GEOLOGICAL REPORT ON CORES FROM COUSLAND-6.

by

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Contents

Introduction

Sixty-four pieces of core were received by the writer on 5th January 1960, from the well Cousland-6. The samples cover two main intervals, the upper from 1365 to 1424 ft. and the lower from 1494 to 1540 ft. There are five groups of samples in the upper interval and three in the lower, the samples being generally spaced at depth intervals of one foot within the groups, with gaps of several feet between groups.

Apart from relatively thin shaley intervals the samples consist mainly of sandstones ranging from very fine to medium in grain size. All show some degree of cementation and the porosity varies from poor to fair. There are four intervals of reasonably uniform sandstones of fair porosity. These are from 1365 to 1372 ft., 1401 to 1410 ft., 1497 to 1504 ft. and 1526 to 1539 ft; all these except the second are oil stained. The lithology is summarized in the

Table I.

Volume % composition and grain size by point counting.

Sample depth, ft.	1366	1402	1409	1494	1500	1514
Detrital quartz*	54.6	58.0	60.6	57.2	63.0	46.7
Felspars	5.1	3.3	4.2	-	2.0	3.0
Micas	1.8	2.3	1.2	-	-	3.3
Clay (mainly kaolin)	15.7	8.0	6.6	-	9.3	13.3
Secondary quartz	20.2	19.0	19.9	-	12.9	18.7
Microcrystalline carbonate	-	0.3	-	-	-	7.0
Coarse carbonate	1.5	4.0	1.8	42.8	10.7	3.0
Visible pores	0.9	5.9	5.7	-	2.2	5.0
Ø mean size	3.27	3.43	3.40	2.67	2.57	3.28
Ø standard deviation	0.49	0.39	0.41	0.59	0.47	0.44

Sample depth, ft.	1517	1518a	1518b	1526	1532	Mean
Detrital quartz*	42.8	51.4	58.0	60.0	57.8	55.5
Felspars	5.4	4.2	3.0	3.0	2.7	3.3
Micas	6.7	3.5	1.0	-	0.8	1.9
Clay (mainly kaolin)	10.5	13.2	7.3	10.9	15.5	10.3
Secondary quartz	6.3	11.3	0.3	13.3	13.2	12.3
Microcrystalline carbonate	25.2	5.8	0.7	1.0	1.3	3.7
Coarse carbonate	0.9	4.8	29.3	8.3	7.4	10.1
Visible pores	1.6	6.1	0.3	3.3	1.1	2.8
Ø mean size	3.27	2.40	2.64	2.34	2.56	2.88
Ø standard deviation	0.49	0.75	0.46	0.57	0.47	-

Composition determined on 300 points/section, grain size on 100 points/section.

* Including rare quartzite and chert grains.

accompanying diagram. More detailed core descriptions are given in the appendix, and various aspects are treated in the body of the report.

Thin sections were cut from fourteen of the samples to study the cementation. Table (1) shows the volume composition and grain size of ten of these samples determined by point counting. Porosity determinations were made on eleven samples, and the results are given in table (2).

Wherever bedding can be distinguished the cores show pronounced dip, the angle varying from about 25° to about 60°, 40° to 45° being commonest.

Sedimentary Structures.

Cross bedding, slump structures, compaction structures, and structures due to burrowing organisms are present, sometimes in combination, at various levels.

Small scale cross bedding is especially well developed in the interval from 1365 to 1372 ft. in a hard, grey, fine grained sandstone. It is marked by dark curved and inclined laminae one or two millimetres apart in sets about one centimetre thick, each set truncated by the one above. The laminae are less than one millimetre thick and consist of large flakes of mica, often associated with carbonaceous and possibly bituminous matter; in some other horizons they are also accompanied by blobs of micro-crystalline carbonate. The direction of inclination of the laminae, which presumably indicate current direction, is often consistent in a given section of core. Occasionally it is irregularly reversed. In all cases where it can be recognised, however, it is either up or down the dip or at a small angle thereto, never along the strike.

Dips recorded on adjacent pieces of core (and sometimes in the same piece) often differ in amount by up to 15° or so, and in some cases these differences evidently represent larger scale cross bedding.

Minor slumping is demonstrated by small asymmetric folds and sometimes more chaotic disturbances, usually in thin alternations of sandstone and shale, but also at the junction of highly calcareous and almost non-calcareous sandstones, as at 1516 ft. Many minor "fracture" planes evidently also date from this immediate post-depositional phase. The effect is only local and rarely persists for more than two feet up the section.

Some minor channels leading upwards through alternations of sandstone and shale and filled with material derived from the lowest layer are believed to be caused by fluids escaping during compaction. Irregular masses of sandstone or shale intruded bodily into layers of dissimilar material are attributed to the same general process, which must also have been responsible for a small sedimentary dyke at 1506 ft.

Other cylindrical bodies of contrasting material but more regular appearance, not restricted to any particular lithology, and usually four millimetres in diameter, are interpreted as burrows, probably made by worms. In some instances these are very numerous, and grey bands in the sandstone at 1401 and 1403 ft. appear to have been produced by the almost complete mixing of a shaley and carbonaceous layer with the white sandstone above and below by these burrowers. The same agency may possibly be responsible for the lack of other sedimentary structures or bedding in various beds accompanied by faint mottling now made apparent by slight differences of degree of cementation picked out by varying oil staining, for example in the region of 1497 ft.

Fossils.

Apart from the structure referred to above as worm burrows, and certain carbonaceous markings on some bedding planes with vague plant affinities, no fossil remains of any kind have been discovered.

Fractures and Joints.

Many very minor fracture planes can be found, most of them apparently formed early when the sediment was quite plastic, so that they are "healed". Others, where there may at one time have been some slight separation, are now entirely sealed with calcite, with one exception at 1496 ft. where a porous zone 4 mm wide inclined at 60° is partly sealed by calcite and partly impregnated by black tarry oil.

Porosity.

The porosity of eleven samples (from which thin sections were also cut) was determined by the method of weighing pieces dry, soaked, and suspended in water, the soaking being accomplished by prolonged boiling and cooling under water. Thin slices weighing about 10 gm were used, but as a check four determinations were repeated on pieces weighing 50-100 gm - these gave figures approximately 1% lower. Results are given in Table (2).

For various reasons the determinations are more likely to be under- than over-estimates. Their reliability can, however, be assessed from the apparent grain densities computed from the same raw data and also given in table (2).

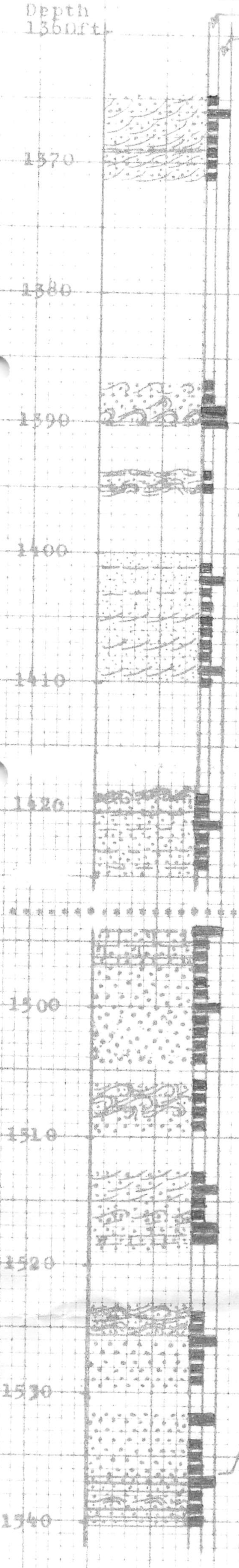
Obviously oily samples were first extracted with carbon tetrachloride. In a few cases the quantity of oil removed in this process was determined. The samples had previously been dried at 105°C, so the "oil saturation" figures given in table (2) refer to the oily extractable matter boiling above this temperature. Not all the tarry matter could be removed, so these figures also are probably underestimates.

Cementation.

All the samples are cemented to some extent, usually by more than one cement, but very few are completely cemented. Four cements can be recognised; these are microcrystalline carbonate, clay, quartz, and coarsely crystalline carbonate.

COUSLAND-6

SUMMARY OF LITHOLOGY, INTERVALS 1365-1424 FT & 1494-1540 FT.



Fine, grey sandstone with small scale cross bedding. Principal cements are kaolin, quartz. Fair porosity, irregular oil stain.

Fine, whitish sandstone, cross bedded, disturbed at top and bottom by slumping and burrowing. Cements are kaolin, quartz, micro- and coarsely crystalline carbonate. Poor porosity. No oil.

Mudstone and shale with sideritic concretions.

Very fine white sandstone, with occasional cross bedding and common mixing by burrowers. Cements are kaolin and quartz. Porosity fair to poor. No oil.

Medium to fine dirty white sandstone becoming shaley and slumped at top. Cements are microcrystalline carbonate, kaolin, quartz, and coarse carbonate. Porosity poor to fair. No oil.

* *

Medium to fine whitish calcareous sandstone Completely cemented by calcite. No oil.

Medium to fine dirty white sandstone, massive. Cements are kaolin, quartz, a little coarse carbonate. Fair porosity. Oil stain.

Sandstone and shale mixed by slumping and compaction. Poor porosity.

Medium, grey sandstone with small scale cross bedding. Cements are microcrystalline carbonate, kaolin, quartz, and variable coarse carbonate. Fair to poor porosity. Oil stain.

Sandstone and shale mixed by slumping. Poor porosity.

Medium, grey-buff sandstone with faint parallel bedding.
Cements are kaolin, rare microcrystalline carbonate, quartz, and coarse carbonate. Fair porosity. Oil stain.

Sandstone and shale in thin alternations.
Cements in sandstone are microcrystalline carbonate, kaolin, quartz, coarse carbonate. Poor porosity. No oil.

Table 2.

Porosity, apparent grain density, and "oil saturation".

Sample depth	Porosity	Apparent grain density	"Oil saturation"
1366	14.4%	2.63	18.3%
"	13.7	2.65	14.7
1389	10.1	2.67	Not determined
1390	7.4	2.66	"
1402	9.3	2.59	"
1409	12.1	2.66	"
1494	2.1	2.69	"
1500	12.1	2.67	7.8
"	10.8	2.64	8.2
1514	10.7	2.53	Not determined
1526	13.8	2.67	10.3
"	12.5	2.66	15.7
1532	14.2	2.66	15.9
"	13.0	2.65	Not determined
1537	7.1	2.44	"

Certain inter-relationships of these cements and other components cannot be treated fully at the present time, but may form the subject of a supplementary report later.

Except in a few beds in which all the space between the detrital quartz grains is occupied by carbonates, as at 1494 ft. clay and secondary quartz appear to be universally present.

The clay consists almost entirely of kaolin, identified by its low birefringence and high refractive index. It appears white in the hand specimen, but pale brown in thin section, probably due to the presence of residual oil. Occasionally small quantities of more birefringent clay are present, possibly illite, In the sandstones the kaolin occurs in pockets about 0.125-0.25 mm across, and also in pores. In the pockets it is frequently accompanied by the remains of decomposed felspars. It is not usually concentrated into the micaceous layers, when these are present.

As a rule the kaolin is only very loosely packed. The spaces occupied by it average around 10% by volume of the sands, but the actual weight of kaolin present is believed to be only 2-3%. The thin section and porosity data combined suggest that most of the porosity measured exists in the kaolin-filled spaces, and usually not more than 5% as open pores, and it is consequently likely that the permeabilities of the sandstones will be lower than the porosities might suggest.

A further consequence of the loosely packed nature of the kaolin pockets is that cut surfaces on cores often present a vuggy appearance due to washing out and tearing out of the kaolin.

The kaolin, which was formed early, appears to be of mainly authigenic rather than detrital origin.

Quartz cement takes the form of secondary overgrowths on the detrital quartz grains, and occupies up to 20% of the volume of the sandstones. As is usually the case, the thickness of the overgrowths is much the same (15-30 microns) in all samples, and the highest proportions are therefore found in the finest sandstones. The size control, however, is overshadowed by the influence of the porosity at the time the secondary quartz was deposited, and the present variations in porosity from sample to sample are not, in general, due to variations in the quartz cementation. Quartz cementation took place later than the formation of kaolin.

The carbonates present are of variable composition. Judging by solubility and appearance in thin section they may range from almost pure calcite to siderite. All apparently contain ferrous iron to a variable extent.

Microcrystalline carbonate occurs in the sandstones at various levels, appearing as light brown pellets in the hand specimen, and as microcrystalline colourless to brownish aggregates in thin section, usually flattened along the bedding and sometimes enclosing isolated quartz grains. The composition appears to range between that of dolomite and siderite and the material may therefore be broadly described as ankerite. This form of carbonate is often strongly associated with mica and carbonaceous material, and is either a primary constituent of the sediment or alteration product therefrom. In some cases biotite appears to be altering to this material.

Usually only a few percent of microcrystalline ankerite is present and its influence on porosity is slight, but occasionally it is a major component, as at 1517 ft. where it reaches 25%.

The most variable cement is coarsely crystalline carbonate, apparently ranging in composition from almost pure calcite to dolomite or even siderite. It occurs as clear anhedral grains filling pore spaces, or, when more abundant, enclosing groups of quartz grains poikilitically. The extinction is often undulating. A small amount at least of this carbonate is invariably present in the sandstones. When present above a few percent it has a pronounced effect on porosity. When present in amounts of 30% or less this coarse carbonate appears to be the latest formed cement and encloses secondary quartz overgrowths and pockets of kaolin. There is a strong tendency for it to attack quartz grains with which it is in contact.

In a sample with over 40% of coarse carbonate (1494 ft.) no secondary quartz overgrowths were present, and in this case the carbonate (almost pure calcite) seems to be an original component rather than a later precipitate.

Indications of Petroleum.

Samples from the intervals 1365-1371, 1497-1504, 1513-1518, and 1526-1534 ft. all exhibit oil staining and odour, and in the top interval there was even slight bleeding evident under the cellotape used to attach the labels. The oil stain is invariably accompanied by a thick black tarry or bituminous residue in some of the pore spaces, probably occupying at least 10% of the pore volume (see table 2).

Conclusions.

The environment of deposition was evidently one of shallow water, and probably non-marine. If the dips shown on the cores are assumed to be uniform in direction, the constancy of direction and occasional reversal of sense of the currents indicated by the cross bedding suggest tidal influence, possibly in an estuary. The cross bedded sands may represent channels, the more massive sands bars or even beaches, and the thinly alternating contorted and burrowed sands and shales, mudflats. Whatever the precise interpretation, the sand bodies are unlikely to be of great lateral extent, although they may be elongated.

Due to the variety and quantity of cements the sandstones are not very porous. It is unlikely that the porosity anywhere exceeds 15%. The presence of loosely packed kaolin in the pores suggests that permeability figures will be lower than might be expected from this porosity, which is in any case further restricted by residual oil.

The ubiquitous presence of this residual oil in all the intervals which show any sign of the presence of petroleum strongly suggests that the reservoirs have been substantially depleted by natural processes.

J. C. M. Taylor.

4th February, 1960.

APPENDIX

Cousland-6, Core Descriptions

1365 ft. SANDSTONE; cross-bedded. The sandstone is hard, grey, fine grained, with fair sorting. There is some clay in pores, and locally slight reaction with 50% HCl. Irregular (banded) oil stain, and some tarry oil in pores; estimated porosity fair. Cross-bedding marked by dark laminae lying concave-upwards 1-2 mm. apart, truncated at the top, each "set" being about 1 cm. thick. Laminae are less than 1 mm. thick and consist of large flakes of muscovite and biotite and rarer amounts of a green flaky mineral (probably chlorite), associated with carbonaceous and possible bituminous matter. The direction of inclination of the laminae is consistent and suggests a transport direction approximately up the dip. The dip is about 30°.

1366 ft. SANDSTONE; as above but laminae fainter and current direction not determinable. Dip about 25°.

1367 ft. SANDSTONE; similar to 1365. Oil stain locally more pronounced.

1368 ft. SANDSTONE; similar to 1365, but less oil-stained.

1369 ft. SANDSTONE; similar to 1365, but in upper inch the dark laminae increase in frequency (not thickness) and coalesce to form a shaley band with thin silty or sandy laminations. Within the sandstone, the dark laminae are inclined less regularly. There is a little more carbonate and less oil stain. Top surface of core is slickensided in a direction about 20° clock-wise from the dip direction. Minor fractures (not necessarily tectonic) with negligible displacement are inclined at about 65° to horizontal; closed.

1370 ft. SANDSTONE; similar to 1365. Oil stain lighter and more even. Slightly harder and with more carbonate.

1371 ft. SANDSTONE; similar to 1370, but with slightly more carbonate than in 1365. Two irregular sealed fractures, sealed by calcite, inclined at about 80° to horizontal.

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1387 ft. SANDSTONE; mottled; light, very hard, fine grained, argillaceous and calcareous; and dark grey, more friable, fine and medium grained, micaceous, more calcareous. Mixture due mainly to slumping, and superimposed are cylindrical burrows about 4 mm. diameter. The dip shown is about 70°, and the direction of slump movement appears to be up-dip. Brownish sideritic masses of irregular shape about 2-3 cms. across.

1388 ft. SANDSTONE; white, medium hard to hard, fine grained, with darker micaceous and sideritic laminae marking small-scale cross-bedding as in 1365 (suggested transport direction predominantly down-dip, but some contrary). Slightly calcareous or dolomitic, with kaolin in pores. Some irregular brownish sideritic masses, mainly concentrated along bedding planes, but one mass several cm. across appears to have been intruded into position. Porosity of sandstone probably fair to poor. No oil stain or odour.

1389 ft. SANDSTONE; similar to 1388, except no intruded mass of siderite.

1390 ft. SANDSTONE/SHALE. Sandstone similar to 1388, with dark laminae increasing in frequency and grading into medium grey, medium hard shale or mudstone at top. Many concretionary sideritic masses as in 1388, and, in upper part, an irregular mass of slightly calcareous white sandstone about 5 by 10 cm., partly interfingering with shale at edges. Adjacent are small slump-folds. Shale also contains sideritic concretions. Poor porosity, no oil stain or odour. Dip about 40°.

1394 ft. SILTY MUDSTONE; light grey, medium hard. Silt grade particles well spaced in argillaceous matrix, non-calcareous, but with lighter irregular hard bands about 3 cm. thick which are probably sideritic or dolomitic. Dip irregular, about 25°. Top and bottom surfaces show slickensiding.

1395 ft. SANDSTONE/SHALE; similar to 1390, but sandy above and shaley below. The whole riddled with cylindrical burrows <u>ca</u> 4 mm. across, at various inclinations. Sandstone mainly very fine, i.e. finer than 1390.

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1401 ft. SANDSTONE; white, to grey due to admixed shale blended by numerous burrows 4 mm. across. Hard to medium hard, very fine grained, slightly calcareous, with kaolin in pores. Estimated porosity moderate; no oil stain or odour.

1402 ft. SANDSTONE; white, even textured and un-bedded, moderately hard to hard, fine to very fine grained; some kaolin in pores and isolated calcareous grains. Poor to fair porosity; no oil stain or odour. Two calcite-filled fractures about 0.5 mm. across, near-vertical.

1403 ft. SANDSTONE; similar to 1401. Dip <u>ca</u> 45°.

1404 ft. SANDSTONE; similar to 1402.

1405 ft. SANDSTONE; similar to 1402, but faint very thin dark micaceous laminae show bedding inclined at about 40°, with small-scale cross-bedding inclined up-dip. Occasional faint signs of burrows. Grain size mainly fine, i.e. slightly coarser than 1402.

1406 ft. SANDSTONE; similar to 1405 but laminae fainter, and sandstone is harder and more kaolinitic. Bottom of core slightly more calcareous or dolomitic than top.

1407 ft. SANDSTONE; similar to 1405, but cross-bedding direction obscure, partly because of disruption by more frequent 4 mm. burrows. Slight mottling in shades of grey-white.

1408 ft. SANDSTONE; similar to 1406.

1409 ft. SANDSTONE; similar to 1405 but dark laminae better developed. Dip about 25°.

1410 ft. SANDSTONE; similar to 1406, but harder, and porosity probably poor.

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1419 ft. SHALE/SANDSTONE. Irregular buckled (slumped) alternations about 5 mm. thick, also several carbonaceous (coaly) bands less than 1 mm. thick. Pellets of sandstone caught up in shale. Sandstone is hard, fine, non-calcareous, kaolinitic, with no oil stain or odour. Shale is black, hard, silty, with small mica flakes. Slump movement direction appears to be up-dip. Dip is ca 45°.

1420 ft. SANDSTONE; dirty white, hard, medium to fine grained. Very faint dark laminae, coalescing at top to form coarse micaceous (muscovite and biotite) shaley and carbonaceous parting. Abundant kaolin; locally also calcareous; fair porosity. Minor fracture planes, sealed with calcite, inclined up-dip at ca 85°. No oil stain or odour.

1421 ft. SANDSTONE; similar to 1420 but without the shaley layer. Poorly sorted. Joint plane 1 mm. wide filled with calcite, inclined up-dip at ca 85°.

1422 ft. SANDSTONE; similar to 1421. With fault plane inclined at 45° orientated at 270° to dip direction. Displacement not less than 4 inches; sealed. Thin carbonaceous or bituminous flakes on one bedding plane.

1423 ft. SANDSTONE; similar to 1421.

1424 ft. SANDSTONE; similar to 1421 but less calcareous.

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1494 ft. CALCAREOUS SANDSTONE; off-shite, even, but with faint shading; very hard, tight, completely cemented, calcareous, not argillaceous, cement probably coarsely granular. Medium to fine grained, poorly sorted. Infrequent small mica flakes throughout.

1495 ft. CALCAREOUS SANDSTONE; as 1494. One calcite vein 1.5 mm. wide inclined at 75°.

1496 ft. CALCAREOUS SANDSTONE; similar to 1494 but hard rather than very hard. One 4 mm. wide joint or fracture plane partly sealed by calcite and partly impregnated with black tarry oil, inclined at 60°. One parallel sealed 0.5-1 mm. calcite vein. Some kaolin.

1497 ft. SANDSTONE; dirty white, moderately hard, grain size from over 0.5 mm. downwards, poorly sorted. Inter-digitating zones of slightly differing cementation; kaolin in pores and slightly calcareous or dolomitic; estimated fair porosity; light oil stain and odour. Faint impressions of bedding inclined at 40°.

1498 ft. SANDSTONE; similar to 1497, but slightly darker oil stain. Common large muscovite flakes on bedding planes.

1499 ft. SANDSTONE; similar to 1498.

1500 ft. SANDSTONE; similar to 1498, but faint traces of bedding at about 50° brought out by alternating whitish and greyish layers due to differences in interstitial matter and oil stain. Cut faces of core have vuggy appearance, but this is due to washing-out of kaolin pockets.

1501 ft. SANDSTONE; similar to 1498. Faint bedding as in 1500, but at 40°. Probably tighter.

1502 ft. SANDSTONE; similar to 1498 but harder and tighter and more calcareous or dolomitic.

1503 ft. SANDSTONE; similar to 1502. Some dead oil in pores. Faint bedding at <u>ca</u> 45°.

1504 ft. SANDSTONE; similar to 1503 but very hard and locally more calcareous. Faint bedding at <u>ca</u> 40°.

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1506 ft. SANDSTONE/(SHALE). Irregular mixture due to slumping and compaction. Probably originally 3 sandstone beds 3-4 cm. thick and about 1 cm. apart. A tongue or dyke of sandy shale appears to be intruded upwards from the remains of one bed 6 cm. through the overlying beds at an angle of 60°; it is 1 cm. wide and slab-shaped, running the full width of the core. Also numerous 4 mm. diam. compaction channels or burrows. Sandstone is grey-white, hard, micaceous, kaolinitic or argillaceous, moderately calcareous or dolomitic, fine grained, tight, with some black tarry oil plugging pores.

1507 ft. SANDSTONE/(SHALE). Sandstone similar to that of 1506 but with grains up to 0.5 mm., with two minor shaley bands 5 and 2 mm. wide about 15 mm. apart. Irregular and cut up by abundant burrows and compaction channels 2-4 mm. across.

1508 ft. SANDSTONE/(SHALE). Sandstone similar to that of 1506, with 3 shaley layers 15, 4, and 5-10 mm. thick, and 10 and 30 mm. apart. Minor irregular shaley laminae in the sandstone between. Intruded coarser irregular tight sandstone mass towards top of core. Dip about 45°. Slickensides on shaley bedding plane at right angles to dip direction. Some very minor calcite-sealed fractures inclined in same direction as dip but at about 70° to horizontal.

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1509 ft. SANDSTONE; grey, even, hard, lightly oil stained and with oily smell. Abundant specks of black tarry oil. Well cemented, highly calcareous or dolomitic; kaolin in pores and some small mica flakes throughout. Grain size from over 0.5 to under 0.125 mm.

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1513 ft. SANDSTONE; grey, hard, medium to fine grained, with thin cross-bedded laminae of carbonaceous shaley matter and large muscovite flakes. Rather argillaceous, non-calcareous with slight even oil stain and odour and abundant black tarry oil specks; estimated porosity poor to fair. No burrows or other disturbance. Dip 45°, cross-bedding inclination consistently down dip.

1514 ft. SANDSTONE; similar to 1513, but dark laminae more pronounced, have associated microcrystalline dolomite or siderite lenses <u>ca</u> 2 x less than 1 mm., and do not suggest current action, being parallel or sub-parallel. Locally sandstone is slightly calcareous or dolomitic. Porosity is fair, petroleum indications as 1513.

1515 ft. SANDSTONE; similar to 1513; locally slightly calcareous; dip 45°; cross-lamination direction of inclination down-dip.

1516 ft. SANDSTONE; junction of two beds seen. Upper part similar to 1514. Lower part contorted with slump folds of up to 3 cm. amplitude, marked by darker layers about 1 mm. thick and 5 mm. apart in whitish sandstone. Sandstone is hard to very hard, completely cemented and tight with coarsely crystalline calcite, and is medium grained. Dip shown by dark bands in upper sandstone is 45°; that on the boundary between the two sandstones is about 40°. The boundary is irregular but the bulk of the upper sandstone is not contorted by the slumping. Direction of slumping appears to have been the same as that of the dip. Minor fracture planes (sealed) in two directions.

1517 ft. SANDSTONE; thin alternations (1-3 mm.) of tight light grey and brownish grey layers, dipping at 45°. The brownish layers become thinner, more micaceous and shaley downwards; otherwise they are rather hard, and composed mainly of irregular sideritic pellets <u>ca</u> 0.5 mm. across embedded in a calcareous and slightly argillaceous matrix. The interbedded light grey layers are fine grained quartz sandstone, with some kaolinitic patches, rare local calcareous patches, and abundant black tarry oil specks. There is a slight oil odour; porosity probably poor.

1518 ft. SANDSTONE; three beds visible. <u>Lower</u>: grey, hard, sandstone, coarse to medium grained and poorly sorted, with abundant kaolin and some microcrystalline siderite or dolomite, micaceous, with some black tarry oil in pores; porosity estimated poor; thickness seen about 3 cm. <u>Middle</u>: sandstone as above inter-bedded (0.5-2.0 cm. parallel bands) with very hard white calcareous sandstone, completely cemented, poikolitic, with occasional pockets of kaolin, finer grained than above (medium) and better sorted, dipping at 45°. Top is truncated at about 40° by the <u>top</u> bed which is: sandstone; similar to white sandstone of middle layer but finer still (fine), and with close faint thin dark laminae marking uncertain cross-bedding. 2.5 cm. up the sandstone becomes grey, only slightly calcareous, medium grained again and poorly sorted, very micaceous (esp. biotite and ?chlorite), and there are black oil specks in pores; porosity probably poor.

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1524 ft. SANDSTONE/SHALE. 6 cms. of white sandstone with slightly contorted thin dark laminae (originally cross-bedding) followed by 5 cm. of dark silty shale with minor light sandy layers and a 1 mm. coaly lense, evenly layered below but with some disturbance at top. The sandstone below is fine grained, micaceous, kaolinitic, slightly calcareous or dolomitic, hard, without oil stain or smell; estimated porosity poor. The contortion is due partly to some compaction channels or burrows. Dip 45°.

1525 ft. SANDSTONE/(SHALE). Dirty white to lightly oil stained and grey-buff sandstone, mixed; hard, medium grained, slightly kaolinitic and calcareous or dolomitic, with abundant specks of black tarry oil. A few widely spaced thin dark laminae of irregular form. Mottling at least partly due to 5 mm. diam. burrows or compaction channels visible on base of core. Basal shaley layer has slickensiding at about 80° clockwise from the dip direction. Dip is 45°.

1526 ft. SANDSTONE; grey-buff, medium hard to hard, medium grained, with kaolin pockets and locally very slightly calcareous or slightly dolomitic. Micaceous partings with very large muscovite flakes and carbonaceous or bituminous flakes. Distinct oil stain and smell, abundant black tarry oil specks, estimated porosity fair. A very vuggy appearance on cut surfaces of the sandstone appears to be due to the washing-out of kaolin pockets.

1527 ft. SANDSTONE; similar to 1526. Faint parallel bedding dipping at 35°-40°.

1528 ft. SANDSTONE; similar to 1526 but coarser and locally more calcareous or dolomitic. Faint bedding inclined at <u>ca</u> 30°. Abundant black tarry oil specks.

1529 ft. SANDSTONE; similar to 1528.

1532 ft. SANDSTONE; generally similar to 1528 but bedding, while still faint, is more distinct in the form of <u>ca</u> 5 mm. alternations of lighter and darker grey-buff sandstone, indistinctly bounded. Lighter layers are due to more abundant kaolin and microcrystalline carbonate, darker layers to less of these and to more abundant tarry black oil specks. Average porosity fair.

1534 ft. SANDSTONE; similar to 1528. Bedding fainter.

1535 ft. SANDSTONE; light grey, hard, medium grained, moderately argillaceous, moderately calcareous and with abundant sideritic pellets. Carbonaceous or bituminous material concentrated in thin wavy anastomising bands, accompanied by biotite flakes. Negligible oil stain, slight odour, estimated porosity poor.

1536 ft. SANDSTONE; similar to 1526 but tighter and with faint dark carbonaceous and micaceous laminae, marking small scale cross-bedding - direction of inclination is down-dip. Oil stain uneven; porosity probably poor.

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1537 ft. SANDSTONE/SHALE. Very thin fairly regular alternations (less than 1 mm.) of black shale and grey-white sandstone, grading upwards into grey-white sandstone with pronounced close shale and micaceous laminae marking small scale cross-bedding - direction of inclination is up-dip. Dip is <u>ca</u> 45°. Irregular fracture plane with small displacement inclined at 80° in approximately the up-dip direction. Rare 4 mm. burrows. Sandstone is hard, fine grained, kaolinitic, essentially non-calcareous, but micaceous streaks are accompanied by abundant micro-crystalline sideritic or dolomitic pellets. No oil stain or odour. Poor porosity.

1538 ft. SANDSTONE/SHALE; similar to 1537 but alternating throughout. Gentle slumping near base. Minor fractures (overthrusts with displacement of 1 or 2 mm.) related to the slumping, fracture plane inclined down-dip at about 60°. Dip is about 45°. Slickensides on lower bedding plane, almost in dip direction.

1539 ft. SANDSTONE/SHALE; generally similar to 1537, with parallel closely spaced and also cross-bedded dark laminae.

1540 ft. SANDSTONE/(SHALE); similar to 1537, but with more sandstone, and patchy variations in cementation. Porosity poor.

MISCELLANEOUS ASPECTS
OF SANDSTONE CEMENTATION
BASED ON SAMPLES FROM COUSLAND-6.

CONTENTS

I. INTRODUCTION AND SUMMARY

The sandstones sampled by the well Cousland-6 are, as recently described (4th February, 1960), of relatively simple composition. Their framework consists essentially of quartz, felspar, and mica; the cements are secondary quartz and two texturally distinguishable varieties of carbonate; the remaining matrix is almost entirely well-crystallised kaolin. This comparative simplicity facilitates certain kinds of investigation, and the analyses previously obtained have now been augmented in order to test certain hypotheses. Some of the points covered are of minor importance, but it was felt to be worth while taking the opportunity of investigating them while it presented itself.

In this report it is shown that, as hinted earlier, some two-thirds of the porosity of the Cousland sands resides in spaces loosely packed with kaolin, and only the remaining one-third in visible open pores. A sideline of the same investigation indicates that several percent of kaolin can be hidden in a carbonate cement.

It is found that mica flakes are more logically considered to be a part of the framework than part of the matrix of a sandstone.

The porosity of the Cousland sandstones tends to be independent of the degree of packing, the amounts of primary carbonate, kaolin, or secondary quartz, taken singly, being reduced to a fairly uniform level by these factors in combination. By contrast, secondary carbonate, itself very variable in quantity, has a profound effect on porosity. Statistical techniques have been employed in an attempt to discover other variables with which the secondary carbonate might be associated. The results are negative.

The alteration of felspar to kaolin in situ is investigated as a source of silica for cementation of the sandstones. It is shown that the quantity of silica released is insufficient by a factor of about four to one to account for the quantity of secondary quartz in the sandstones from Cousland-6.

Heavy minerals from a sample from Cousland-6 are recorded.

Also recorded is a reciprocal type of relationship which tends to occur between secondary carbonate and other components which are liable to be replaced by it diagenetically.

II. MICRO- AND MACRO- POROSITY

It is an inherent limitation of thin section studies that no quantitative distinction - beyond the broadest guess - can be made between a space which is packed with clay and one which has, perhaps, only a few overlapping clay flakes in the thickness of the section. Qualitatively the difference is apparent by the colour, transparency, and the polarisation colours of the area concerned, but these are also influenced by the nature of the clayey matter present. Consequently neither the true porosity nor the clay content of a rock can be deduced accurately from thin sections, except in the extreme cases where there is virtually no clay, or sufficient to tightly pack all the intergranular spaces. Most sandstones fall between these extremes.

The opinion was expressed in the earlier Report on Cores from Cousland-6 (4th February, 1960) that the present porosity of these samples is represented less by vacant pores than by spaces loosely packed with kaolin.

Since the clay fraction appears to be essentially pure kaolin while the framework of (mainly) quartz grains is well-sorted, with a size range which does not appreciably overlap that of the kaolin flakes, it is possible to separate the two mechanically. From the known density of kaolin it is then possible to calculate the volume of solid kaolin actually present in each sample. Knowing the amount of space in which kaolin is present and the volume of visible unoccupied pore space it is then possible to calculate a "theoretical porosity" for each sample, such that "Theoretical porosity"= visible pores + space occupied by loosely packed kaolin - volume of solid kaolin. This value can then be compared with the porosity measured physically. Exact agreement for individual samples is not to be expected, but the degree of correlation for a group of samples would serve as a check on the various methods of determination used and also show whether or not porosity is concealed in other ways, for example as sub-microscopic cracks between quartz overgrowths.

Porosity determinations were completed for the 14 samples from which thin sections had been cut. Point count analyses were already available for these samples and the figures included the volumes occupied loosely by kaolin. It remained to determine the amount of kaolin by weight present in each sample.

Pieces of sample already used for the porosity determinations were roughly dis-aggregated by gently crushing, and weighed. Dis-aggregation was completed by removing all carbonates and organic matter by repeated alternate treatments with hot concentrated hydrochloric acid and hydrogen peroxide. This process took very much longer than expected owing to the low solubility of some of the carbonates, the refractory nature of the organic matter, and the need to allow long standing periods for the clay to settle completely between successive treatments. In the end, only nine of the fourteen samples were treated in this way, and these took a month to complete. After complete dis-aggregation the kaolin was removed by repeated decantation, it being found that a separation at 15 microns gave a fine fraction containing little but kaolin and a coarse fraction containing little but quartz, felspar, and mica. The kaolin fraction was finally dried and weighed. The complete quantitative data now available are given in table (1).

The theoretical and measured porosities are plotted in figure (1). Although several of the points lie up to 5% away from their expected values represented by the straight line, a good general agreement is apparent. In fact, the mean theoretical porosity is 9.6%, and the mean measured porosity is 9.2% for these samples. Taking the matter a little further statistically, the correlation coefficient between the theoretical and measured porosity is 0.98, which is a very high correlation, and it turns out that, for the number of samples concerned, this value would only have arisen by chance less than once in a thousand times. We may therefore safely consider the relation established. In other words, the porosity not accounted for by the open pores visible in thin section is present as micro-pores between the loosely packed clay particles, and is not hidden in any other manner.

About one-third of the total porosity is visible as open pores, the remaining two-thirds being hidden in the clay fraction.

HIDDEN KAOLIN IN CALCITE

A further point arises from the new data. Sample 1494 is cemented by coarse calcite, apparently to the exclusion of other cements. No clay was recorded in the point-counting figures, determined at a magnification of x4000, yet this sample is found to contain 6.9% of clay by weight, equivalent to a volume of 2.6%. The explanation is simple, for the high refractive index and low birefringence of kaolin combine to render small amounts dispersed in calcite almost invisible.

The relation that when very high proportions of calcite occur in a sandstone clay appears to be absent is one which can be widely observed. It is also a common observation that coarse calcite in sandstones is

Table I

Sample number	1366	1390	1402	1409	1421	1494	1500	1514
Detrital quartz	54.6	55.0	58.0	60.6	54.0	57.2	63.0	46.7
Felspars	5.1	4.0	3.3	4.2	5.5	0.0	2.0	3.0
Micas	1.8	8.7	2.3	1.2	4.0	0.0	0.0	3.3
Porous clay	15.7	12.7	8.0	6.6	11.2	0.0	9.3	13.3
Visible pores	0.9	2.6	5.0	5.7	4.2	0.0	2.2	5.0
Clay by weight	-	11.6	4.6	5.4	4.4	6.9	-	7.9
True vol. of clay	-	4.5	1.8	2.1	1.7	2.6	-	3.0
Fine carbonate	0.0	1.7	0.3	0.0	8.0	0.0	0.0	7.0
coarse carbonate	11.5	4.3	4.0	1.8	1.8	42.8	10.7	3.0
Secondary quartz	20.0	10.3	19.0	19.9	11.2	0.0	12.9	18.7
Porosity	13.7	7.4	9.3	12.1	11.3	2.1	10.8	10.7
Ø mean size	3.27	3.40	3.43	3.40	2.84	2.67	2.57	3.28
Ø std. deviation	0.49	0.40	0.39	0.41	0.47	0.59	0.47	0.44
*Quartz & felspar	59.7	59.0	61.3	64.8	59.5	57.2	65.0	49.7
*Quartz & felspar & mica	61.5	67.7	63.6	66.0	63.5	57.2	65.0	53.0

(continued overleaf)

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* See page 5.

Table I (continued).

Sample number	1517	1518a	1518b	1526	1532	1537	**Mean**	**Standard deviation**
Detrital quartz	% 42.8	51.4	58.0	60.0	57.8	48.3	54.8	5.73
Felspars	% 5.4	4.2	3.0	3.0	2.7	7.0	3.7	1.73
Micas	% 6.7	3.5	1.0	0.0	0.8	5.7	2.8	2.69
Porous clay	% 10.5	13.2	7.3	10.9	15.5	15.7	10.7	4.32
Visible pores	% 1.6	6.1	0.3	3.3	1.1	1.0	2.8	2.09
Clay by weight	% 8.6	-	6.7	4.6	-	-	6.7	2.36
True vol. of clay	% 3.3	-	2.6	1.8	-	-	2.6	0.91
Fine carbonate	% 25.2	5.8	0.7	1.0	1.3	8.0	4.2	6.81
Coarse carbonate	% 0.9	4.8	29.3	8.3	7.4	1.7	8.7	12.21
Secondary quartz	% 6.3	11.2	0.3	13.3	13.2	8.7	11.8	6.60
Porosity	% 11.8	10.1	6.0	12.5	13.0	7.1	9.9	3.2
Ø mean size	3.27	2.40	2.64	2.34	2.56	3.53	2.97	0.433
Ø std. deviation	0.49	0.75	0.46	0.57	0.47	0.43	0.49	-
*Quartz & felspar	% 48.2	55.6	61.0	63.0	60.5	55.3	58.6	5.41
* Quartz & felspar & mica	% 54.9	59.1	62.0	63.0	61.3	61.0	61.3	4.13

* See page 5.

rarely optically uniform and usually contains numerous minute transparent inclusions. Sometimes these appear to be calcite in random orientations, but in the Cousland samples close examination confirms that they might easily be kaolinite.

It is therefore necessary to bear in mind that several percent of clay may be concealed from all but the most searching examination in calcite cement in sandstones (the same may be true of limestones), and that the apparent disappearance of clay from sandstones rich in calcite may not be as complete as it sometimes appears in thin sections.

IV. PACKING INDEX: THE EFFECT OF MICA

The use of the percentage of "framework" constituents in a sandstone as a measure of the density of packing has been discussed in earlier reports; the measure is identical with the "Packing Index" of Kahn.

When dealing with a rock in which the framework consists almost entirely of detrital quartz and felspar grains the percentage of quartz plus felspar is obviously the measure required. In a rock with an abundance of mica (as in some Cousland cores) the question arises whether the mica should also be regarded as part of the framework and added to the quartz and felspar, or not. Owing to their flexibility, flakes of mica are often bent around the other grains to such an extent that it might almost seem that the mica had little effect on the spacing of the grains and so might more logically be relegated to the "matrix".

One approach to this question is to examine the variability of the packing index obtained with and without the addition of mica; the best measure should be that with least variation. In the case of the Cousland-6 samples it can be seen from figure (2) and from the values of the standard deviation about the mean for quartz, quartz plus felspar, and quartz plus felspar plus mica in table (1) that by this criterion quartz plus felspar gives, as we expect, a better measure of packing than quartz alone, and that the addition of mica gives a better measure still. The improvements are not large, however, and the appropriate statistical test suggests that it might have arisen by chance rather more often than once in every five times, so that it would be necessary to examine a somewhat greater number of samples in the same way before considering the point proved.

If the mica is included in the framework, the average value for the packing index of the Cousland samples is 61.3%, very close to the expected result for a normal sandstone.

Unless contrary evidence is gathered, therefore, it appears logical to include mica flakes comparable in size with the other detrital grains as part of the framework rather than the matrix of a sandstone when estimating packing.

V. VARIABILITY OF DIFFERENT COMPONENTS AND THEIR EFFECTS ON POROSITY

The principal data of table (1) are represented diagrammatically in figure (2), from which several points arise.

The first is an appearance of correlation between the space in which loosely packed clay is present and the amount of secondary quartz. Since it is always observed in thin section that the presence of clay restricts the development of secondary quartz this apparent correlation is immediately suspect, and in fact further examination shows that there is no correlation between the two, the apparent correlation being due to the negative correlation between each of them and the amount of carbonate present.

The second is the impression that the porosity is the least variable of all the components. This is confirmed from an inspection of the standard deviations compared with the respective means of all the components in table (1). Most samples have a porosity quite close to 10%, and this is not much affected by quite large changes in packing, clay content, secondary quartz, grain size or sorting. In one sample (1517) even the presence of 25% of primary, fine grained, carbonate does not depress the porosity below the average. It is only when the coarse, secondary carbonate jumps to large proportions that the porosity is significantly reduced. Much the same conclusion was reached by Griffiths on studying a Virginian Cretaceous sandstone formation by rather elaborate statistical methods (Journ. Sed. Pet. 28, 15-20, January 1958), and the feature may be a general one.

This lack of dependence between the final porosity and the porosity which must have existed before the secondary cements were precipitated is the result of the levelling effect of secondary quartz. No exceptions have yet been found to the observation that in a given area or formation there is a tendency for the maximum thickness of the shell of secondary quartz developed around the detrital grains to be reasonably constant, and that this maximum is reached unless primary interstitial matter of one kind or another or adjacent overgrowths get in the way. Consequently, apart from any later carbonate cement, the porosity of any sand where quartz cementation has occurred on a regional scale tends to be reduced towards the value it would have had if quartz were the only cement, <u>unless</u> primary cements exceed in quantity the expected amount of quartz. For example, if a perfectly clean sand had 20% secondary quartz, the porosity would be about 100-(60+20)=20%. Another sand in the same formation with 10% clay would not have a porosity of 20-10=10%; instead the secondary quartz would be reduced to 10% and the final porosity remain the same at 20%. If, however, there were, say, 25% clay, the secondary quartz would be reduced almost to zero and the porosity would be 100-(60+25)=15%.

These examples have been over-simplified, but serve to illustrate the principle. The effect of grain size has been omitted, but in any case the increase in packing density with increasing grain size usually seems to cancel out most of the expected increase in porosity that is due to the decrease in secondary quartz.

The levelling effect which the secondary quartz has on porosity will not, of course, extend to the permeability which, owing to the size and shape of the pore passages involved will be higher in the clay-free and coarse sands even though these have the same porosity as the others.

Coarsely crystalline carbonate is by far the most variable component of the Cousland-6 samples, with a standard deviation of ±12% and a total range of from less than 1% to more than 40%. This extreme variability also seems to be a feature of calcareous cementation in general. It is often found that in adjacent beds abrupt changes occur, and it is not uncommon for layers only a few millimetres thick to alternate in composition between practically zero and over 40% carbonate. Quite clearly, calcareous cementation is not (or commonly not) a regional effect like that of secondary quartz.

The logical end of research directed to problems of cementation is to improve the chances of predicting changes which may affect porosity and permeability, even though prediction in an exact sense prove ultimately unattainable. According to the present working hypothesis, the effects of quartz cementation in typical sedimentary basins are in principle predictable. Secondary carbonate cements, on the other hand, not only behave in a capricious manner, they have usually a more pronounced effect on porosity variations within a formation than any other cement. If the variations in carbonate content can be understood, then so can the variations in porosity.

Since the pattern of calcareous cementation itself is not clear, one approach to further understanding is to discover whether its variations can be correlated with other properties of the rock whose variations may be more easily understood.

As a first approximation we may assume that directly or indirectly the amount of carbonate in a given layer is related to some feature connected with the depositional environment; if this were not so it would be difficult to account for the usual arrangement of carbonate layers parallel to the bedding. The precise mechanism need not concern us immediately, although several might be envisaged.

The influence of the environment may make itself felt on the chemical constitution and on the physical nature of the sandstone. Many chemical features (such as the nature of the clay minerals and their exchangeable bases, trace elements, composition and pH of connate waters, etc.,) are beyond the scope of the present study, but some (such as the gross mineralogical composition, the alteration of felspars and other minerals, etc.,) show themselves in thin sections and are amenable to the present quantitative compositional approach. Physical factors influenced by the environment include the average size and range of sizes of the particles, and their density of packing. Biological factors, which may well prove to have the foremost controlling influence on calcareous cementation have, in the case of the Cousland cores, left no recognisable traces in the form of fauna, and so cannot be studied directly, although they may have an effect on the other recognisable chemical or physical properties.

Any or all of the measurable properties might be linked in some way with the degree of calcareous cementation. As an example of this approach Griffiths (op. cit.) was recently able to demonstrate a significant correlation between the amount of coarse calcite cement in a formation and the grain size. The coarser the sand, he found, the more likely it was to be cemented. Unfortunately the explanation he offers, namely that the coarser layers, being more permeable, allowed cementing solutions to pass through them more freely, does not seem to have universal application. It only explains matters when the flow of solutions is essentially parallel with the bedding, and it does not explain how some layers become completely cemented, since the reduction in permeability caused by cementation should soon stop the preferential flow through the coarse layers.

The correlation, however, remains. The most calcareous of the Cousland samples analysed are also amongst the coarsest (fig.2). It is not, however, true that the coarsest beds are always the most calcareous, nor that the finest sandstones are never heavily cemented. If grain size is a factor in calcareous cementation, it is evidently not the only one.

Since fairly full and accurate analyses were available for a number of samples from Cousland-6, and since the mineralogy of these is comparatively simple, an attempt was made to utilise these in a search for alternative properties correlated with carbonate cementation.

The usable measured properties are the relative proportions of detrital quartz (with minor amounts of quartzite, chert, etc.,) felspar, mica, fine carbonate, coarse carbonate, secondary quartz, clay (determined on a weight basis), porosity; also the mean grain size and the sorting (standard deviation about the mean) - ten variables in all. Since we know that the solid components plus the porosity must add up to 100%, the porosity can be dropped from this list. It is unlikely that the amount of detrital quartz, as such, can have much influence on the carbonate cementation, and it seems more profitable to substitute the packing, defined as the sum of the percentages of quartz, felspar and mica. Also, the absolute values of the felspar and mica will each be affected by the packing, but this effect can be removed by expressing the mica and felspar as percentages of the total of framework materials. This gives a new list which for purposes of tabulation, may be abbreviated as follows:-

P = quartz + felspar + mica
$F = \frac{\text{felspar}}{P}$
$M = \frac{\text{mica}}{P}$
Q = secondary quartz
C_1 = fine carbonate
C_2 = coarse carbonate
K = kaolin (solid volume)
d = ϕ mean diameter
s = ϕ standard deviation,

giving the series of values shown in table (2) overleaf.

Inter-relationships can be studied by means of bardiagrams, as in figure (2), but with a large number of variables it is impossible to assess the more subtle correlations.

A step further is to study the variables in pairs. This can be done graphically, but with nine variables there are thirty-six possible pairs, and it is less unwieldly to compute their correlation coefficients and tabulate them (table 3, p. 10b).

At this stage a number of relationships are disclosed which may be discussed in passing. The most significant correlation (statistically) is the negative one between between ϕ mean size and ϕ standard deviation (i.e., a positive correlation between grain size and sorting). This relation has repeatedly been observed by the writer in grain size measurements made on thin sections, and part of it at least is inherent in the method of measurement. The correlation coefficient of -0.978 would only occur by chance in less than one occasion in one thousand, but the geological significance may not be great.

Next in significance, with a probability of chance occurrence lying between 1:20 andl:50, is a negative relation between coarse carbonate and felspar. It is invariably obvious in thin section that felspar is

Table 2.

Sample	C_2	P	F	M	Q	K	C_1	d	s
1390	4.3	67.7	5.9	12.9	19.1	4.5	1.7	3.40	0.40
1402	4.0	63.7	5.2	3.6	32.8	1.8	0.3	3.43	0.39
1409	1.8	66.0	6.4	1.8	32.9	2.1	0.0	3.40	0.41
1421	1.8	63.5	8.7	6.3	20.7	1.7	8.0	2.84	0.47
1494	42.8	57.2	0.0	0.0	0.0	2.6	0.0	2.67	0.59
1514	3.0	53.0	5.7	6.2	40.1	3.0	7.0	3.28	0.44
1517	0.9	54.9	9.8	12.2	14.7	3.3	25.2	3.27	0.49
1518_b	29.3	62.0	4.8	1.6	0.5	2.6	0.7	2.64	0.46
1526	8.3	63.0	4.8	0.0	22.2	1.8	1.0	2.34	0.57
Mean	10.7	61.2	5.7	5.0	20.3	2.6	4.9	3.03	0.47
Standard deviation	14.9	5.04	2.76	4.89	13.91	0.86	8.15	0.41	0.06

Table 3.

	C_2	P	F	M	Q	K	C_1	d	s
C_2	1	−.176	−.727	−.490	−.704	−.022	−.345	−.527	+.588
P	−.176	1	+.044	−.158	+.073	−.074	−.533	+.075	−.615
F	−.727	+.044	1	+.561	+.333	+.061	+.616	+.392	.469
M	−.490	−.158	+.561	1	+.113	+.657	+.570	+.495	−.536
Q	−.704	+.073	+.333	+.113	1	−.148	−.013	+.532	−.589
K	−.022	−.074	+.061	+.656	−.148	1	+.235	+.371	−.034
C_1	−.345	−.532	+.616	+.570	−.013	+.235	1	+.181	+.034
d	−.527	+.075	+.392	+.459	+.532	+.371	+.181	1	−.978
s	+.588	−.615	−.469	−.536	−.589	−.301	+.034	−.978	1

particularly susceptible to replacement by coarse carbonate cements, so this correlation causes no surprise. At the same level of significance is a negative correlation between secondary quartz and coarse carbonate. This reflects the obvious relationship between any two secondary cements that if there is a lot of one there is less room for the other. It may also be influenced by the replacement of quartz by carbonate that invariably occurs to some extent.

Of more doubtful significance statistically (probability of chance correlation between 1 in 20 and 1 in 10) are five more correlations:-

Kaolin is positively correlated with mica; this is of some interest as it suggests that some of the kaolin may be allogenic, settling out in the same lulls of current velocity that were responsible for the layers of mica. Alternatively, as there is a correlation between felspar and mica it may merely be a cross-correlation effect, the felspar having decomposed to kaolin.

Primary carbonate is positively correlated with felspar; this is probably also due to cross-correlation between these two components and mica (see below), all with a common origin in sorting or provenance.

Secondary carbonate is positively correlated with ∅ standard deviation i.e. coarse carbonate increases as the sorting becomes poorer (or *vice versa*). This is on the face of it an interesting conclusion, but the relation is investigated further in the next chapter with unfavourable results.

Packing density and secondary quartz are both correlated negatively with ∅ standard deviation, i.e. they increase as the sorting becomes better. The relation between packing and sorting, if true, is not unexpected. The relation between secondary quartz and sorting probably results at least in part from cross correlation between these items and grain size.

Various other correlations fail to reach the 0.1 significance level, and although their statistical significance is therefore negligible, a few of these have observable geological causes:-

Mica and primary carbonate are positively correlated. Both are commonly concentrated in the same layers, as may be seen in the hand specimens and thin sections.

Coarse carbonate is negatively correlated with ϕ mean size, i.e. coarse carbonate increases with increasing grain size. As it stands this is in agreement with Griffith's findings, but this point is investigated further below.

Secondary quartz is positively correlated with ϕ mean size, i.e. increases as the grain diameter decreases. This, if true, is in agreement with the present writer's general observations.

It is worth noticing that the degree of correlation between coarse carbonate and packing, kaolin, and primary carbonate is in each case quite negligible, thus apparently eliminating some of the most promising relations which might have been imagined.

Multiple correlations

When there are more than two variables in a system apparent correlations are often produced between two of them as a result of mutual correlation with a third variable; there may be no true correlation between the first two at all.

Several examples of this have been quoted above. It can similarly happen that a real correlation between two variables can be completely obscured by their mutual correlations (in this case of opposite sign) with a third variable. As the number of variables increases, so does the chance of this kind of interference, so that in most geological problems the subtle interactions of the numerous variables (not all of which, of course, are necessarily recorded in the rock as it finally appears) completely hide all but the most obvious correlations.

There exists a standard mathematical device for alleviating this difficulty. So-called "partial regression coefficients" or "partial correlation coefficients" are calculated relating the variable of interest to all the other variables in turn. Unlike the ordinary correlation coefficient, the partial correlation coefficient is calculated in such a way that any part of the total correlation that is due to cross-correlation with the other variables is removed, and only the part intrinsically associated with the pair under investigation is retained. Similarly, when the gross correlation between two variables has been reduced by cross-correlation with other variables, this effect is removed when the partial coefficients are calculated, and the correlation reappears in its true intensity.

Unfortunately the computations involved are heavy and become progressively more so as the number of variables (and therefore the need for applying the method) increases. In effect they involve solving as many simultaneous equations as there are variables to be considered. It is possibly for this reason more than any other that the application of mathematical methods of analysis to geological problems is usually so unrewarding, for the number of variables that ought to be taken into account is so large that the computation becomes prohibitive, and the simplification of the data that has therefore to be made to reduce a problem to workable dimensions usually means that the only results obtained are too obvious to justify the effort involved. There is, however, some hope that modern high-speed computors may in time change this picture. Professor Krumbein (personal communication) is at work on a programme which will enable an electronic computor to carry out multiple correlation analyses on up to twelve variables, though even this can only be considered a beginning.

In connection with the present work, it was thought that it might be at least educational to discover to what extent the apparent correlations between coarse carbonate and other variables depended on cross-correlations, even if no significant results were obtained. Partial correlation coefficients were therefore calculated between coarse carbonate percentages and the eight other variables listed in table (2). Using a calculating machine (Curta), the computations occupied about a week. The results are given in the first row of the table below:-

	P	F	M	Q	K	C_1	d	s
Partial correlation coefficients	-0.03	-0.33	-0.11	-0.52	-0.03	-0.18	+0.33	+0.39
Ordinary correlation coefficients	-0.18	-0.73	-0.49	-0.70	-0.02	-0.35	-0.53	+0.59

The second row gives, for comparison, the correlation coefficients already calculated and shown in table (3). From this it appears that there is no outstanding correlation obscured by cross correlations, but on the other hand all the apparently significant correlations (for example with felspar, secondary quartz, sorting, and mean diameter) were spuriously inflated by cross correlations. The relation between size and calcareous cementation found by Griffiths therefore cannot be confirmed in the present study.

As it happens, none of the partial correlations tabulated above are statistically significant. As might have been foreseen, for such a large number of variables a very much greater number of sample analyses than the nine available would have to be made. From the present results, however, it does not appear that the extra work entailed would be particularly useful. The only coefficient of any magnitude relates coarse carbonate negatively to secondary quartz, and as already mentioned this is to be expected and not helpful in understanding why some beds are cemented more densely than others.

VI. NATURE OF THE RELATIONSHIP BETWEEN SECONDARY CARBONATE AND SOME OTHER MINERALS

It is shown above that no light is at present shed on the distribution of coarse carbonate cement by an analysis of the relations between its proportions and those of other components in the same samples. In the course of preliminary graphical investigation, however, a form of relation between coarse carbonate and certain other components was observed which may ultimately be found to have some significance.

It is usually found in practice that relations between pairs of components in sandstones assume an approximately linear form if they exist at all. This observation can be justified theoretically by the additive nature of the system, whereby more of one component means less of another, in a strictly linear way; on the other hand, the dependence of the existence of two components on some common cause also implies an interrelationship of direct proportionality.

When, however, experimentally plotting coarse carbonate against fine carbonate percentages, (figure 3), against mica (figure 4), and felspar (figure 5), it was found that the points tended to be concentrated in the vicinity of the two axes. The two components thus tend to be mutually exclusive to some extent, or looking at it another way, they bear a relation to one another which is very roughly hyperbolic. This relation is not apparent in the correlation coefficients quoted in the previous section, because the correlation coefficient, as ordinarily calculated, only expresses the degree of linear correlation between a pair of variables.

It so happens that it is suspected that there is replacement of mica by coarse carbonate, and it is definitely known that there is replacement of felspar by coarse carbonate. It is possible, therefore, that where a reciprocal relation rather than a linear relation occurs between two components it may suggest that one is replacing the other during diagenesis.

VII. DECOMPOSITION OF FELSPAR IN RELATION TO QUARTZ CEMENTATION

The kaolinization of felspar grains in situ in sandstones is a process which has sometimes been put forward as a source of silica capable of cementing the sand. The samples from Cousland-6 recently analysed offered an opportunity to test the quantitative implications of this hypothesis.

In the decomposition of felspar (for which orthoclase may be taken as the model) to kaolin, one molecule of $K_2O.Al_2O_3.6SiO_2$ yields one molecule of $Al_2O_3.2SiO_2.2H_2O$ and four of SiO_2. Making use of the appropriate molecular weights and densities it is found that one part of felspar by volume yields 0.458 parts/vol of kaolin and 0.419 parts/vol of quartz.

The Cousland cores analysed contain an average of 11.8% secondary quartz, 2.6% of kaolin and 3.7% felspars by volume (table 1). Thus if all the secondary quartz was formed by the release of silica in the decomposition of orthoclase there should originally have been 28.2% felspar in addition to the present 3.7%, i.e. a total of 31.9%. Although not impossible, this is an unusually high percentage for a rock which in other respects appears to be rather mature.

If all the kaolin now present came from felspar in situ the original felspar content should have been 5.6% plus the present 3.7%, a total of 9.3% which is not unreasonable for a sandstone of this kind. This change, however, would only have released 2.4% silica, leaving 9.4% of the secondary quartz unaccounted for. Since some of the kaolin may have been contributed by other sources the discrepancy may be even greater.

The time relations of the relevant components are shown in thin section to be decomposition of felspar to kaolin first, followed by precipitation of secondary quartz, rather than the simultaneous decomposition and precipitation which the in situ hypothesis would appear to favour. Finally, there is no correlation between the amount of kaolin and the amount of secondary quartz in the different samples.

Even if, to overcome the quantitative objections, the secondary quartz in a given bed were presumed to be obtained from felspar decomposing in some other bed, to maintain the observed time relation it would be necessary for the solutions carrying the silica to move consistently downwards. This is an awkward assumption, and it seems better to reject the kaolinization of felspars as an important cause of siliceous cementation in the present case, and hence in the majority of cases where there are large proportions of secondary quartz and where this has been deposited after the decomposition of felspars.

VIII. HEAVY MINERALS FROM COUSLAND-6

Heavy minerals were separated from one Cousland-6 core. About half the grains were opaque minerals, mainly limonite and leucoxene. The transparent minerals consisted of rounded colourless zircon (abundant); rounded pink zircon (fairly common); large etched colourless garnet (abundant); dark red-brown and yellow-brown irregular to sub-euhedral rutile (common); green flakes of tourmaline (rare); and chlorite (a trace).

J.C.M. Taylor
Imperial College
23rd May 1960

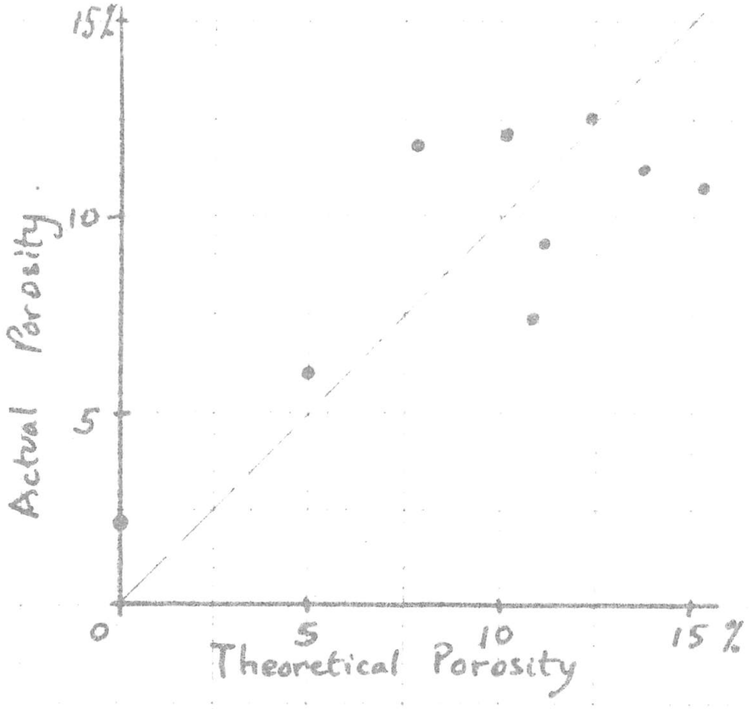

Fig. 1. Porosity determined directly plotted against porosity calculated from thin section and weight of kaolin, Cowland-B, 1390', 1402', 1409', 1421', 1494', 1514', 1517', 1518$_B$', and 1526'.

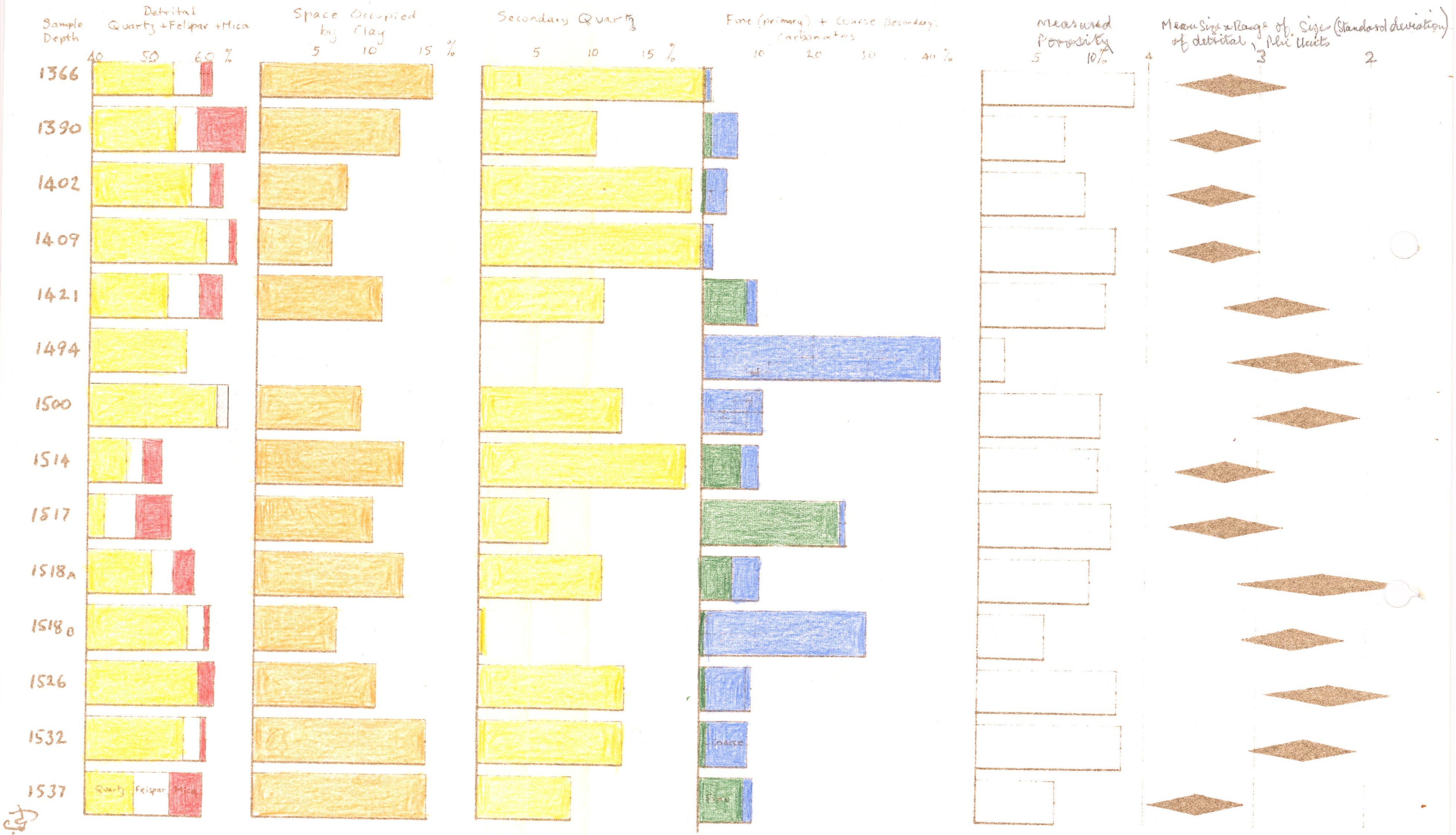
Sample Depth
Detrital Quartz + Felspar + Mica
40
50
60 %
Space Occupied by Clay
5
10
15 %
Secondary Quartz
5
10
15 %
Fine (primary) + Coarse Secondary Carbonates
10
20
30
40 %
Measured Porosity
5
10%
Mean Size x Range of Sizes (Standard deviation) of detrital, Phi Units
4
3
2
1366
1390
1402
1409
1421
1494
1500
1514
1517
1518A
1518B
1526
1532
1537
Quartz
Felspar
Mica
Coarse
Fine

Fig. 2.

Fig. 3

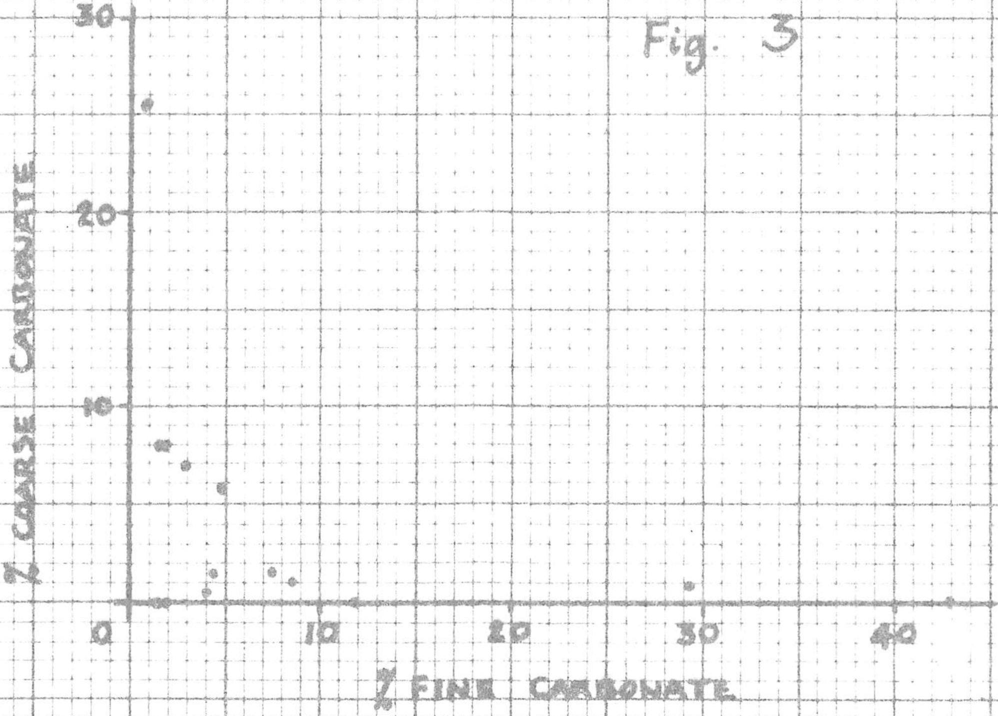
% COARSE CARBONATE
30
20
10
0
10
20
30
40
% FINE CARBONATE

Fig. 4

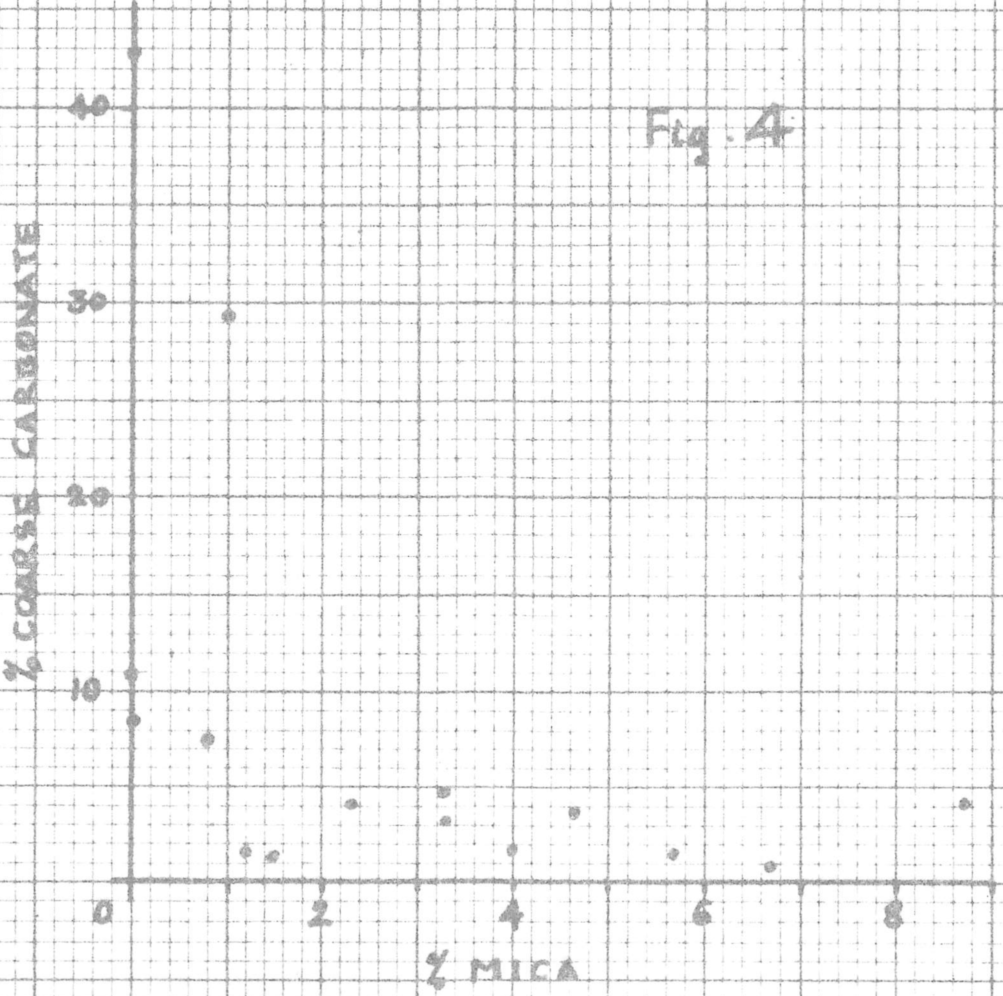
% COARSE CARBONATE
40
30
20
10
0
2
4
6
8
% MICA

Fig. 5