is made between what will be called planar spaces in the rock and true interstitial spaces. The planar spaces, as the name suggests, are those spaces between the individual crystallites occupied by planar water, and it is assumed that the bonding which holds the molecules of water to the crystallites is such that fluids cannot flow through these spaces.

The true interstitial spaces in the rock are all those spaces which are not planar spaces and which are capable of holding reservoir fluids. It can be assumed that the glauconitic sandstone is water-wet and that the oil and gas it contains are confined to the larger pore spaces and consequently to the more permeable parts. The oil, gas, and water saturations of the interstitial spaces in a sample from 1212 feet 6½ inches to 1212 feet 8 inches for various assumed percentages of planar spaces are shown in Table IV. If the experimental work of Leverett and Lewis (1941) on the flow of gas-oil-water mixtures through permeable media could be applied to the glauconitic sandstone in the Pilot Bore, it might be concluded that the gas, oil, and water saturations which correspond to the measured production ratios of these three fluids, namely 4/1/0.1, would be of the order - gas 10-20 percent, oil 60-70 percent and water 20-30 percent. To obtain saturations of this order it is necessary, according to Table IV, to assume that between 60 and 80 percent of the total voids are planar voids.

These figures are necessarily approximate as Table V will show. In this table six measurements by Leverett and Lewis are given, and though no individual measurement gives production ratios sufficiently close to approximate those of the Pilot Bore, they at least show the general trends of the production ratios as the saturations of the individual fluids vary. The production ratios for the Pilot Bore correspond to the sandstone adjacent to the bore hole and are not typical of the reservoir rocks in situ because it can be assumed that the gas saturation would be zero under reservoir conditions. In arriving at the values of the relative composition of the fluid yielded, use has been made of the experimental results of Leverett and Lewis that the isoperms of all components are independent of the viscosity. The viscosity ratio used in the calculations was gas/oil/water = .012/95/.68 corresponding to methane, water and oil respectively at 100°F.

It must be emphasized however that these workers used unconsolidated sands of permeabilities ranging from 5.4 to 16.2 darcies and though they do not comment on the effect of specific permeability on their results, it is evident that the relative permeabilities to the three phases of fluid flow are substantially independent of the permeability over the range of permeabilities used.

Tests of permeability were not made on samples from the Shaft Bore, but visual inspection of the cores suggests that they do not differ substantially in permeability from the glauconitic sandstone in Bore No. 10. The average permeability of that section of Bore No. 10 (Thyer,1944) which corresponds to the sandstone exposed in the Shaft Bore was only 2.16 millidarcies, but microscopic comparison of oil-bearing and barren sandstones suggests that the oil-bearing parts have much less glauconitic mud matrix than barren sandstone, and have a relatively spongy appearance; consequently one would expect them to have much higher permeability than barren sandstone. It is therefore a reasonable assumption that the permeability of those sections of the Shaft Bore which contain oil would be comparable with the samples of relatively high permeability from bore No. 10, e.g. 1272 to 1273 feet, etc. which averaged 5 millidarcies and ranged up to 50 millidarcies.

Observations made at the time the Bore No. 10 samples were tested showed that some samples contained patches whose permeability was much higher than the permeability of the remainder of the sandstone in the samples. It was estimated that the permeability of one such patch in a sample from 1294 to 1300 feet was of the order of 120 millidarcies. It is now believed that these so-called patches may have corresponded to oily patches. No oil or oil-staining was seen in them, but this is not surprising because in the present examination it was found that the ultra-violet light clearly indicated oil which was invisible in ordinary light, in many such patches.

It is concluded, therefore, that the permeability of the oily patches might be considerably higher than the average for the whole section exposed, and may exceed 100 millidarcies for dry samples.

It is seen that a comparison between the results of Leverett and Lewis (1941) and those from the glauconitic sandstone is one between materials of very different permeabilities. In addition, their tests were made on unconsolidated sands, whereas the sandstone is cemented with glauconitic mud. It follows therefore that the results of their studies may not be strictly applicable to the glauconitic sandstone.

The influence of permeability on the saturations required to give certain production ratios for oil, gas, and water has not been investigated as thoroughly as other phases of the problem. The work of van Wingen (1938) and others shows, however, that when oil is forced through a rock saturated with water, the fluid issuing from the rock at first contains some water but eventually consists entirely of oil. The quantity of water remaining in the rock is found to be inversely proportional to the permeability. This might be interpreted as meaning that in such a two-phase flow (and in the reservoir it can be assumed that all the gas is in solution) the limiting oil saturation at which the flow through the rock will be 100 percent oil gets progressively less as the permeability decreases, and tends towards zero as the permeability approaches zero. The inference is that for the glauconitic sandstone of low permeability the water saturation at which the rock will produce substantially and gas is probably considerably higher than has been predicted from the work of Leverett and Lewis. This trend means in effect that a smaller proportion of planar voids in the samples than the 60-80 percent quoted above can be assumed; and this would be consistent with the observation that the oil-bearing portions of glauconitic sandstone seem to contain less of the cementing mud than barren portions.

It is concluded therefore that when due allowance is made for the space occupied by planar water, and for the low permeability of the sandstone, the low oil saturations found by experiment are not necessarily inconsistent with the fact that the oil zones produce liquid which contains more than 90 percent of oil.

It must be emphasised, however, that none of the assumptions made regarding the quantity of planar water present (and consequently the actual porosities) in any way effect the conclusions arrived at regarding the total quantity of oil present in situ in a given volume of sandstone. Consequently the volumes (given in Table VI) of oil estimated as being present in an area of 1 acre by using the average oil saturations listed in Table III are unaffected by these assumptions.

TABLE III.

THE AVERAGE SATURATIONS OF THE OIL ZONES.

Zone No.	Sample	Sample Length (inches.)	Porosity	Percent Saturation Oil	Percent Saturation Water	Water loss ‡ percent	Estimated Saturation of Samples in Situ oil ø	Estimated Saturation of Samples in Situ water †
1.	x. 1200' 6" - 1200' 7"	1	40.0	4.15	84.2	5.0		
	a. 1200' 7" - 1200' 9"	2	47.6	6.9	77.0	5.0		
	1200' 9" - 1200'10"	1	49.6	5.6	82.0	5.0		
	y. 1200'10¼" - 1200'11"	¾	40.7	5.9	78.0	5.7		
	b. 1200'11" - 1200'11¾"	¾	42.6	5.0	83.5	5.0		
	c. 1201' 4" - 1200' 4½"	½	37.8	5.1	75.0	6.0		
	x. 1201' 4½" - 1201' 5½"	1	40.0	4.15	84.2	5.0		
	a. 1201' 5¾" - 1201' 7" a. 1201' 7½" - 1201' 8¼"	2	38.2	3.9	75.0	7.0		
	x. 1201' 8½" - 1201' 9½"	1	40.0	4.15	84.2	5.0		
	x. 1202' 1¾" - 1202' 2¼"	½	40.0	4.15	84.2	5.0		
	d. 1202' 5½" - 1202' 6"	½	44.5	8.0	75.0	5.0		
Weighted averages for 1" (total thickness 11")			42.5	5.12	79.7	5.5	14.8	85.2
2.	e. 1206' 5¼" - 1206' 6"	¾	40.9	3.3	90.0	4.0		
	x. 1206'11" - 1207'	1	40.0	4.15	84.2	5.0		
	f. 1207' 0¼" - 1207' 1"	¾	39.5	6.6	85.0	5.0		
	x. 1207' 1" - 1207' 4"	3	40.0	4.15	84.2	5.0		
	h. 1207' 4" - 1207' 5"	1	36.2	7.1	81.0	5.0		
	g. 1207' 5" - 1207' 6"	1	39.4	5.1	80.0	5.0		
	1207' 6" - 1207' 7"	1	44.4	11.6	72.0	5.0		
	1207' 7" - 1207' 8"	1	42.7	5.6	81.0	5.0		
	y. 1207' 8" - 1207' 8½"	½	40.7	5.9	78.0	5.7		
	x. 1207' 8½" - 1207' 9¼"	¾	40.0	4.15	84.2	5.0		
	y. 1207' 9¼" - 1207'10¼"	1	40.7	5.9	78.0	5.7		
	x. 1207'10¼" - 1207'10½"	¼	40.0	4.15	84.2	5.0		
Weighted averages for 1" (total thickness 12")			40.3	5.5	82.0	5.0	13.0	87.0
3.	y. 1210' 9" - 1210' 9¾"	¾	40.7	5.9	78.0	5.7		
	1210' 9¾" - 1210'10¾"	1	35.4	4.5	71.0	8.0		
	g. 1210'10¾" - 1210'11¾"	1	34.0	10.8	69.0	8.0		
	y. 1210'11¾" - 1211' 1"	1¼	40.7	5.9	78.0	5.7		
	a. 1211' 1" - 1211' 4"	3	39.3	4.8	83.0	5.0		
	y. 1211' 4" - 1211' 5"	1	40.7	5.9	78.0	5.7		
Weighted averages for 1" (total thickness 8")			38.7	5.9	78.0	6.0	16.0	84.0

‡ Based on time exposed and expressed as percent of pore volume occupied by air which replaces water lost.
ø Based on assumption that pore spaces not filled by water when the samples were in situ were occupied by oil - values given are regarded as maximum possible oil saturations.
† Arrived at by adding averaged measured water saturation to average water loss.
a. Original sample selected pieces - adjusted to true average by assuming average core section 80% oil-bearing.
b. Measured saturations adjusted because 1" sample contained ¼" grade 4 sandstone which has been assumed to have 90% water and 2% oil saturation.
c. Measured saturations adjusted - ¾" sample contained ¼" grade 4 sandstone.
d. " " " - 1" " " ½" " " "
e. " " " - 1" " " ¼" " 5 " (assumed 95% water. No oil).
f. " " " - 1" " " ¼" " 4 "
g. Measured saturations recalculated on basis of average grain density = 2.90
x. Core section not actually sampled but given the average saturation and water loss of grade 2 sandstone.
y. Core section not actually sampled but given the average saturation and water loss of grade 1 sandstone.

TABLE IV.

EFFECT OF PLANAR WATER ON OIL, WATER AND GAS SATURATION.

Sample 1212 ft. 6½ inches - 1212 ft. 8 inches.

Oil Extracted = .72 cc., Water Extracted + Water Evaporated = 4.65 cc.

Total Voids cc	Planar Voids cc.	Planar Voids % of Total	Interstitial Voids cc.	Actual Porosity %	Saturation of Interstitial Voids Percent Oil	Water	Gas.	Total oil in situ Percent of Interstitial Voids
5.9	0	0	5.9	41	12.2	79	8.8	21
5.9	1.18	20	4.72	33	15.3	73	11.7	27
5.9	2.36	40	3.54	24.8	20.3	65	14.7	35
5.9	3.54	60	2.36	16.5	30.5	47	22.5	53
5.9	4.65	79	1.25	11.2	45.0	0	55	100

TABLE V.

RELATION BETWEEN RELATIVE PERMEABILITY, PERCENTAGE SATURATION AND RATIOS OF STREAM COMPONENTS FOR GAS, OIL AND WATER.

Based on experimental results by Leverett and Lewis on sands of permeability 5.4 to 16.2 darcies; calculations based on viscosity ratios gas/oil/water = .012/95/.68 corresponding to methane, Lakes Entrance oil and water respectively at 100°C.

Saturation Percent Gas	Oil	Water	Relative Permeability K'g	K'o	K'w	Stream Components Percent. Rg	Ro	Rw	Effluent Ratios Rg/Ro	Ro/Rw
27.7	49.3	23.0	.0015	.291	0	80.5	19.5	0	4.1	--
15.6	64.4	20	.0019	.464	.0005	76.2	23.5	0.36	3.2	65
11.3	63.6	25.1	.0004	.517	.0032	36.0	59.0	5.0	0.61	12
12.0	61.5	26.5	.0003	.418	.0039	31.0	62.0	7.0	0.50	8.8
7.3	62.9	29.8	.0003	.196	.0006	54	44	1.9	1.2	23
0	69.5	30.5	0	.659	.0004	0	99.1	0.9	--	110

TABLE VI.

OIL CONTENT OF PORTION OF THE GLAUCONITIC SANDSTONE.

IN THE VICINITY OF THE OIL SHAFT - LAKES ENTRANCE.

Zone.	Approximate Upper & Lower Limits of Zone below top of Glauconitic Sandstone	Aggregate thickness of productive Sandstone. Inches.	Average Porosity. %	Average Oil Saturation Per cent.		Total Oil Content Barrels$^{\phi}$ per acre	
				Observed	Maximum Possible	Based on observed Saturation	Based on Maximum possible Saturation.
1	1' 8" - 3' 8"	11	42.5	5.12	14.8	150	450
2	7' 7" - 9' 1"	12	40.3	5.5	13.0	170	400
3	11'11" -12' 7"	8	38.7	5.9	16.0	120	320
		31				440	1,170

$^{\phi}$Barrels of 35 Imp. gallons.

OIL CONTENT OF THE GLAUCONITIC SANDSTONE

By using the figures obtained for the aggregate thickness of productive sandstone and the average porosity and oil saturation for each zone (see Table III), it is possible to calculate approximately the total amount of oil per acre contained in the three productive zones in the uppermost 13 feet of the glauconitic sandstone. The results of the calculations are set out in Table VI, which shows the total oil content in barrels per acre. Two figures for the oil content of each zone are given: one is based on the averages of the measured or residual oil saturations of the cores, and the other is based on the averages of the maximum possible oil saturations. The latter are calculated on the assumption that the space in the cores occupied by gas, other than the air replacing water lost, was formerly occupied by oil.

It has been pointed out already that these figures only apply to the uppermost 13 feet, and take no account of oil which almost certainly exists in the lower part of the sandstone. It was not possible to calculate figures for the lower part because none of the bores which provide detailed information penetrated deeper than 23 feet below the top of the sandstone.

However, the recovery of oil in appreciable quantities from oil zones in the lower portions of the sandstone by horizontal drilling may be impossible for the reasons given below, and consequently the zones are considered to be economically unimportant.

i. It is very doubtful whether the main shaft could be sunk sufficiently far into the sandstone to enable horizontal holes to be drilled into the lower portion.

ii. It is doubtful whether horizontal holes designed to tap the lower oil zone could be controlled sufficiently closely to prevent penetration of the artesian aquifer underlying the glauconitic sandstone.

iii. The amount of oil which could be obtained from the lower oil zones by horizontal bores at levels substantially above the zones is likely to be small.

It is considered therefore that only the upper portion of the glauconitic sandstone needs to be taken into account in calculating the total oil content per acre. In Table VI the total oil contents per acre for the three zones combined are given as 440 and 1170 barrels respectively, depending on whether the calculations are based on the measured saturations or the maximum possible saturations. The actual total oil content lies therefore, between 440 and 1170 barrels per acre, but is probably much closer to 1170 than to 440.

If the maximum figure for oil content per acre be used, the total amount of oil contained in the productive zones for a distance of 1000 feet in all directions for the Oil Shaft will be approximately 80,000 barrels, and, if the limits of the area are extended to 2,000 feet from the shaft, the amount will be 320,000 barrels.

It should be emphasised however, that the above figures represent the total amount of oil thought to be contained in a restricted area and depth of glauconitic sandstone, and must not be regarded as "reserves". In oil geology, "oil reserves" usually signify the volume of oil which can actually be recovered from an oil reservoir and are therefore less than the total amount of oil present in it. It is also apparent that oil reserves can only be calculated for a reservoir as a whole and not for any arbitrary section of it, since oil withdrawn from one section of the reservoir will normally be replaced by oil migrating inwards towards the low pressure area established at the point of withdrawal.

In the Lakes Entrance field, oil reserves could only be calculated if definite boundaries for the oil reservoir were established; if sufficient information were available to determine average saturations and porosities for the whole field; and if all the factors influencing recovery were known. Since these factors are not known, it is impossible to deal with the reservoir as a whole and the above method of calculating the amount of oil in situ in a given area has been adopted as a means of investigating the economic possibilities of the project. These calculations, however, do not take into account the amount of oil which might migrate into horizontal drill holes from glauconitic sandstone lying outside the limits of 1000 and 2000 feet set by the lengths of the holes. However, in the light of the known physical characteristics of the reservoir, it is considered that the quantity of oil likely to be recovered in this way would not constitute an important economic factor.

The total oil contents are shown in Table VI, but no figures are given for recoverable oil because at present there appears to be no way of determining accurately what percentage of the total oil content could be recovered in horizontal wells. It is proposed therefore to discuss in the next section the principal factors affecting recovery from the glauconitic sandstone, and later to estimate the percentage likely to be recovered.

FACTORS AFFECTING RECOVERY

Distribution of the Oil

The examination of the cores by ultra-violet light shows that the proportion of oil-bearing rock in the oil zones varies from about 50 to over 90 percent. In the Shaft Bore about 10 inches of the total 31 inches of productive sandstone consists of beds or lenses almost entirely composed of oil-bearing sandstone. The remaining 21 inches consists of sandstone with irregular patches of both barren and oil-bearing sandstone in approximately equal proportions. It has been shown elsewhere that the permeability of the oil-bearing sandstone is believed to be considerably higher than that of the normal glauconitic sandstone which carries no oil. In a zone almost entirely composed of oil-bearing sandstone the permeability of the zone and the flow of oil from it will be relatively high, but in a zone in which the oil-bearing sandstone occurs as irregular patches or lenses the permeability of the zone as a whole and the flow of oil from it will be lower and will be dependent on the extent to which the patches or lenses are connected. It is obvious that where lenses or patches of oil-bearing sandstone are completely surrounded by barren glauconitic sandstone they cannot contribute to the flow of oil produced by the zone, unless they are actually penetrated by the drill. In the Pilot Bore over 80 percent of the oil is produced from one major zone, and the remainder from two minor zones whose yield is comparatively low. The explanation appears to be that, whereas the major zone includes a lens or lenses of considerable horizontal extent, almost entirely composed of oil-bearing sandstone, the minor zones consist of poorly connected lenses or patches through which oil flows with difficulty.

Although the productive zones appear to have horizontal continuity the character of any one zone may vary considerably from place to place. Thus a productive zone may be a major producing unit in one bore but may produce little oil in another bore a few hundred feet away owing to a change in the distribution and proportion of the oil-bearing sandstone in it.

A further consideration is that the oil occurs in zones which are separated by glauconitic sandstone of extremely low permeability, so that vertical migration of oil from one zone to another is practically impossible. The presence of cracks, joints, or faults in the formation might allow vertical migration, but there is no evidence to suggest that fracturing or jointing of any significance exists in the rock.

<u>Exposure of oil-bearing sandstone in horizontal drill holes</u>

If the Oil Shaft were sunk some 16 feet into the glauconitic sandstone, it might be possible to drill horizontal wells in the upper 13 feet of the formation. Provided a hole could be kept within these limits, it should penetrate oil-bearing rock but the proportion of oil-bearing to barren rock exposed would depend on various factors, and largely on chance.

In the first place, a hole may be started in a major producing zone, perhaps a foot in thickness, but any or all of the following difficulties might be encountered -

i. The zone may grade into a minor producing zone.

ii. It may not be possible to prevent the hole wandering a foot or so vertically without incurring heavy cost.

iii. The hole may pass a few inches above or below lenses of high oil content within the zone and fail to tap them.

iv. The top of the glauconitic sandstone will probably show slight irregularities in dip and these may be reflected in the oil zones themselves.

In general these difficulties become greater with increasing length of the drill holes and the penetration of oil-bearing rock some hundreds of feet from the shaft becomes a matter of pure chance. Furthermore, if chance is the only factor, the drill at any one point is more likely to penetrate barren rock than rock capable of producing oil, since the latter aggregates only one-fifth of the total 13 feet of formation involved.

In the second place, since the three productive zones each contain approximately the same quantity of oil per acre, any one drill hole, even if maintained solely within a zone, could not tap more than one-third of the available oil. This position might be improved if artifical cracks were formed in the formation (e.g. by shooting the wells) to enable migration of fluids from one zone to another, but the possible effects of the shooting cannot be visualised.

Nature of Motive Force

The percentage of oil recovered from a reservoir depends on the type of motive force causing the oil to flow to the bore or bores which tap it. It is generally accepted in oil technology that the maximum recovery with gas drive is 30 percent of the oil in the reservoir, while recovery by water drive may reach as high as 80 percent.

Gas drive results from gas coming out of solution when the reservoir pressure is reduced on penetration by the bore. This gas occupies some of the pore spaces and forces oil from them into the bore. The gas/oil ratio of the Pilot Bore, which is regarded as being typical of the area, is very low (approximately 4/1 or 22 cubic feet/barrel). A considerable reduction of pressure would have to occur before any appreciable quantity of gas came out of solution and consequently it is believed that at Lakes Entrance gas drive may not be the principal motive force but is probably operative within a few feet of the bore.

Water drive occurs when water at or above reservoir pressure replaces liquids withdrawn through the bore and includes replacement by artesian water, or by expansion of large volumes of water surrounding the reservoirs. It is believed that the principal motive force operative at Lakes Entrance is water drive, although there is no direct evidence to support this belief. It is relatively unimportant to know whether this drive is due to artesian water or to water expansion, providing the volume of water available for expansion is sufficient to replace all the liquids withdrawn. To get maximum recovery under water drive it is essential that the recovery rate should not exceed the rate at which water replaces the liquids withdrawn. In view of the many unknown factors involved in the estimation of recovery by this means it is believed that an assumption of recovery in excess of 40 percent from any oil zones effectively tapped at Lakes Entrance would be unjustified.

Another possible motive force might be the collapse of incompetent beds when the fluid pressure is relieved by boring. Compressive strength tests made on 12 samples of water-saturated glauconitic sandstone from Bore No.10 gave an average compressive strength of 1294 lb/square inch but some of the samples had strengths as low as 700 lb/square inch. It is believed that the open-textured oil-bearing portions of glauconitic sandstone might have strengths nearer to 700 lb/square inch than 1294 lb/square inch. The pressure due to the overlying rocks depends on their density, which is not accurately known, but if a density of 2.3 is assumed the pressure will be 1 lb/square inch for each foot of depth, i.e. 1200 lb/square inch at the top of the glauconitic sandstone.

If the compressive strength of any section of the glauconitic sandstone is less than the rock pressure the rock is only prevented from collapsing by virtue of the pressure of the liquid filling the pores. The relief of this pressure would surely lead to the collapse of the rock structure, with a resulting decrease in pore volume and expulsion of liquids. Such a collapse would extend progressively outwards from the point of pressure relief, but it is believed that the decrease in permeability which must result from the collapse would result in a rapid decline in the rate of production and consequently low percentage recovery from the oil zone.

Viscosity of the Oil

In theory the high viscosity of the Lakes Entrance oil (95 centipoise at 100°F) should not affect the ultimate recovery of oil because low pressure gradients will overcome the resistance to flow resulting from this viscosity if given sufficient time. In practice, however, viscosity is a factor influencing percentage recovery, because with highly viscous oil the production rate will decline to a non-profitable stage earlier than with a more mobile oil.

Permeability of the Sandstone

The low average permeability of the glauconitic sandstone will adversely effect the decline rate and consequently the ultimate recovery.

Decline Rate

The rate at which the unrestricted production from any bore tapping the reservoir declines is an indication of the ultimate recovery.

The Pilot Bore is the only bore in the Lakes Entrance field for which sufficient information is available to determine even an approximate decline curve. Bailing tests carried out at intervals over a period of about twelve months showed a decline in production of dry oil from 40 pints a day, initially, to 27 pints a day, i.e. a decline of about 33 percent. The quantity of oil which could have been produced during this time had the bore been bailed every day would have been of the order of 1500 gallons. If the same percentage decline is maintained over the next few years it has been estimated that at the end of three years the rate of production will have fallen to about 8 pints a day and the yearly production in each of these three years will be 1000, 660 and 440 gallons respectively, making a total of 3600 gallons produced in four years. If the same decline rate is maintained for a period of 10 years, the ultimate yearly production will have dropped to about 40 gallons and the total production over the ten years period would be about 4400 gallons. The latter might be regarded as the ultimate recovery from the Pilot Bore.

If a horizontal bore hole were to tap the same oil zones that were tapped by the Pilot Bore, the initial production rate would be much greater than for the Pilot Bore because a greater length of the bore would intersect the zones: but the decline rate will also be very much greater, because in the Pilot Bore (where a vertical hole intersects a horizontal oil zone), drainage of oil to the hole would be uniform from all directions (radial flow), but in the horizontal hole, drainage would be limited to flow more or less normal to the hole in the horizontal plane of the oil zone (linear flow). The ultimate pressure distribution in the oil zone for which the flow to the hole would be insignificant would be attained much more rapidly by linear flow than by radial flow or in other words the decline rate for the former would be much more rapid than for the latter. Although no estimate can be made of the quantity of oil likely to be yielded by a horizontal hole, it is evident from the rapid decline in production from the Pilot Bore that the reservoir energy responsible for this production is dissipated rapidly, and consequently the area drained by the Pilot Bore and the recovery from this area must be small. It is concluded, therefore, that the rapid decline in production from the Pilot Bore is an indication that the ultimate recovery from any acre of glauconitic sandstone in the vicinity of the Lakes Entrance shaft will necessarily be low.

The actual area drained by the Pilot Bore cannot be determined, but if it were one acre, which according to the calculations shown in TableVI contains 1170 barrels, the ultimate recovery from this area, namely 4400 gallons or 125 barrels, represents a recovery of about 11 percent. A circular area of radius 120 feet about the bore contains one area; so another way of expressing the above is that if the drainage radius is 120 feet the recovery will be 11 percent of the oil in the area drained. Assumption of a larger area or drainage radius will necessarily reduce the percentage recovery. The inference of this is that to get a reasonable recovery from an area surrounding the shaft the density of the drainage points must be high. If the recovery has to be obtained from vertical bores it is seen that a density of one bore per acre might lead to an ultimate recovery of about 11 percent, providing of course that the production from the Pilot Bore and its decline represents the average for the area. A similar basis would have to be used to determine the number of horizontal holes required to get comparable recovery.

<u>Number and distribution of the Horizontal Wells</u>.

The deductions in the preceding section are based on the somewhat inadequate information about the decline in production from the Pilot Bore, and must therefore be regarded as very approximate. It is believed, however, that they at least indicate the order of magnitude of the ultimate recovery and consequently the approximate drainage radius. If drainage conditions at the Pilot Bore can be accepted as average for the area, and if a drainage radius of 120 feet is accepted for this bore, a similar drainage radius or distance might be applied to drainage to a horizontal well. For a horizontal drill hole 1000 feet long, the area of the upper 13 feet of sandstone within 120 feet each side of it would be 5.5 acres and the total of content and 6,400 barrels. If an ultimate recovery of 11 per cent is assumed, the recovery from 1000 feet of drill hole would be approximately 700 barrels or 0.7 barrels per linear foot of drilling.

If this argument is extended to a project in which 20 equally spaced horizontal holes each 1000 feet long are drilled from the shaft, the area within 120 feet laterally of the bores will be 68 acres, compared with 70 acres in a circular area of 1000 feet radius. If the same bores are extended to 2000 feet from the shaft, the area within 120 feet laterally of the bores will be 178 acres, compared to 280 acres for a circular area of 2000 feet radius. It is seen, therefore, that, if drainage is restricted to a limited distance from the bores, the longer the bore hole the less effective is the drainage and recovery from a circular area about the shaft. It must be clearly understood however, that the figures given above for the area drained and for the ultimate recovery are based on very poor evidence and they should not be used as a basis for estimating the ultimate recovery from any area about the shaft. However, they serve to illustrate the fact that the number and distribution of the horizontal wells must be factors influencing the ultimate recovery of oil from an area about the shaft, and for this reason it is believed that their inclusion in this report is justified.

Conclusions concerning Recovery

Taking all the above factors into consideration it is concluded that, if water drive is the motive force, the recovery of oil by horizontal wells from an area in the vicinity of the Oil Shaft would not exceed 15 to 20 percent and if gas-expansion drive is the principal motive force the recovery would be less than this and probably not greater than 5 to 10 percent.

It was shown in an earlier section of this report that the total amount of oil contained in the productive zones in the uppermost 13 feet of the sandstone for a distance of 1000feet in all directions from the Oil Shaft is approximately 80,000 barrels and if the limits are extended to 2000 feet from the shaft, the amount would be 320,000 barrels.

These quantities are based on an assumption that in the upper 13 feet of sandstone the average thickness of oil-bearing rock is 31 inches throughout the area and that the oil content is equal to that determined for the 31 inches of sandstone included in zones 1, 2 and 3 in the Shaft Bore. Any errors involved in these assumptions will necessarily be reflected in calculations of the quantity of oil which might be recovered.

If a maximum recovery of 20 percent is assumed for the circular area with a 1000 feet radius the quantity of oil which might be recovered is 16000 barrels. Because the horizontal wells become farther apart as the distance from the shaft increases the percentage recovery from the larger area (radius 2,000 feet) would be less than from the smaller and a maximum recovery of 15 percent or 48,000 barrels might be expected. If an area of 400 acres (the area for which Ranney and Fairbank (1941) calculated oil content and recovery) is considered the total oil content would be 470,000 barrels and a 15 percent recovery would give approximately 70,000 barrels.

CONCLUSIONS

The report has dealt with the examination of diamond drill cores from the bottom of the Shaft at Lakes Entrance, and includes the results of petrological examination, examination under ultra-violet light and determination of oil, water, and gas saturation. The drill hole penetrated 19 feet 2½ inches in glauconitic sandstone with a core recovery of 82 percent, consisting mainly of unbroken lengths of core. The 18 percent not recovered probably did not include any significant proportion of oil-bearing glauconitic sandstone.

The oil fluoresced under ultra-violet light and this method was used to determine in detail the distribution of oil in the cores. The examination allowed the division of the glauconitic sandstone section into five oil-bearing zones of which the bottom two zones, i.e. zones 4 and 5, were insignificant and were excluded from the calculations of total oil content. The upper three zones (zones 1, 2 and 3) were the main oil-bearing zones, and occurred in the top 13 feet of glauconitic sandstone. Evidence has been gathered on the distribution of oil in several additional bores in an area surrounding the shaft and indicated that the occurrence of oil in the top 13 feet of glauconitic sandstone was a feature common to all of them. It was found that there was a close parallel between the oil zones as indicated by bailing tests in the Pilot Bore with those in the Shaft Bore 100 feet away.

The evidence showed that oil from other bores referred to above also occurs fairly generally in the lower portion of the glauconitic sandstone, but neither the Pilot nor the Shaft Bore intersected this portion, which has therefore been excluded from any conclusions regarding the oil content of the reservoir.

Two kinds of oil distribution were noted; one in which oil occurred almost entirely throughout the cores and the other in which the oil occurred as irregular patches throughout the cores. The cores in which the patches exceeded 50 percent of the volume of the cores were included in the oil zones.

The aggregate thickness of oil-bearing zones included in the calculation of total oil content per acre was 31 inches, comprising 11, 12, and 8 inches in zones 1, 2, 3 respectively.

Petrological work indicated that oil-bearing glauconitic sandstone contains less glauconitic mud matrix than barren or 'normal' sandstone. Because of this it is believed that the permeability of oil-bearing glauconitic sandstone is considerably higher than that of normal glauconitic sandstone and and this belief is supported by a critical examination of the results of permeability tests on samples from No. 10 Bore. It appears that the sandstone as a whole is not an oil reservoir, but contains a series of thin stratigraphical traps. The horizontal extent of any one trap has not been determined; but it is thought that they occur as a series of lenses. They occur at fairly definite horizons and form the oil zones already described.

Saturation andporosity tests were made on all sections of the core which the ultra-violet light examination had shown to contain appreciable quantities of oil, and on eleven samples of barren sandstone. The porosities ranged from 27.4 to 49.6 percent, oil saturations from 0 to 12.2 percent, water saturations from 63.5 to 99 percent, and gas saturations from 1 to 26.6 percent. The porosities were determined on dry samples, and it is believed that they are greater than the actual porosities of the reservoir rocks in situ. Planar water would have been driven off from the dry samples but would be present in the reservoir rocks, and consequently the volume of interstices available to oil and true interstitial water has been reduced by the swelling of the clay and clay-like minerals in the glauconitic mud. This swelling is due to planar water in these minerals.

Tests were made at the Pilot and Imray Bores to determine the quantity of gas yielded by each, and the results indicated gas/oil ratios of 4 and 70 respectively: these ratios, however, must be regarded as approximate and subject to large error. It is believed that the gas produced was substantially methane and that therefore the gas in the cores was methane and was originally in solution in the oil.

Tests were made to determine whether any of the drilling water had entered the cores. An indicator chemical, glucose, was added to the drilling water and six core samples were analysed for glucose. None was found in the cores and it has been concluded that none of the drilling fluid entered them.

A test was made on a sample of glauconitic sandstone to determine the water lost at various temperatures between 14°C and 106°C, and it was concluded from the results that none of the water collected during the saturation tests was water of crystallisation. The water collected included true interstitial water and planar water. There appears to be no means of determining by direct measurement the quantity of planar water in a sample.

Tests were made to determine the quantity of water lost by evaporation during the time the samples were exposed before their saturations were determined; and in calculating the final figures for oil, gas and water saturations, allowance was made for the space in the samples occupied by air which has replaced evaporated water.

It has been assumed that the space in the cores occupied by gas other than air mentioned above was formerly occupied by oil which it has replaced.

The total oil saturation in situ was calculated by assuming that it was the sum of the oil saturation found experimentally and the corrected gas saturation. Weighted averages of total and residual or measured oil saturations were calculated for each of the three oil zones by weighting the individual samples in accordance with their lengths. These averages for zones 1, 2 and 3 were 14.8, 13.0, and 16.0 percent for the total oil saturations and 5.12, 5.5, and 5.9 percent for residual oil saturation. It has been concluded that these figures for total and residual oil saturations are not inconsistent with the experimental results of Leverett and Lewis on the flow of gas-oil-water mixtures through permeable media if due allowance is made for the low permeability of the glauconitic sandstone and the effect of planar water on the porosities and saturations. On the basis of the above figures the oil contents per acre for the three zones combined are estimated at -

(1) Total oil content	1170 barrels per acre.
(2) Oil content from residual saturations	440 " " "
(A barrel contains 35 imperial gallons)	

It is concluded that through lack of appropriate data there is no reliable way in which the area of reservoir rocks likely to be drained by any well or series of wells in a field such as Lakes Entrance can be estimated, nor is there any satisfactory basis for estimating the quantity of oil which might be recovered from such an area. However, it is possible to estimate the total oil present in a given area around the shaft, and to make an approximate estimation, based on the factors influencing recovery, of the proportion of this oil which might be recovered by horizontal drilling.

Factors influencing ultimate recovery are:

(1) Those dependent on reservoir conditions:

(a) The oil occurs in three thin zones separated by layers of impermeable sandstone.

(b) Of the 31 inches included in the three zones, only 10 inches were composed entirely of oil-bearing sandstone and it is believed that most of the oil produced in the Pilot Bore came from zones of sandstone entirely oil-bearing, the permeability of sandstone corresponding to the remaining 21 inches being too low to allow any appreciable flow into the hole.

(c) There may be no great horizontal continuity in an individual oil zone.

(d) High viscosity of the oil and low permeability of the oil zone.

(e) The motive force causing the oil to flow. It is generally conceded that, under the most favourable conditions, if oil if flowing under gas drive the ultimate recovery may be 25 to 30 percent and that with carefully controlled water drive, which includes artesian and expansive water drive, the recovery may be 60 to 70 percent.

(f) A rapid decline in the rate of production such as that determined for the Pilot Bore (from 40 to 27 pints per day in 340 days) usually indicates low ultimate recovery.

(2) Those dependent on recovery from horizontal drill holes -

(a) Any hole could tap only one of the three zones because of the impermeable sandstone between them.

(b) It will be very difficult, if not impossible, to keep a horizontal drill hole within any one of the thin oil-bearing zones.

(c) The number and distribution of the horizontal drill holes.

(d) The unknown influence of fracturing the sandstone by exploding charges in the bore holes.

Taking all these factors into consideration it has been estimated that if water drive is the motive force, the recovery would not exceed 15 to 20 percent, and if gas-expansion drive is the motive force the recovery would be considerably less than this and probably not greater than 5 to 10 percent.

Finally it is concluded that the volume of oil present in the three oil zones in a circular area 2,000 feet diameter would be approximately 80,000 barrels, of which a maximum of 16,000 barrels might be recovered. These figures refer to the top 19 feet of the glauconitic sandstone.

It is known from other bores that oil occurs in the lower portion of the glauconitic sandstone. This portion was not, however, intersected in the Pilot and Shaft bores and therefore no attempt has been made to estimate the oil content. Even if the total oil content could be estimated, it would be inadvisable to attempt to estimate the possible recovery because of the engineering difficulties associated with the sinking of the shaft to a sufficient depth to recover such oil by horizontal holes. The possibility of recovering any of the oil from horizontal holes in the upper portion of the sandstone would depend upon the fracturing by explosive charges, and, as already stated above, the possible effect of such charges is not known.

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REPORT ON THE PERMEABILITY, POROSITY, AND OTHER PHYSICAL PROPERTIES ON A NUMBER OF ROCKS AND MINERALS

INTRODUCTION

This report is written primarily to present the determination of the permeability and porosity of a number of rocks and minerals from No. 10 Bore, Lakes Entrance, and Lakes Entrance shaft, but it has also been considered advisable to give a brief description of the different kinds of apparatus designed and used in making the determinations.

The method of presentation adopted in this report is first to describe the apparatuses used in making the determinations and the technique adopted in preparing the specimens for testing and secondly to discuss the results obtained for each set of specimens.

In addition to the permeability and porosity tests already mentioned, a number of tests of compressive strength were made on wet and dry samples of glauconitic sandstone from Lakes Entrance.

The writer wishes to acknowledge the assistance given to the investigation by Professor C. R. McRae, Principal of the Sydney Teachers' College, who made available the facilities of the College Workshop. Mr. R. Cullen of the workshop staff made the mechanical parts of the apparatuses and the design of the model II sample holder was largely influenced by his helpful criticism and advice.

Acknowledgement is due also to Mr. L. Thornton, Roads and Bridges Section, Department of the Interior, for permission to use the diamond drilling machine for preparing the test samples and other machines used in determining the compressive strength of the glauconitic sandstone. Thanks are also due to Dr. F. W. Clements, Director of the Commonwealth Institute of Anatomy, who made available some of the auxiliary apparatus used in making the determinations and calibrating the permeameter flowmeter.

APPARATUS AND METHODS USED

PERMEABILITY

The apparatuses used in making the permeability and porosity determinations were designed by the writer and were constructed in the workshops of the Sydney Teachers' College.

Two separate apparatuses were used in the permeability tests. They are similar in principle, but differ in the way in which the sample is held and in the construction of the flowmeter and manometer. They will be referred to as models I and II permeameters.

Model I Permeameter

Fig. 3 shows the general layout of the permeameter. It consists of (a) a sample holder in which cylindrical samples are held under compression in a tapered rubber stopper, (b) a flowmeter comprising a capilliary tube connected across a differential manometer, (c) a needle valve for controlling the rate of flow through the system. Auxiliary equipment includes a drying tube on the intake side of the sample holder and a vacuum pump.

The manometers are filled with oil of low vapour pressure and of specific gravity 0.865.

Preparation of the samples

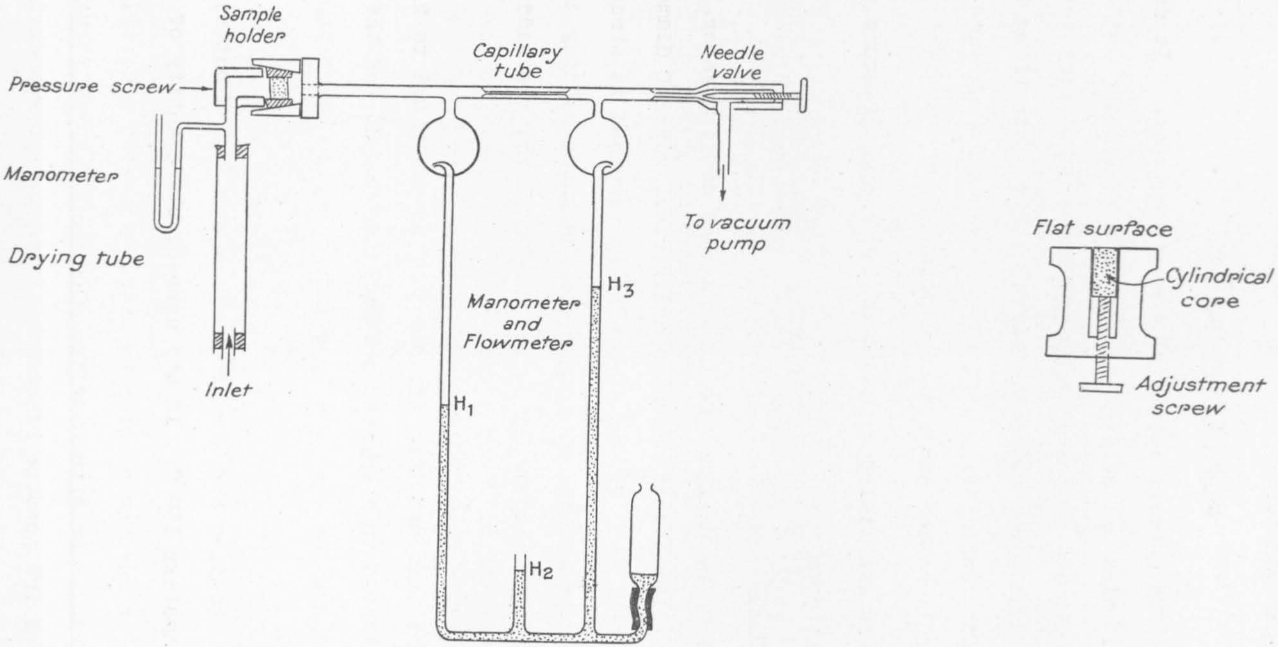
The material to be examined is first saturated with water. It is then mounted in a diamond drilling machine and a cylindrical core of diameter approximately 1 inch is cut from it. If the sample being prepared is stratified the axis of the core is made parallel, or normal, to the known bedding depending on whether the permeability in the direction of, or normal to, the bedding is to be determined.

The cores are then cut into desired lengths (from 0.5 to 2.0 cm.) by means of a hacksaw, mounted in a special holder (see Fig. 3) and the ends made flat and normal to the axis of the core by means of coarse emery paper or a coarse file.

The prepared samples are then thoroughly dried in a hot air oven at a temperature of approximately 150°C. If any appreciable quantity of oil is present in the sample it must be removed by extraction with redistilled benzene or other suitable solvent. An apparatus was constructed for forcing benzene through the samples for the purpose of washing them, but it was obvious from the lack of discoloration of the emerging benzene that no appreciable quantity of oil was present in the samples so treated.

Fig. 3

MODEL I · PERMEAMETER



Mounting the Sample for Testing

The design of the model I sample holder follows that described by H. C. Pyle and J. E. Sherborne (1939). The dried cylindrical samples are mounted by pushing them into the cylindrical hole (diameter slightly less than 1 inch) in a tapered rubber stopper which in turn is mounted in the tapered brass sleeve of the sample holder. This sleeve is then seated on the rubber gasket in the base of the holder and the cap is fitted. Pressure is applied through the cap to the rubber stopper by means of the compression screw. The action of this screw is to force the rubber stopper into the tapered sleeve, at the same time compressing the rubber and making a tight seal between it and the sides of the sample.

The drying tube, manometers, needle valve and vacuum pump are connected as shown in Fig. 3 and the apparatus is ready for making a permeability determination.

Reading

The vacuum pump is now started and the needle valve adjusted until the oil level (H_1) in the left hand manometer tube rises about two inches. The oil is maintained at this level by manipulating the needle valve while the levels H_1, H_2, and H_3 are read. This process is repeated with H_1 at different levels from 0 to the maximum obtainable. The maximum obtainable depends on the reading H_3, which is always greater than H_1 by an amount depending on the rate of flow and hence the drop in pressure through the capillary tube. The apparatus is provided with interchangeable capillary tubes so that a wide range of rates of flow can be handled conveniently.

The small U-tube manometer mounted at the top of the drying tube is observed from time to time to make sure that there is no drop in pressure across the drying tube. The rates of flow generally observed are found to be too low to cause readings other than zero on this manometer.

The vacuum pump used in these tests was a small oil pump, but this could be replaced by a water jet pump because the vacuum pump need only provide a vacuum of approximately 10 cm. of mercury at a low pumping rate to provide satisfactory working conditions.

Calculation of Permeability from the Readings

Providing the flow is 'streamlined', the rate, Q, at which a fluid will flow through an area A depends on:-

(1) the area A;

(2) the thickness of material t;

(3) the pressure difference P_1-P_2;

(4) the viscosity of the fluid N;

(5) a factor characteristic of the specimen and called its specific permeability (K).

These parameters are connected by the following expression:-

$$K = \frac{Nt}{A} \cdot \frac{Q}{P_1-P_2} \text{ ------------------------------------ } (1)$$

For a compressible fluid (air) the rate of flow Q must be expressed as the mean rate of flow within the specimen (usually written $\overline{Q}$). Q is determine experimentally by measuring the drop in pressure across the capillary tube, i.e. by (H_3-H_1). An initial calibration gives the values of Q corresponding to different values of H_3-H_1. This calibration is made with the inlet end of the capillary tube at atmospheric pressure, i.e. $H_1 = 0$. The values of Q obtained experimentally must be adjusted to the mean rate of flow $\overline{Q}$ by means of a correction factor which depends on the values of H_1 and H_3.

The drop in pressure (P_1-P_2) across the sample is determined by the reading H_1 (H_2 being assumed to be zero) because P_1 = atmospheric pressure, and P_2 = atmospheric pressure - H_1 inches of oil.

If the flow through the specimen is viscous (streamlined) over the observed range of values of H_1 then a straight line will be obtained by plotting $\overline{Q}$ against P_1-P_2. Conversely if a straight line is obtained by plotting $\overline{Q}$ against P_1-P_2 then the flow through the specimen is streamlined and the relationship (1) can be applied.

In practice it is found that small experimental errors are present and a 'mean' straight line is drawn through the points. The slope of this 'mean' line is used as the ultimate value of $\overline{Q}/P_1-P_2$. If $\overline{Q}$ is expressed cc/sec., P_1-P_2 in atmospheres, t in cm., A in sq. cm. and N in centipoise, then K according to equation (1) is in darcies. It is usual to express permeabilities in millidarcies, and this practice has been followed in expressing the results obtain in this investigation. A typical set of readings shows the method of working out the results:

MODEL I. PERMEAMETER.

Specimen:- Glauconitic sandstone, Bore 10, Lakes Entrance, 1291.5 ft. - 1294.5 ft., No. 48.

Diameter = .97 inches.

Area (A) = 4.75 cm^2.

Thickness (t) = .838 cm.

Air temperature = 62°F.

Air viscosity (N) = 181 x 10^{-4} centipoise.

H_1 Inches	H_2 Inches	H_3 Inches	H_1-H_2 Inches	P_1-P_2 Atmphs.	H_3-H_1 Inches	Q cc/sec	$\bar{Q}$ cc/sec	$\frac{\bar{Q}}{P_1-P_2}$
1.90	-.06	2.17	1.96	.0042	.27	.033	.033	7.85
3.37	-.12	3.88	3.49	.0075	.51	.062	.061	8.13
5.07	-.18	5.85	5.25	.0112	.78	.094	.093	8.29
6.98	-.23	8.06	7.21	.0154	1.08	.130	.129	8.38
8.69	-.32	10.05	9.01	.0193	1.36	.164	.162	8.40
10.52	-.36	12.13	10.88	.0232	1.61	.195	.192	8.28
12.29	-.41	14.19	12.70	.0272	1.90	.230	.226	8.32

$$K = \frac{N\ t\ \ \bar{Q}\ 10^3}{A\ \ (P_1-P_2)} \text{ millidarcies}$$

$$= \frac{1.81 \times .838 \times 8.35 \times 10}{4.75} = 26.7 \text{ millidarcies}$$

Model II Permeameter.

Model II is identical in principle with Model I but the sample holder, flowmeter, and manometer designs are different. This permeameter is 'direct reading' because the pressure difference in atmospneres and the rate of flow in cc/sec. are given directly by readings on the appropriate scales. Fig. 5 illustrates the general layout.

The Sample Holder

The sample holder is designed to mount hollow cylindrical samples up to 5 cms. in diameter and 5 cms. long.

The samples are seated on a soft rubber gasket with a central hole coinciding with the air outlet. The top of the sample is covered by a soft rubber gasket and metal disk on which the compression screw bears. Pressure is applied by means of this screw and the sample is held firmly between the gaskets in such a way that no leakage can occur between the gaskets and sample.

A small bell-jar covers the mounted sample and pressure screw and makes a gas-tight seal with the sample-holder base-plate. The air, which flows through the sample, enters the space enclosed by the bell-jar through a tube let into the base-plate as shown in Fig. 4. After passing through the sample, the air is drawn through the outlet tube in the centre of the base-plate and passes through the flowmeter.

The Manometer

A U-tube manometer of special design is connected across the inlet and outlet sides of the sample holder. The LHS of the manometer comprises a 1.5 cm. diameter tube connected at its lower end to the reservoir (diameter 4 cm.) and also connected near the top to the drying tube and air intake.

The RHS tube is 0.5 cm. diameter but is enlarged to 1.5 cm. diameter where it joins the outlet of the sample holder and the connexion to the flowmeter. The manometer is filled with oil of low vapour pressure and of S.G. 0.865. The scale on the RHS is calibrated directly in atmospheres and represents the drop in pressure across the sample under test.

Fig. 4

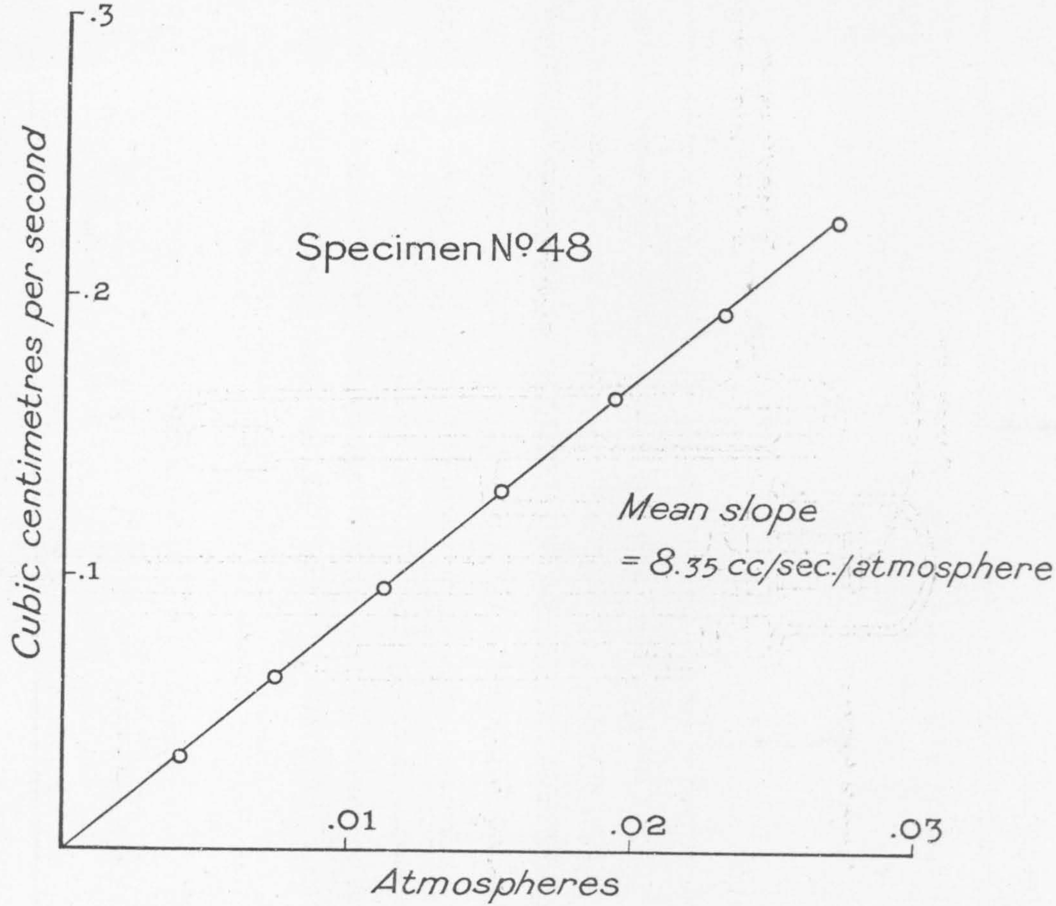
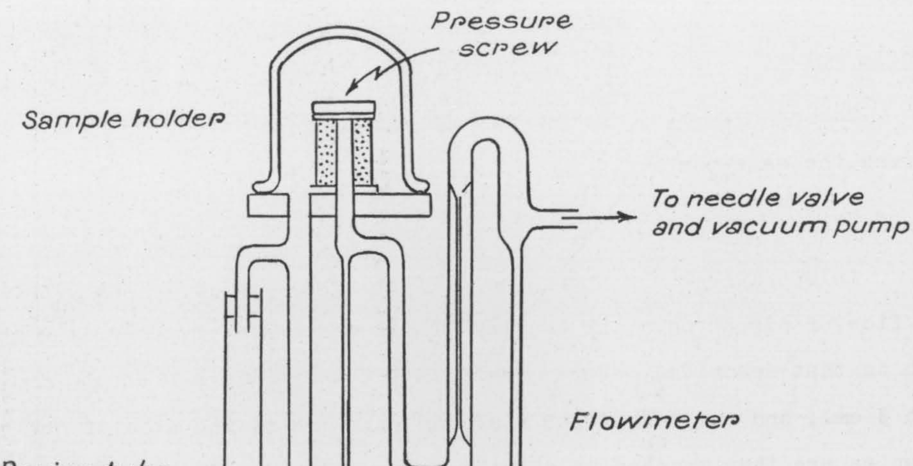

.3
.2
.1
Cubic centimetres per second
Specimen Nº 48
Mean slope
= 8.35 cc/sec./atmosphere
.01
.02
.03
Atmospheres

Fig. 5

MODEL II · PERMEAMETER



The Flowmeter

This part of the apparatus comprises a capillary tube connected across a differential manometer. The manometer is filled with oil (S.G. 0.865) and the scale on the RHS gives directly the rate of flow in cc/sec.

In the instrument described, full scale reading of the flowmeter is approximately 8 inches of oil, corresponding to a flow rate of 1 cc/sec. This range is sufficient for permeabilities up to 500 millidarcies, but for values greater than this a second flowmeter roading up to 10 cc/sec. would be necessary.

The needle valve

The needle valve is the same as that used in the Model I apparatus and serves the same purpose.

Method of Using Permeameter

In operation this apparatus differs from Model I in the direction of the flow of air through the sample. The samples are prepared in a manner sililar to that described before except that the cylinders are cut into lengths of 2 to 3 cm., and the ends filed flat and parallel to the axis of the cylinder. The samples are then mounted in a lathe and a hole (diam. about 7-8 mm.) drilled through them. The surfaces of this hole are roughened by means of coarse emery paper to remove any fine material which might clog the pores and, after drying, the samples are ready for mounting.

It will be appreciated that the air flow in this case is radially inward. For such a direction of flow, the expression connecting the permeability (K) with the dimensions of the sample, pressure differences and rate of flow is as follows:-

$$K = \frac{\bar{Q}\,N}{2\pi t} \cdot \frac{\log_e \frac{r_1}{r_2}}{P_1 - P_2} \qquad \text{------------------------(2)}$$

where K, $\bar{Q}$, N, t and P_1-P_2 have the same meaning as in equation (1), and r, is the external and r_2 the internal radius of the cylinder.

Reading

The procedure adopted in taking readings is similar to that for Model I, the values of Q and (P_1-P_2) being given directly by readings on the appropriate scales. The value of Q obtained must be corrected to the value $\bar{Q}$, i.e. the mean rate of flow within the specimen, the correction factor depending on the values of Q and (P_1-P_2).

As in the previous case, values of $\bar{Q}$ are plotted against (P_1-P_2) values. A straight-line plot represents streamlined flow and hence equation (2) may be applied.

A typical set of readings and plot are set out below and illustrate the method of working out results. It will be noticed that the straight line drawn through the points on the $\dfrac{\bar{Q}}{P_1 - P_2}$ graph does not pass through the origin. This is because the flowmeter has a slight zero error which was corrected for later tests.

The permeability (K) follows from the application of the equation (2), the mean slope of the graph being used for the value of $\dfrac{\bar{Q}}{P_1 - P_2}$.

MODEL II. PERMEAMETER.

Specimen:- Glauconitic sandstone, Bore 10, Lakes Entrance, 1291.5 ft. - 1294.5 ft. No. 54.

External diameter = .99 inches ($2r_1$)

Internal diameter = .30 inches ($2r_2$)

Thickness (t) = 3.26 cms.

Air temperature = 63°F.

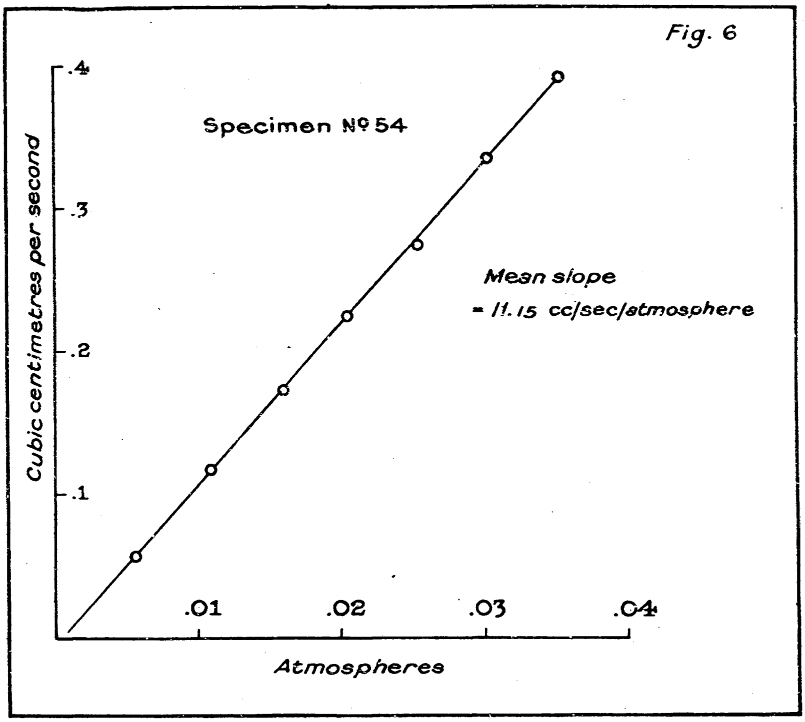
Air viscosity = 181×10^{-4} centipoise.

$P_1 - P_2$ Atmospheres	Q cc/sec	$\bar{Q}$ cc/sec	$\frac{\bar{Q}}{P_1-P_2}$
.0056	.060	.0595	10.6
.0107	.119	.117	10.9
.0160	.173	.171	10.7
.0205	.230	.226	11.0
.0252	.281	.276	10.9
.0302	.342	.335	11.1
.0353	.405	.395	11.2

$$K = \frac{N \log_e \frac{r_1}{r_2}}{2\pi t} \times \frac{\bar{Q}}{P_1 - P_2} \times 10^3 \text{ millidarcies}$$

$$= \frac{1.81 \times 1.19 \times 11.15 \times 10}{6.28 \times 3.26}$$

$$= 11.65 \text{ millidarcies}$$



POROSITY APPARATUS

Fig. 7 represents the layout of the porosimeter. The apparatus comprises two glass vessels of known volumes V1 and V2 connected by a glass tap (3 mm. bore).

The upper vessel (V_1) is a cylinder approximately 2.5 cm. in height, 2.5 cm. in diameter, terminated at its upper edge by a ground glass flange. It can be sealed by means of a plate glass cover through one edge of which a small hole has been drilled. The seal is made airtight by applying a smear of vaseline or vacuum grease to the ground glass flange. The volume enclosed between the glass tap and the plate glass seal is carefully measured by filling the vessel with mercury, applying the cover plate and allowing the excess mercury to escape through the small hole.

The volume of the lower vessel, between the glass tap and zero mark, is also carefully determined.

The lower vessel is attached at its bottom end to a manometer tube 4. mm. in diameter and approximately 30 inches long which in turn is connected at its bottom end to a second manometer tube approximately 40 inches long and also 4 mm. in diameter. The manometer tubes can be filled with mercury from the mercury reservoir which is attached to their lower end by means of rubber tubing. The mercury reservoir is mounted on a sliding carrier which is fitted with a clamping screw and level adjustment screw. The length of the slide is such that the reservoir can be elevated to a height slightly in excess of that of the upper vessel and lowered to the base of the apparatus.

Method of Using Porosimeter

Cylindrical samples are prepared in the same manner as for the permeability determinations. The upper vessel, into which the sample is placed for testing, will permit the use of a sample 2.5 cm. diameter and 2.5 cm. in height.

The lower vessel is first evacuated. This is done by raising the mercury reservoir until the mercury rises through the lower vessel and reaches the base of the tap. The tap is then closed and the mercury reservoir lowered to its lowest level. In doing so, the level of the mercury in the lower vessel is made to fall below the zero mark on the LHS manometer-tube and a vacuum is created above it. It is generally found that a certain amount of air adheres to the glass walls of the lower vessel and this air is yielded up upon the evacuation of this vessel. The mercury reservoir is raised and lowered a number of times (the tap meanwhile remaining closed) to assist in the elimination of the 'adhering' air and finally the level is raised once more, the tap opened and any air collected is pushed through the tap into the upper vessel. The mercury level is adjusted so that the mercury fills the hole in the tap without entering the upper vessel. The tap is now closed and the reservoir again lowered until the mercury in the LHS manometer tube stands level with the zero mark. The reading on the RHS manometer tube gives the atmospheric pressure in inches of mercury.

The sample, after careful drying, is placed in the upper vessel and the vessel sealed by placing the cover plate on the ground glass flange which has been smeared with a thin coating of vaseline or vacuum grease. The cover plate is first fitted so that the hole connects with the upper vessel, the cover plate pressed firmly onto its seat and then slid sideways until the hole no longer connects with the upper vessel. If an airtight seal has been made the vaseline or vacuum grease will appear clear and free of air bubbles. This procedure ensures that the sample is sealed in the upper vessel at atmospheric pressure.

Fig. 7

POROSIMETER

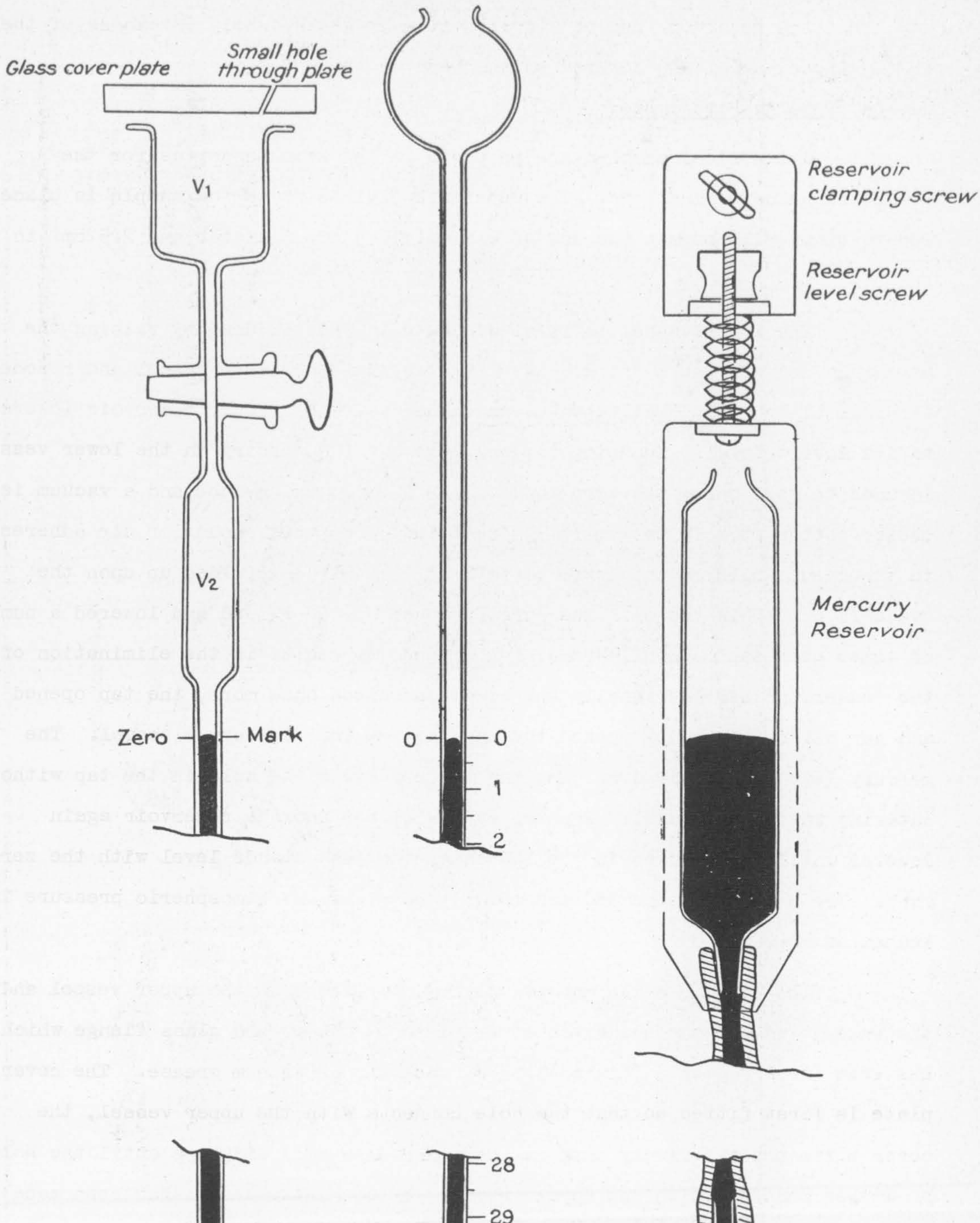
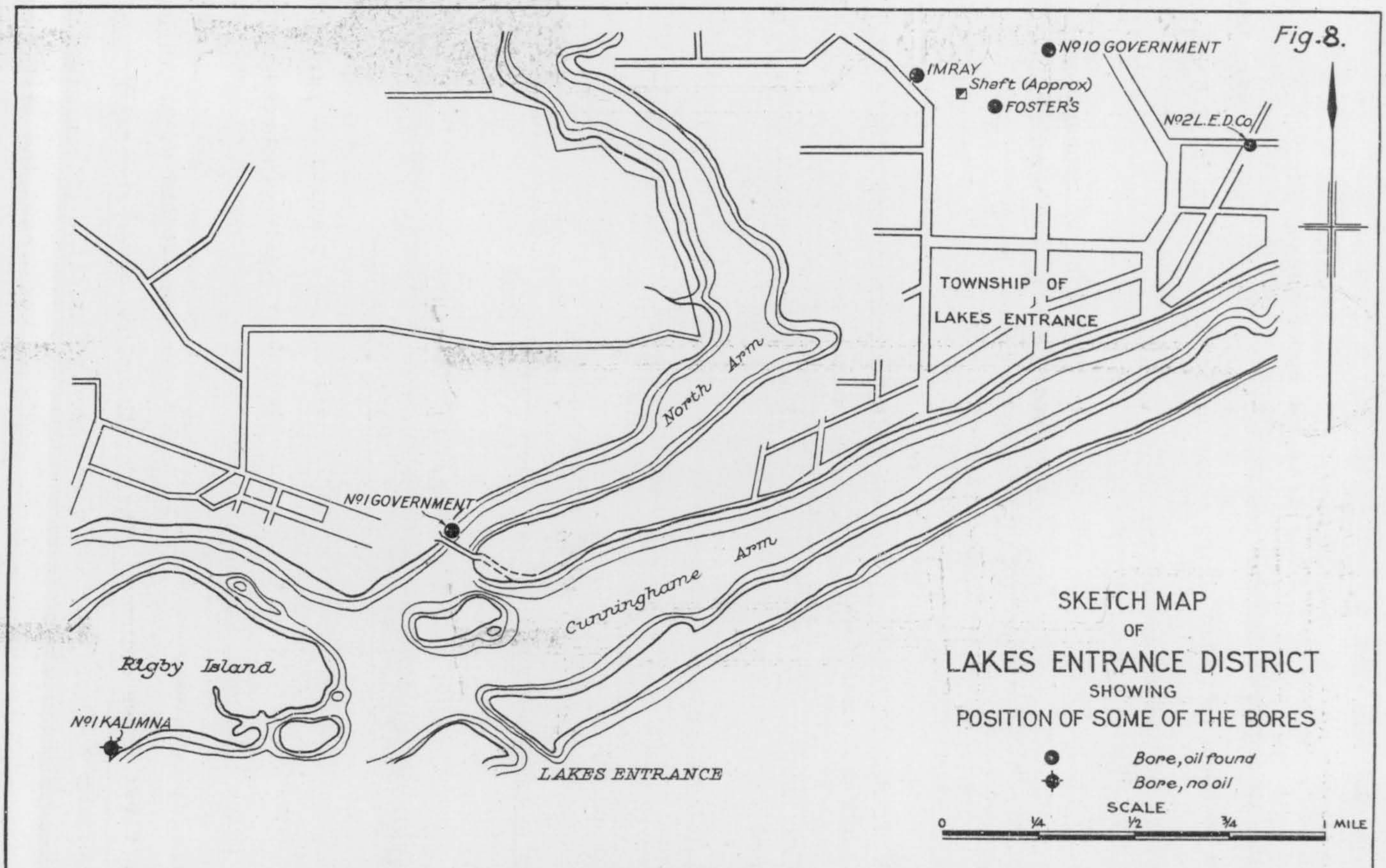


Fig. 8.



SKETCH MAP
OF
LAKES ENTRANCE DISTRICT
SHOWING
POSITION OF SOME OF THE BORES

The vessels are now interconnected by means of the tap and the reservoir level adjusted until the mercury in the LHS manometer tube is level with the zero mark.

Owing to the air from the upper vessel expanding adiabatically, some time is required for the temperatures to adjust themselves. One hour was found to be necessary when using solid cylinders, 2.5 cm. by 2.5 cm.

Let V1 be the volume of the upper vessel.
V2 " " " " " lower "
Vc " " " " " specimen (obtained by measurement).
Vp " " " " " air spaces within the specimen.
At " " atmospheric pressure in inches Hg.
(At-H) " " final pressure when the two vessels are interconnected and temperatures adjusted (in inches of Hg).

Before interconnection we have a volume of air equal to (V1-Vc) + Vp at atmospheric pressure.

After interconnection we have a volume (V1-Vc) + Vp + V2 at a pressure of (At-H).

By Boyles Law

$$\left\{ (V1-Vc) + Vp \right\} At = \left\{ (V1-Vc) + Vp + V2 \right\} (At-H)$$

from which

$$Vp = V2 \left(\frac{At-H}{H}\right) - (V1 - Vc)$$

The percentage porosity is $\frac{Vp}{Vc} \times 100\%$

RESULTS OF TESTS

GLAUCONITIC SANDSTONE, BORE 10, LAKES ENTRANCE.

The accompanying table sets cut the results of permeability, porosity and strength tests made on a representative suite of specimens from No. 10 bore at Lakes Entrance, Victoria.

The bore log compiled by H. G. Raggatt and J. W. Binney is given in the first three columns. The fourth column gives the depth from which the specimens used in the test were taken. The fifth column gives the distinguishing number appropriate to each test piece or sample and the sixth column shows the measured permeability expressed in millidarcies. The direction of flow relative to the bedding is indicated by means of the letters P N or C depending on whether the rate of flow, and hence permeability, is measured paralled to the bedding, normal to the bedding, or part normal part with the bedding.

The following columns are devoted to the porosity, measured and calculated, apparent density and compressive strength.

Permeability Results

Previous Determinations

Reference can be found to two previous determinations of permeability of Lakes Entrance glauconitic sandstone. I.C.H. Croll of the Victorian Mines Department [2] gives the results of a number of tests on specimens from No. 1 Government bore, No. 2 Lakes Entrance Development bore, and the No. 1 Kalimna bore, Lakes Entrance. For the location of these bores see Fig. 8.

Permeabilities measured ranged from 450 to 4 millidarcies. Croll's analysis of the results shows an average permeability of 223 millidarcies along the bedding and 15 millidarcies across the bedding with an approximate mean permeability of 77.5 millidarcies. After discussing possible sources of error in his determinations, Croll concludes that "the weight of evidence is in favour of regarding the results calculated from those tests as being lower than the actual permeability."

The only other reference that can be found for permeability measurement occurs in a report by K. Washington Gray and I.C.H. Croll [3]. On page 98 reference is made to a test conducted by Oliver Streeton on a specimen of the "normal rock" (glauconitic sandstone) using Lakes Entrance crude oil. He found that with a plate of rock 2 mm. thick and half a square inch in area at a temperature of 50°F. and a pressure differential of half an atmosphere, the rate at which the oil would pass through the rock after it has been thoroughly saturated was 0.1 cubic cms. per 12 hours.

Making use of equation (1), page 66, and putting $N = 6.25$ poise (by extrapolation from figures given by Croll in Redwood units).

$Q = 2.3 \times 10^{-6}$ cc/sec.

$P1-P2 = 0.5$ atmospheres.

$T = 0.2$ cm.

$A = 3.2$ sq. cm.

we find that K is equal to 0.18 millidarcies. This figure differs considerably from Croll's average figure (77.5 millidarcies), but a study of the tabulation will show that permeabilities as low as 0.18 millidarcies are not uncommon in the specimens from No. 10 Bore.

PHYSICAL PROPERTIES OF GLAUCONITIC SANDSTONES, BORE 10, LAKES ENTRANCE, VICTORIA.

Description of Section No. 10 Bore (after H.G. Raggatt & J. W. Binney)			Position of Test Sample in Section	Sample Number	Permeability in millidarcies			Porosity Percent Voids			Density Gm/cc	Compressive Strength lb /square inch
Depth	Thickness	Description			Observed		Average	Observed	Calculated	Average Observed		
			1257' to 1259'		Specimen too soft to prepare for tests							
1255' to 1257'	2' 0"	Fine-grained. No oil.	1259' to 1261'	1 2	0.17 0.078	P P	.12					2860 Dry 1090 Wet
1257' to 1261'3"	4' 3"	Medium-grained. Oil streaks throughout especially in lower 2 feet.	1261' to 1263'	3 4	1.33 1.08	P P	1.2					2420 Dry 1060 Wet
			1264' to 1265'	5 6 7 8	x 0.01 0.103 x 0.05 x 0.015	C P P P	.045	38.9 41.0 35.5 39.0		38.6		2680 Dry 2400 Dry 1240 Wet
1261'3" to 1264'	2' 9"	Hard, Shelly Slight oil showing.										
1264' to 1267'	3' 0"	Hard, Shelly, Some thin soft bands with a little oil.	1265' to 1267'	9 10	0.20 0.52	P P	0.36					2980 Dry 1295 Wet
1267' to 1268'7"	1' 7"	Several shelly bands, Oil streaks a few inches from top of core.	1268'		Specimen very shelly - unsuitable for tests.							
1268'7" to 1272'1"	3' 6"	Hard, Shelly with two soft bands near bottom, Dry	1268' to 1270'	11	0.154	P	0.15					1350 Wet
			1270' to 1272'	12 13 14	0.072 0.053 0.93	P P P	0.38					1450 Wet
1272'1" to 1273'7"	1' 6"	Fairly Hard, Dry										
1273'7" to 1275'1"	1' 6"	Slightly softer than previous 18", Dry	1272' to 1273'	15 16 17	11.8 38.3 1.39	P P P	17.2					1850 Dry 1010 Wet
			1273' to 1275'	18 19 20 21	x .08 x .2 x .03 x .07	P P P C	.13	32 37 37 39		36.2		1020 Wet
1275'1" to 1277'11"	2'10"	Very hard with two thin soft bands, Dry	1275' to 1276'		Specimen very hard - found impossible to shape test samples							
			1277' to 1278'	22 23 24 25 26 27 28	.48 1.31 2.04 2.40 .71 5.86 .41	C C P P N N N	1.86	43.5 42.2 33.7	34 34 34	39.7	1.72 1.73 1.715	1580 Wet
1277'11" to 1280'11"	3'0"	Alternating hard and soft bands. Oil showings in latter.	1278' to 1280'	29 30	7.12 4.25	P P	5.69					2960 Dry
1280'11" to 1283'11"	3' 0"	Hard mainly, Three 1" soft bands, Dry	1280' to 1282'	31	0.096	P	0.096					
			1282' to 1284'	32 33	0.093 0.059	P P	0.076					1850 Wet
1283'11" to 1285'5"	1'6"	Hard, Shelly, Dry	1285'	34 35	.73 .99	N N	.86					
1285'5" to 1287'5"	2'0"	Top 1' soft, bottom hard			No samples available							
1287'5" to 1291'6"	8" 1'5" 1'0" 1'0"	Soft, Oily, loose fine, even grains highly polished and well rounded. Soft, slightly oily, fairly firm, oily at base.										
1291'6" to 1294'6"	3'0"	Friable, dark greenish-grey sandstone. No reaction with petroleum ether. (Core recovered 1'10")	1291' to 1294' (Sample from Victorian Mines Dept.)	36 37 38 39 40 41 42	19.7 32.5 26.8 6.4 83.3 119 135	P P C N N P P	60.4	37 35 38	31 32.4 36	36.7	1.82 1.77 1.67	700 Wet
1291'6" to 1294'6"	3'0"	Friable, dark greenish-grey sandstone. No reaction with petroleum ether. (Core recovered 1'10")	1291'6" to 1294'6" (Sample from M.R.S. collection)	43 44 45 46 47 48 49 50 51 52 53 54 55 56	23.2 33.6 25.7 27.5 24.9 26.7 47.2 82.0 12.1 45.7 4.8 11.9 16.3 60.9	P P P P P P P P P N N P P C	31.5	}29.1 32.3 }35 39.6 42.0		35.6		
1294'6" to 1300' 0"	5'6"	Light grey, fine, even grained sand-stone with some coarser grained hard bands. Fossils at top. Very slight reaction to petroleum ether (Core recovered 5'6").	1294' to 1300'	57 58 59 60 61 62 63	55.5 40.5 56 34 64 39.5 26	P P N N N C P	45.1	38.39 41.2 31.8	31 33 28	37.5	1.81 1.75 1.89	730 Wet
MEAN VALUES.			1255' to 1291'6"				2.16			38.2	1.72	2590 Dry 1294 Wet
			1291'6" to 1300'				45.7			36.6	1.78	715 Wet

x Permeability values marked thus are approximate.

Results of Tests

The specimens used in these tests were selected by the Victorian Mines Department as representative of the glauconitic sandstone proved in No. 10 Bore, Lakes Entrance. Twenty-one specimens were forwarded, of which 18 represented the hard strata in the section and three the soft. The specimens of the hard strata comprised half sections of drill core approximately 5 inches in diameter and averaging three inches in length. They had been split in halves in an axial plane.

Test samples were prepared from all the hard specimens but not from the soft, which consisted of small lumps of unbroken rock cemented by drilling mud. Attempts were made to drill samples from the largest of these lumps, but they became semi-fluid and disintegrated when drilling was attempted.

Cylindrical samples were prepared from the specimens by means of a diamond drill as explained in an earlier section of this report. The accompanying sketch illustrates the way in which these cylinders, 2.5 cm. in diameter and up to 4 inches in length, were cut so that their axes were normal or parallel to the bedding.

Sketch of half section of 5 inch drill core showing 2.5 cm. diameter cylindrical samples cut parallel and normal to bedding.

Bedding Planes

The glauconitic sandstone exposed in the No. 10 Bore yielded oil at the rate of approximately 10 gallons per day during bailing tests, but a remarkable feature of the specimens tested was that without exception they appeared to be free of oil.

Earlier reference has been made to the fact that when redistilled benzene was forced through some of the samples no discoloration was noticed. A number of specimens had a faint oily smell, and these were tested for the presence of oil by pulverizing a piece of the specimen and boiling it in a small quantity of benzene. As no discoloration of the benzene was noticed in any of the tests so made, it is concluded that none of the specimens were oil-bearing. The specimen, 1259 feet - 1261 feet, corresponds to a part of the glauconitic sandstone section where oil has been reported as occurring in streaks throughout. The extremely low permeability (0.12 millidarcies) found for this specimen seems to preclude the possibility that the specimen would lose much oil if any had been present. The fact that no oil could be detected in this specimen suggests that the three-inch piece submitted for examination corresponds to an unproductive part lying between the streaks of oil recorded when the two-foot section was first cored.

A similar reason may account for the absence of oil in the other specimens submitted for examination; and the permeability results, therefore, may not be a true indication of the permeability of those parts of the section that have yielded oil.

Between 1255 feet and 1291.5 feet, which has been logged as glauconitic sandstone, permeabilities varied over wide limits; the lowest value was 0.01 millidarcies and the highest (1272 feet - 1273 feet) was 38.3 millidarcies.

The average value for each specimen is shown in column 8 and the mean value of these averages (1255 feet - 1296.5 feet) is 2.16 millidarcies.

Specimens from 1291.5 feet to 1300 feet were more sandy in appearance than those higher in the section; they were not included in the glauconitic sandstone section when the bore log was originally compiled, because the quartz grains seemed more polished and abundant than in the higher specimens and the typical greenish colour of the glauconitic sandstone was masked through water seeping in from the bottom and wetting them. Some time later when the cores had dried out it was evident that they had the typical colour of the glauconitic sandstone and they were subsequently included in the glauconitic sandstone section. They were later examined by the Commonwealth Palaeontologist and their classification as glauconitic sandstones confirmed. This classification makes the glauconitic sandstone series 45 feet thick instead of 36 feet 6 inches as shown in the original log.

Permeabilities of the samples corresponding to the interval 1291 feet - 1294 feet 6 inches range from 4.8 to 138 millidarcies with average values of 60.4 and 31.5 for the two specimens examined.

The reason for such large variations in permeability was made apparent when a number of the hollow cylindrical test samples were mounted in the oil extraction apparatus. This apparatus was designed to force benzene from the inside of the sample, through the walls to the outside, where the benzene accumulated in a vessel surrounding the specimen. The apparatus made provision for forcing only a limited amount of benzene through the sample, and it was noticed that after this had passed through and the sample submerged in the effluent, the compressed air which had been used to force the benzene through issued from the core very irregularly. For example in sample 53 (1291 feet 6 inches - 1294 feet 6 inches), which was a hollow cylinder 2.5 cm. diam. by 2.24 cm. high, it was observed that the greatest part of the air issued from an area of approximately 2 sq cm. of the cylinder's surface. From a study of the size, number, and distribution of the emergent air bubbles, it was possible to form a picture of the relative permeability of various sections of this sample. It was estimated that 2 sq cm. of the total surface area of 17.5 sq cm. was responsible for not less than 80% of the total permeability. On this basis, it is estimated that the small very permeable section of the sample has a permeability of approximately 120 millidarcies, which is comparable with the highest permeabilities found for the test samples. Other samples showed similar irregularities in the distribution of the permeability.

A notable feature of the distribution was that it was obviously not an effect due to bedding. The very permeable section of No. 53 sample appeared on only one side of the cylinder and was not distributed over any particular layer within the sample as would have been the case if bedding had been the chief factor.

The glauconitic samdstone in general is heterogeneous in lithology with small inclusions of material differing considerably in permeability from the average for the specimen. The large variations in the observed permeability must, therefore, be explained in terms of this heterogeneity, made noticable because the test samples were small.

Effect of Bedding on Permeability

In the preceding section it has been shownthat variations (such as the size, distribution, or arrangement of the grains) due to bedding were not responsible for the variations in permeability observed in a set of test samples cut from the one specimen.

Variations in the lithology of the glauconitic sandstone at different horizons, which may be called a bedding effect, are accompanied by variations in the average permeability, and in this sense it may be said that permeability varies with the bedding. For instance the beds at the base of the glauconitic sandstone section are much more permeable than those higher in the section. Tests were made to determine whether there was any appreciable change in permeability when the fluid flow was measured in the direction of the bedding or normal to it. The results of these tests are tabulated below:-

Permeability in Millidarcies

Sample	In direction of bedding.	Normal to Bedding.	Part normal - part with bedding.
1277'-1278'	2.40	5.86	1.31
Nos. 22 to 28	2.04	0.41	0.48
	0.71		
1291'-1294'	135	83.3	
Nos. 36 to 42	119		26.8
	32.5	6.4	
	19.7		
1291'6"-1294'6"	82.0	45.7	
	47.2	4.8	60.9
	26.7		
Nos. 48 to 56	16.3		
	12.1		
	11.9		
1294'-1300'	55.5	56.0	
	40.5	34.0	39.5
Nos. 57 to 63	26.0	64.0	

The permeabilities tabulated above show variations within wide limits but there is no consistent difference between permeabilities normal to the bedding and those in the direction of the bedding. The results for samples 57 to 63 (1294 feet - 1300 feet) which are more uniform than the others suggest that the permeability is the same whether measured normal to or parallel to the bedding. It is obvious from the results that a vast number of determinations would need to be made before satisfactory average figures could be obtained.

The weight of evidence however, suggests that the permeability is not influenced by the direction of flow relative to the bedding. This is contrary to Croll's findings for specimens from No. 1 Government Bore, No. 2, Lakes Entrance Development and No. 1 Kalimna bores. Croll prepared his specimens by shaping them into 2 cm. cubes and measuring the permeability between opposite faces. The variations in measured permeability were ascribed to bedding and on this basis he arrived at the following averages:-

Permeability along bedding 223 millidarcies.
" across " 15 "

If the glauconitic sandstones examined by Croll are heterogeneous in lithology like those examined by the writer from No. 10 Bore, it seems more likely that the variations noted by Croll are due to local variations within the specimens rather than to a bedding effect. If Croll's interpretation of his results is correct then it is obvious that the lithology of the glauconitic sandstones in the bores from which his specimens were derived differ considerably from those in No. 10 Bore.

Effect of Moisture on Permeability

The permeabilities given in the main tabulation refer to oven-dried specimens in which the free water content was very small. The permeabilities of three samples 54,55, and 56 were measured after air-drying and repeated after the samples had been dried in the oven. It was found that the permeability increased appreciably upon drying. In order to confirm this and to see if any relationship existed between percentage moisture content and permeability, the test was repeated on nine specimens which were weighed before and after drying to determine the loss of water on drying. The results of this test are set out in the following table.

Permeability: Dry and Wet

Millidarcies

Specimen	Dry	Wet	Percent Moisture	Percent Change Per 1 Percent Moisture
1291'6"-1294'6"			-	-
No. 54	11.8	11.6		
No. 55	16.4	14.3	-	-
No. 56	60.9	54.5		
1277'-1278'				
No. 22	0.48	0.28	3.8	11
No. 23	1.31	0.83	4.1	8.9
No. 26	0.71	0.42	3.6	11.3
1291'-1294'				
No. 36	19.7	17.0	2.8	4.9
No. 37	32.5	28.7	4.4	2.7
No. 38	26.8	21.7	3.9	4.9
1294'-1300'				
No. 57	55.5	48	2.8	4.8
No. 58	40.5	38.8	2.3	1.8
No. 62	39.5	38.2	2.1	1.6

The figures in the fifth column are obtained by expressing the change in permeability between dry and wet samples as a percentage of the dry value and dividing this total percentage change by the percentage moisture content of the wet sample.

A study of the results shows that there is an increase in permeability when the sample is dried. The relative amount of this increase varies for the different samples tested, being considerably greater in the low permeability samples from 1277 feet - 1278 feet than in the samples from 1291 feet - 1294 feet and 1294 feet - 1300 feet. These last mentioned two samples are similar in appearance and are much coarser grained than the first mentioned. The reason for the change in permeability is not definitely established. Two possibilities will be considered.

(1) That moisture occupies and partly closes some of the air channels and in effect reduces their cross section. Such a reduction might conceivably be responsible for the increase in resistance to flow which is apparent in the changed permeability. In connection with this possibility similar wet-dry tests were carried out on a number of diatomite specimens. These tests showed that up to 15 percent moisture could be present without seriously affecting the measured permeability. This being so, it can reasonably be assumed that the small moisture content in the wet glauconites does not reduce the air channel cross section in the manner suggested above.

(2) An alternative possibility is that the glauconite or some other constituent of the rock swells under the influence of the added water and that this swelling is responsible for the reduction in the cross section of air channels. Thus the porosity of the specimen would be affected. Porosity tests might have confirmed this explanation, but unfortunately the porosity apparatus was broken before the tests could be carried out. However, the suggested tests will be made as soon as the porosity apparatus is repaired and opportunity offers.

Although the cause is unknown, the permeability of glauconitic sandstones is largely influenced by the presence of moisture. The observed data are insufficient to arrive at any satisfactory basis for estimating the permeability when 'dry' permeability and moisture content are known. If some sections of the glauconitic sandstones in situ are saturated with water, it is probable that their permeability would be less than half their 'dry' value.

Accuracy of Results

An examination of the results shows that large variations in permeability occur between samples cut from relatively small specimens. For instance the specimen representing 1277 feet - 1278 feet was approximately 30 cubic inches in volume, but permeabilities of the seven test pieces cut from this specimen varied between .41 and 5.86 millidarcies.

It is obvious, therefore, that a high degree of accuracy for each individual test is unnecessary and all that is required of the permeability determination is that it should give the order of magnitude. Nevertheless, the procedure followed and precautions observed were based on the A.P.I. standard procedure for determining permeability (4) and it is of interest to make an approximate determination of the probable error in any individual result.

Errors may be classified as being of two kinds, namely (1) changes in permeability introduced through poor or incorrect technique in preparing the test samples or (2) errors in measurement.

Errors in Preparation. The principal sources of errors in the preparation of the test samples are:-

(a) Clogging of pores by mud introduced during the cutting processes.

(b) Incomplete removal of oil and water.

(a) Every care was taken to ensure that these errors would be as low as possible and the precautions listed in the A.P.I. Code were followed. In addition, tests were made in the Model I apparatus on cylindrical tablets with 'fracture' faces and faces prepared in the fashion outlined in the opening sections of this report. These tests showed that no serious clogging resulted from grinding the faces on coarse emery paper.

(b) As regards removal of oil and water, it has been mentioned above that no trace of oil could be discovered in the specimens subjected to test so that the necessity for removing oil did not arise. As regards water removal, it is believed that the prolonged heating to which the samples were subjected effectively removed all free water. The temperature (150°C) at which the samples were dried was higher than recommended in the A.P.I. Code. Some tests were carried out in which the permeability of a sample was determined before heating and after heating 24 hours, 48 hours and 60 hours respectively. The permeability changed due to loss of water during the first 24 hours heating, but remained unaltered by the additional 24 hours and 48 hours heating. These tests showed that prolonged heating at 150°C did not alter the permeability and it is assumed that apart from the loss of free water the samples were unaltered by the heating.

<u>Errors in Measurement</u>. In Model I apparatus the permeability is given by the expression:-

$$K = \frac{Nt}{A} \times \frac{\bar{Q}}{P_1 - P_2} \qquad \text{------------------------------------(1)}$$

The viscosity of air (N) was known to within $\pm \frac{1}{2}\%$. The measurements of the thickness (t) and the diameter (D) were subject to errors of approximately $\pm$ 1%. The area, A, was proportioned to D^2 and hence was subject to an error of $\pm$ 2%.

The value of $\frac{\bar{Q}}{P_1 - P_2}$ was subject to errors in calibrations of the flowmeter and manometer tubes, but a number of determinations was made for each sample and the error in the average value is certainly not greater than $\pm$ 1%.

K was, therefore, accurate to better than ± 5%. In Model II permeameter, similar errors in measurement apply and K as measured by this instrument has an accuracy better than ± 5%.

Errors due to leakage past the rubber gaskets holding the specimens can be regarded as negligible.

Porosity Results

Previous Determinations

The only reference that can be found to previous determinations of porosity occurs in the previously mentioned report by K. Washington Gray and I.C.H. Croll. (3) On page 97, mention is made of two determinations by J. C. Watson of the Victorian Mines Department on samples from Foster's Bore, the location of which is shown on the plan (fig. 7). Effective porosities of 54 percent and 53 percent respectively were obtained for samples from 2 to 3 feet and 16 to 17 feet below the top of the glauconitic sandstone. In addition to Watson's results mention is made of a determination by Oliver Streeton on a sample from 15 feet below the top of the glauconitic sandstone in the same (Foster's) bore. Streeton's figure was 29 percent.

Results of Tests

The apparatus used to measure porosity is described in an earlier section of this report. It should be noted that the method measures the apparent or effective porosity, i.e. the porosity of the inter-connected pore spaces, and any pore spaces completely sealed would not influence the results.

Porosities were relatively uniform throughout the glauconitic sandstone series and varied from 29.1 to 43.5 percent for the individual samples, but the averages for each horizon were more uniform, varying between 35.6 and 39.7 percent.

In addition to porosities measured with the apparatus, a number of porosities were calculated from the apparent density of the samples. The calculations were based on the assumption that the solid matter comprising the 'frame-work' of the glauconitic sandstone had a density of 2.62. The calculated porosities are shown in the main tabulation and they are (with one exception, viz. No. 26) lower than those measured. The average value of nine calculated porosities is 32.6 percent compared with the average measured porosity of 37.3% (23 determinations).

If a density of 2.8 is assumed for the solid matter then the calculated porosities become approximately equal to the measured.

The average measured porosity is intermediate in value between Watson's (53-54%) and Streeton's (29%) determinations.

Accuracy of Results

The accuracy of any porosity determination depends on the accuracy with which the various factors used in the calculation are measured. A figure for the theoretical accuracy can be obtained by applying to each factor involved a relative accuracy and then calculating the mean and maximum value for porosity assuming that all the individual errors are additive.

For example, if

$$V_1 = 17.40 \pm 0.05 \text{ cc.}$$
$$V_2 = 5.07 \pm 0.05 \text{ cc.}$$
$$V_c = 10.0 \pm 0.2 \text{ cc.}$$
$$A_T = 28.00 \pm 0.02 \text{ inches.}$$
$$H = 8.67 \pm 0.02 \text{ inches.}$$

Then $V_p = 3.9 \pm .4$ cc. and $\frac{V_p}{V_c} \times 100 = 39 \pm 5.$

The above calculation gives the maximum possible error for any one determination, but it must be borne in mind that the probability of the maximum possible error occurring (or in other words of all the individual errors acting in the same sense) is infinitesimally small. The accuracy of the apparatus and technique was tested by placing in it a solid brass cylinder of zero porosity. The porosity calculated from the volume and pressure readings was - 0.25% (instead of zero).

In addition to the above test, determinations on a single glauconite sample were repeated and the measured porosity could be repeated with an accuracy of better than ± 2%.

It is believed that in practice the porosities determined by means of the apparatus are within 5 percent of their correct value, a degree of tolerance which is quite sufficient for most purposes.

Relationship Between Permeability & Porosity

An examination of the corresponding permeabilities and porosities from the separate test samples shows clearly the fact that there is no relationship between these two quantities. Although the porosity of various zones within the glauconitic sandstone varies very little, the permeability varies over wide limits. In connection with this point the following tabulation, based on permeability and porosity measurements made by the writer on various materials, is of interest.

Material	Porosity Percent.	Permeability Millidarcies	Remarks.
Mt. Gambier limestone	52	5,182	One determination.
Roma 'Gas' sandstone	16	57.0	Average of seven determinations.
Glauconitic sandstone No. 10 Bore, 1255' - 1291'	38.2	2.16	Average of 35 determinations.
Glauconitic sandstone No. 10 Bore, 1291' - 1300'	36.6	45.7	Average of 28 determinations.
Diatomite	72	24.3	Average of seven determinations.

Apparent Density

The apparent density of dry glauconitic sandstone was determined for nine samples; values ranged from 1.67 to 1.89 grm./cc.

Compressive Strength

Tests of compressive strength were carried out in the testing laboratory of the Department of the Interior on a Tinius Olsen testing machine capable of providing loads of 1200 kilograms. The machine was designed for moulding concrete cylinders 1 inch diameter, but was eminently suitable for compression tests on cylindrical specimens of this diameter and of low strength.

Test samples were drilled from the raw material by means of the diamond drill mentioned previously and cut into lengths of approximately 1 inch. The ends of the cylinders were made truly parallel to one another and normal to the axis of the cylinder in the special holder (Fig. 3).

Tests were made on a number of samples which had been oven-dried and a number which had been saturated with water.

The pressure in lb.per square inch necessary to crush the specimen was calculated and a correction applied for the finite size of the specimen. This correction converted the measured pressure into the pressure per square inch needed to crush a cylindrical sample of height equal to twice its diameter, i.e. the compressive strength of the material.

The results of these tests appear in the main tabulation.

It will be observed that there is a considerable difference in compressive strength between dry and wet glauconitic sandstone.

Seven samples from the glauconitic sandstone section 1255 feet - 1291 feet were oven-dried before testing and their average compressive strength was found to be 2590 lb. per square inch. Ten samples from the same section were saturated with water prior to testing and their average compressive strength was found to be only 1294 lb. per square inch or approximately half the average of the oven-dried samples.

Tests made on two samples of the more sandy and friable glauconitic sandstone, corresponding to the section 1291 feet to 1300 feet, proved them to be the weakest of any tested. A sample corresponding to the section 1291 feet - 1294 feet and saturated with water was found to have a compressive strength of 700 lb. per square inch. The second sample corresponding to the section 1294 feet - 1300 feet was tested after being saturated with water and found to have a compressive strength of 720 lb. per square inch.

The Victorian Mines Department had a test carried out on a sample of glauconitic sandstone from No. 10 Bore. The sample was 5½ inches diameter and 3⅛ inches long, but no indication is given as to whether the test piece was wet or dry.

The specimen broke under a pressure of 2420 lbs. per square inch. The application of a correction factor to convert the result to that for a standard cylinder reduces this strength to 1380 lb. per square inch. This figure is somewhat higher than the average value obtained by the writer for wet specimens, but as no indication is given as to what horizon the Mines Department sample represents it is not possible to make any direct comparison between the two results.

Permeability Calculated from Oil Production Figures, Imray Bore, Lakes Entrance

The average permeability of a producing 'sand' can be calculated from the rate at which oil, water and gas are produced from a bore if the thickness of the 'sand' and the pressure within the 'sand' are known. The Imray bore is a suitable one on which to base calculations of permeability because the glauconitic sandstone appears to have been successfully sealed off from water horizons above and below it. The fluid entering the bore casing probably has come entirely from the glauconitic sandstone.

The location of this bore relative to No. 10 bore is shown on the locality plan (Fig 8).

In the Imray bore, twenty feet of glauconitic sandstone are exposed which yielded 0.29 gallons of oil, 0.05 gallons of water per hour, and an undetermined but very small quantity of gas when the bore was bailed dry, i.e. when the pressure inside the bore was atmospheric. Upon standing for a period of about 24 months, the liquid level rose to within 100 feet of the surface under the influence of reservoir pressure. It is estimated that the level which would have been reached after an infinite time would have been about 30 feet from the surface. As the glauconitic sandstone is at a depth of 1250 feet, the reservoir pressure is not less than 34 atmospheres (assuming a specific gravity of 0.95 for the liquid column).

The equation for radial fluid flow can be used to calculate the permeability of the yielding layer from the above data if the gas flow is neglected.

The effective permeability may be expressed as:-

$$K = \frac{N\ Q\ \log_e \frac{r_1}{r_2}}{2\ \pi\ t\ (P_1 - P_2)} \quad \text{------------------------------------}(2)$$

where N = viscosity in centipoise

Q = rate of flow in cc/sec.

t = thickness of producing sand.

$P_1 - P_2$ = pressure drive.

r_1 = radius of reservoir.

r_2 = radius of the bore hole.

Owing to the large difference in viscosity between the oil ($N = 94$ centipoise at $100^{\circ}F$) and water ($N = 0.6$ centipoise at $100^{\circ}F$) and the relatively small quantity of water yielded, the flow of the latter is neglected in the following calculations:-

For the Imray bore the following values hold:-

$N = 94$ centipoise (at $100^{\circ}F$)

$Q = 0.29$ gallons per hour $= 0.36$ cc/sec.

$\log r_1/r_2 = 7.6$ (assuming $r_1 = 500$ feet and $r_2 = 0.25$ feet)

$t = 20$ feet $= 610$ cm.

$P_1 - P_2 = 33$ atmospheres.

Placing these values in equation (2) we find that $K = 2.03$ millidarcies.

It is a remarkable result that this figure for the Imray Well should be so close to the average permeability (2.16 millidarcies) obtained from tests on the glauconitic sandstone from the upper 36 feet of No. 10 Bore.

In the first place it has been assumed that the whole of the 20 feet exposed in Imray Bore has yielded oil. This is evidently not the case and the thickness (t) used in expression (2) should be modified to make allowance for this factor. If it were assumed that the whole of the production was from only 5 feet of sandstone whilst the remaining 15 feet were impermeable then the average permeability of this 5 feet would be four times as great as the figure given above, namely $4 \times 2.03 = 8.12$ millidarcies. Nevertheless the 'weighted' average permeability for the whole 20 feet under this condition would be the figure arrived at originally, namely 2.03 millidarcies.

The average permeability given for the upper 36 feet of No. 10 bore is not a 'weighted' average, but merely the arithmetical average of a number of determinations. However, if the specimens examined are truly representative of the various horizons within the glauconitic sandstone then because the specimens were more or less evenly spaced throughout the section, the arithmetical average stated would roughly equal the "weighted" average.

The error introduced through neglecting the influence of water and gas flow in the calculations of permeability is probably small, but if these flows had been allowed for in the calculations of permeability, then the permeability finally arrived at would have been greater than 2.03 millidarcies. It must be conceded, therefore, that there is some justification for claiming that the calculations based on production from Imray Bore confirm at least in order of magnitude the permeability figure obtained from measurement of specimens from No. 10 Bore.

Summary

Permeability, porosity, apparent density and compressive strength tests have been carried out on a number of specimens of glauconitic sandstone from No. 10 Bore, Lakes Entrance.

Permeability varied widely throughout the section represented by the specimens, the average permeability for dry samples being 2.16 millidarcies for the top 36 feet and 45.7 for the lower 9 feet. A considerable part of the top section, however, was less than 1 millidarcy.

Permeability was found to vary with the moisture content of the sample and it is estimated that the permeability of water-saturated glauconitic sandstone would be less than half the 'dry' sample value.

It is of interest to compare the permeability and porosity of the glauconitic sandstone with the permeability and porosity of known producing sands. Fancher, Lewis and Barnes [5] give a table in which the permeability and porosity of 127 sands, from American oil fields, are listed. Those sands exhibit a wide variation in permeability, ranging from over 3000 millidarcies for one sample of Woodbine sand to zero permeability under test conditions. The range in permeability found for 47 Bradford sands is comparable with that found in the tests described in this report. The maximum for the Bradford sand, 153 millidarcies, can be compared with the maximum for the glauconitic sandstone, namely 135 millidarcies. The comparison is also good for the lower values measured although the percentage of permeabilities lower than 0.2 millidarcies is much higher for the glauconitic sandstone than for the Bradford sand.

Other sands in the table, particularly Speechley, Windfall and Clarenden sands, have permeabilities comparable with those found for the glauconitic sandstone.

As the sands tested by Fancher, Lewis and Barnes were taken from oil fields in which the productivity greatly exceeds that of the Lakes Entrance field, it can be concluded that the low average permeability of the glauconitic sandstone is not entirely responsible for their low productivity.

Porosity was found to be relatively uniform throughout the section, the average value for the top 36 feet being 38.2 percent and for the bottom 9 feet 36.6 percent. There was no correlation between permeability and porosity.

The porosity of the sands in the tables given by Fancher, Lewis and Barnes ranges from 2% for one of the Bradford sands to 28.8% for one of the Woodbine. Most have porosities ranging from 10% to 20%. It is stated that the more representative samples of Bradford sand range in porosity from 11% to 13%.

None of the oil sands in the table has a porosity as high as the glauconitic sandstone.

A search was made through numerous reports on the porosity of oil sands and in none was reference found to an oil sand with a porosity as high as that found for the glauconitic sandstone.

Its high average porosity (36% to 38%) therefore seems to distinguish the glauconitic sandstone from other known oil sands; for this the glauconite is probably responsible.

Apparent densities varied between 1.67 and 1.89 grams per cc., averaging 1.72 for the top 36 feet and 1.76 for the bottom 9 feet.

Compressive strength tests showed substantial differences between wet and dry samples, wet samples having considerably lower strength than dry. The average 'dry' sample compressive strength for the top 36 feet was 2,590 lb. per square inch while the average for wet samples from the same part of the glauconitic sandstone section was 1,294 lb. per square inch.

Calculations based on oil production and known pressure drive in the Imray bore give an approximate figure of 2.03 millidarcies for the average permeability of the 20 feet of glauconitic sandstone exposed. This figure confirms, at least in order of magnitude, the average of the permeabilities observed (2.16 millidarcies) for the top 36 feet of the glauconitic sandstone in No. 10 Bore which corresponds stratigraphically to the glauconitic sandstone exposed in the Imray bore.

POLYZOAL LIMESTONE - LAKES ENTRANCE SHAFT

Two specimens of polyzoal limestone were submitted for permeability tests. These corresponded to depths of 320 feet and 428 feet respectively from the surface in the shaft at Lakes Entrance. The position of this shaft is shown on the locality plan (Fig. 8). The specimens were found to have no appreciable compressive strength when thoroughly wet and were readily deformed by the pressure of the fingers. It was not possible to prepare test pieces in the standard fashion, but some cylinders were cut from the specimens by the diamond drill in the dry state.

These cylinders were cut into suitable lengths and the ends squared off in the special holder (Fig. 3). The sides of the cylindrical samples, however, were somewhat irregular and it was thought that serious leakage might occur down the sides of the samples when mounted in the rubber stopper of the Model I permeameter. In order to eliminate this possibility the sides of the cylindrical samples were sealed by means of plaster of paris. The samples were dampened to ensure that the plaster adhered but were not sufficiently wet to permit serious ingress of the plaster into the central part of the cylinders. The plaster when dried was smoothed by means of coarse sandpaper and after thorough drying the samples were mounted in the Model I permeameter

No bedding was discernible in either specimen. Three cylindrical test samples were prepared from the specimen collected at a depth of 320 feet, but the orientation of their axes relative to the bedding was unknown. However, the axes of the three cylinders were parallel to one another.

Two sets of cylindrical test samples were cut from the specimen collected at a depth of 428 feet, the axes of the two sets being at right angles to one another, but their orientation relative to the bedding was unknown.

The results of the tests are set out in table form below.

Sample	Permeability millidarcies.
320' No. 1.	161
320' No. 2.	193
320' No. 3.	148
Average 320'	167
428' A No. 1.	87
428' A No. 2.	150
428' A No. 3.	172
428' B No. 1.	140
428' B No. 2.	139
Average 428'	138

Samples Nos. 1 and 2 (depth 320 feet) were slightly imperfect cylinders and had to be built to cylindrical shape with plaster of paris. The permeability figure given for these samples is, therefore, not as reliable as other figures quoted.

The axes of the cylinders cut from the samples marked A (depth 428 feet) were cut at right angles to those marked B. The fact that there is no appreciable difference in permeability between the A and B samples suggests that bedding has no appreciable influence on permeability although the possibility that each axial direction is at 45° to the bedding must be borne in mind. To be certain of the influence, if any, of bedding, a third set of values corresponding to samples with axes at right angles to A and B would be needed.

The average values of 167 millidarcies (320 feet) and 138 millidarcies (428 feet) were for dry samples. It is probable that permeabilities of corresponding wet samples would be considerably less than these figures.

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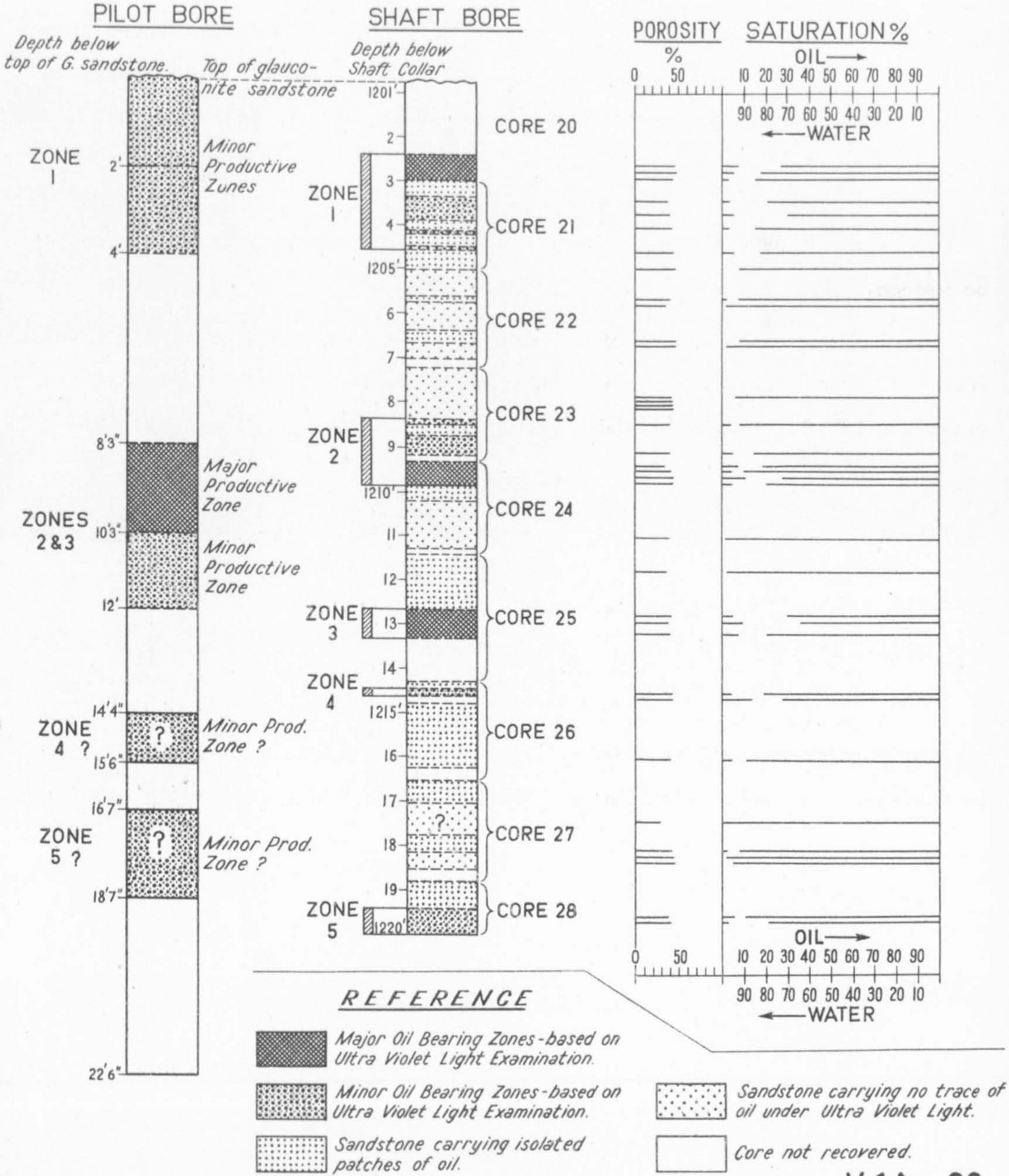
PLATE 1

DISTRIBUTION OF OIL IN CORES FROM THE SHAFT BORE

LAKES ENTRANCE - VICTORIA

Based on Ultra Violet Light Examination & Porosity & Saturation determination
(Pilot Bore Log included for comparison)



Bureau of Mineral Resources, Geology and Geophysics. December 1954.

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MK

PLATE 2
Sheet I

DISTRIBUTION OF OIL IN CORES

FROM SHAFT BORE
LAKES ENTRANCE

AS DETERMINED BY ULTRA VIOLET LIGHT EXAMINATION OF CROSS SECTIONS OF CORE.
SHOWING, ALSO, DETERMINATIONS OF POROSITY AND OIL-WATER SATURATIONS.

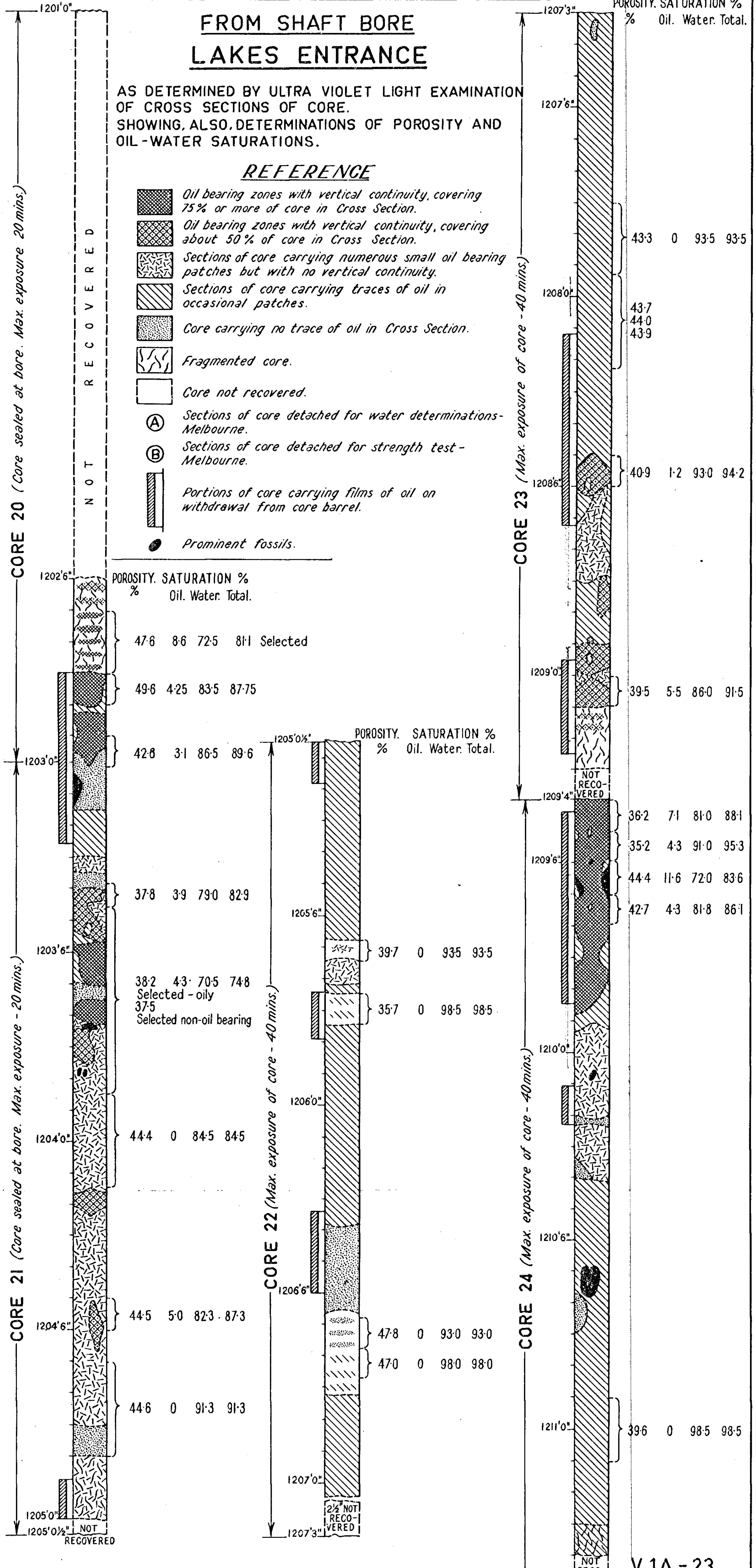

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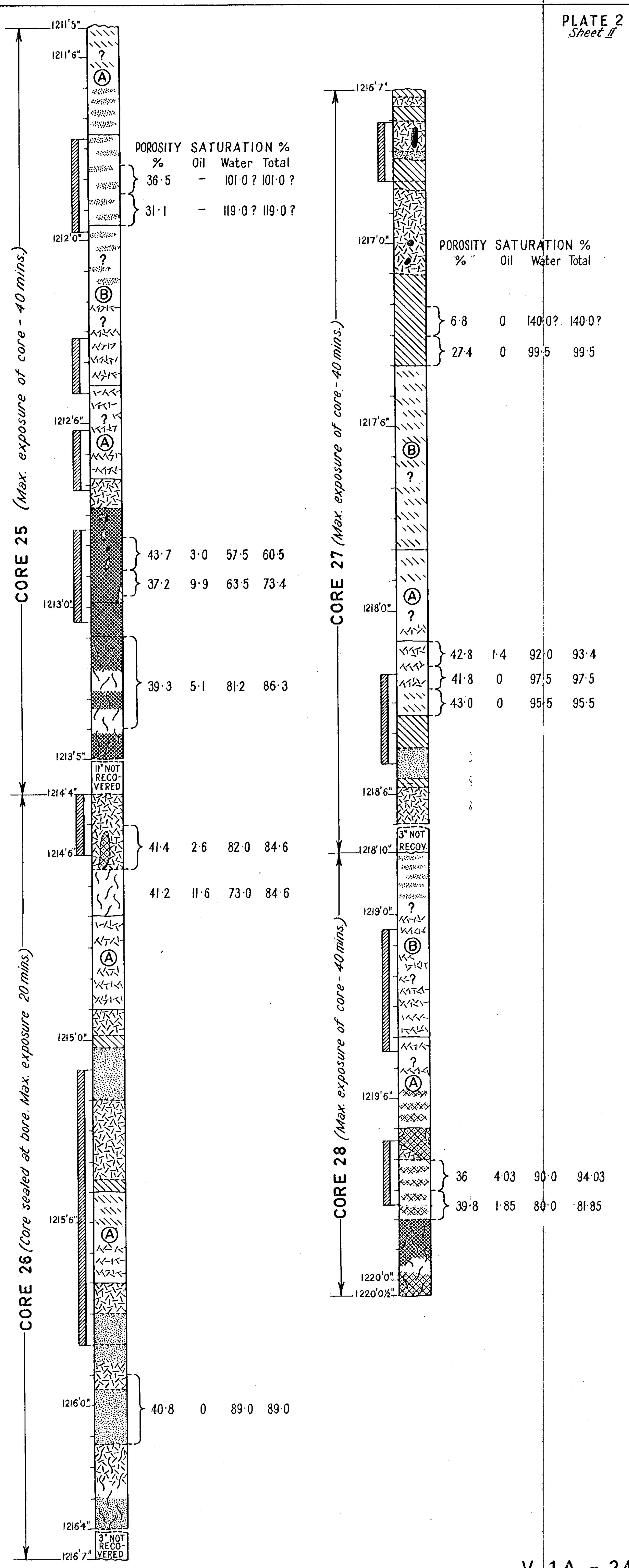
PLATE 2
Sheet II



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