BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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THE ROLE OF CLAYS IN FORMATION DAMAGE IN MESOZOIC RESERVOIR SANDSTONES OF THE EROMANGA BASIN

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SUMMARY

Cored sandstone units from the Mesozoic of the Eromanga, Surat, and Bowen Basins and early Palaeozoic of the Amadeus Basin were tested for the presence and effect of pore space clays, which may react to drilling, testing, and other downhole operations, and cause significant formation damage. The Eromanga sequence is noted for the common presence of kaolinite and some smectite, whereas the Surat and Bowen Basin units contain a high proportion of authigenic kaolinite. The Pacoota Sandstone of the Amadeus Basin sequence appears largely clay free and is principally composed of quartz with minor traces of illite.

Reservoir cores were studied through a series of tests on the types and quantities of clays present (X-ray diffraction, benzidine reaction, cation exchange capacity, and Qv values) and flow characteristics of the samples (fresh water index, surge pressure tests and clay stabiliser flow tests). These tests briefly outlined some of the difficulties which might be experienced with drilling and production in certain reservoirs in terms of clay type and content, and precautions to be taken in down-hole operations.

Some of the Eromanga Basin sandstone reservoirs appear to be highly susceptible to formation damage via contact with fresh water - eg, from drilling muds, completion fluids, particularly in the eastern region. Surge pressure testing produced significant permeability changes in practically all the samples, the implication being that down-hole operations which produce high well bore pressure differential may cause reservoir damage.

INTRODUCTION

In the early history of petroleum production, most formation damage was attributed to water absorbing, swelling clays, such as smectites, which blocked the reservoir pore system when contacted with fresh water. (Fig 2) However, with the advent of modern research methods and tools for studying formation clays, it is now appreciated that severe damage can also occur from non-swelling clays.

This damage is largely caused by mobility of the clays, often through high differential pressures in various down-hole operations. Even swelling clays are subject to this damage mechanism whereby they may move to a pore neck after being dislodged in the body of the pore by expansion through changed ionic conditions of the pore fluids.

Although clay linings in the pore system may reduce the permeability of a reservoir, the absence of clays can also adversely affect porosity. This latter effect is evident in the Amadeus Basin Pacoota sandstone, where clean quartz surfaces with low clay content favour quartz overgrowths during diagenesis. All fine fraction X-Ray Diffraction analyses (Table 3) of this formation indicate quartz as the dominant mineral and scanning electron microscope photo micrographs (Plate A) show prolific euhedral quartz overgrowths which have significantly reduced porosity.

The type and amount of clays present in a permeable formation can also have a significant effect on enhanced oil recovery techniques, because of the large surface area and reactivity of such clays. Slobod (1952) suggested that the presence or absence of clays as pore space linings also may have a bearing on the wettability characteristics of sandstones: however, these aspects of clays are not covered in this paper.

Clay evaluation and formation damage studies described herein were carried out on core samples from various potential reservoirs in five Australian sedimentary basins, to evaluate their clay content and formation damage characteristics. The basins are the Bowen, Surat and Eromanga in Queensland (Fig 1) with limited tests on samples from the Cooper Basin (South Australia) and the Amadeus Basin (Northern Territory). The main emphasis of the work was on samples from the Central Eromanga Basin as part of a multidisciplinary BMR study of that basin.

In some areas investigated, notably the Cooper and Amadeus Basins, the number of samples tested was limited because only a few core samples were available for analysis. Many more samples from each area need to be examined before a general conclusion can be drawn as to whether certain clay minerals are common to specific formations or areas.

THE AUTHIGENIC CLAYS

Clays contained in the pores of reservoir rocks are mainly of authigenic origin and occur either as continuous pore linings or as discrete colonies attached to the host rock, growing perpendicularly to the pore wall. The most commonly occurring varieties are kaolinite, illite, smectite, chlorite, and mixed layer types; the grain size of these clays is often less than 5 um (Davies, 1980). Any of these clays may be dislodged from the pore walls and move into pore restrictions during drilling, testing and production operations, resulting in formation damage.

A description follows of these clays and their reaction to reservoir fluid flow conditions.

Kaolinite is not securely attached to the pore wall and will break away under sudden pressure surges or turbulence. Authigenic plates of this material have been measured at up to 100 um (Almon 1981). Kaolinite, if dislodged, may remain as pore fill if the disturbance ceases, however, continued turbulence may cause sets of plates to move to pore throat restrictions where they may impede fluid flow (Fig 3).

Illite may exist as a hair-like growth extending from the pore walls into the pore body. If growth is extensive then illite from opposite walls may meet and form fluid flow restrictions, or turbulence may break these hairs which will then be free to move to pore throat restrictions to form a brush-heap structure preventing easy fluid flow.

Where illite exists as a pore lining its very large micro-porosity may entrap water on the pore wall. Water saturations measured from electric logs may thus be interpreted as mobile or free water when, in fact, this water is bound to the illite by surface tension. Pittman and Thomas (1978) have suggested that micro-porosity due to clay linings could result in log interpretation indicating a water saturation of greater than 60% yet the zone may produce water-free oil.

The specific surface areas in the following list (which are proportional to micro-porosity), indicate the importance of discovering whether clay minerals, particularly illite, are present (Almon 1981).

Mineral	Surface Area
Quartz	0.15 cm^2/g*
Kaolinite	23 m^2/g
Chlorite	42 m^2/g
Smectite	82 m^2/g
Illite	113 m^2/g

* Dependent on grain size and distribution.

Smectite normally occurs as a pore lining, the thickness of which may not be sufficient to close a pore body. However, at the pore throat, where layers come together, they may close the pore outlets. Linings of smectite and some illites have been measured at a maximum thickness of 25 um (Almon 1981). Naturally if the water existing in the pore changes to one of significantly lower ionic concentration, then the smectite lining will swell, lowering the permeability (Fig 2).

Grim (1962) reports that out of 90 samples from a wide selection of reservoir sands of different geological ages and geographical locations only one suite of samples older than Mesozoic was found to contain smectite; these were of Permian age.

Chlorite, apart from reducing permeability due to its formation on pore walls, may also have its iron, which is contained in the lattice, dissolved during acidising operations. This may be precipitated later, upon contact with some formation waters, as high volume, gelatinous, ferric hydroxide which may plug pore throats.

Mixed Layer Clays may exist as illite/smectite, illite/chlorite or smectite/chlorite.

ANALYSES PERFORMED

The following tests and examinations were implemented to determine the effect that authigenic clays may have on petrophysical properties of porous sandstones.

X-ray Diffraction Analysis: fine fraction X-ray examination was carried out to determine the dominant minerals.

Scanning Electron Microscope: Photomicrographs were taken of typical clay mineral assemblages in areas studied (Appendix 1)

Routine Core Analysis: to determine the pore space (porosity) and flow capacity (permeability) of the test samples.

Permeability to Various Liquids: flow to NaCl brine, fresh water and clay stabiliser solutions were conducted at various flowing pressures to determine their effect on clays in the pore space.

Benzidine Test: this is a qualitative test for determining the presence of swelling clays.

Fresh Water Index (FWI): this test measures the loss of formation permeability resulting from contact with fresh water.

Simulated Downhole Pressure Surge Tests: a test designed to discover if pore clays might be dislodged during turbulent flow (eg down-hole pressure surges) such as would occur during drillstem testing or other well-site operations (Figs 4, 5).

Clay Stabiliser Tests: these were conducted to determine the fluid flow characteristics of core samples after pore clays had been treated to obtain clay stabilisation.

Cation Exchange Capacity (CEC): is an indication of the clay concentration in the rocks.

Typical CEC values are shown in the following table derived by Whitaker and Dyson (1980):

Mineral	CEC(me/100 g)	Ave.
Quartz	0	0
Kaolinite	3-15	9
Chlorite	1-30	15
Illite	10-40	25
Smectite	80-150	115

Cation exchange values are also used in a formula developed by Waxman and Smits (1968) to determine "Qv" values. These values are used as an aid in electric log interpretation.

$$Qv = \frac{CEC\ (1 - \phi)pm}{\phi \times 100}$$

where:

Qv = Milliequivalents of cation exchangeable material per cu cm of pore space

CEC = Cation exchange capacity in milliequivalents per 100 g of rock

ϕ = Porosity fraction

pm = Grain density of rock in g/cu cm.

Neasham (1977) conducted further research with Qv values derived from the Waxman and Smits formula, and suggested that formations could be classified according to these values.

Clean value	-	Qv 0.03 me/cu cm pore space
Slightly shaley	-	Qv 0.11 me/cu cm pore space
Very shaley	-	Qv 0.69 me/cu cm pore space.

Further detailed descriptions of sample preparations and testing procedures used in this paper can be found in appendix 2.

DISCUSSION OF RESULTS

X-RAY DIFFRACTION ANALYSIS (Bulk sample and -5um fraction)

Eromanga Basin, (Tables 1A to 1D and Table 2)

Quartz was found to be the dominant mineral in 62 of the 64 samples examined by bulk X-Ray Diffraction Analysis. However, examination of the -5um fractions from this basin showed that only 10 of the 64 samples exhibited quartz as the dominant mineral.

This demonstrates the importance of carrying out the fine fraction X-Ray examination, as the fine authigenic clays are most probably derived from permeable passages where they could be affected by chemical or physical changes.

The dominant, fine fraction mineral existing in the pore spaces throughout the Eromanga Basin samples (Table 2A) is kaolinite, followed by smectite, quartz, illite and chlorite. Table 2B, which shows the fine fraction minerals present in each formation tested in the Eromanga Basin, also shows the dominance of kaolinite in this area.

Bowen Basin (Table 1D and Table 3)

Only one well in this basin, (Taroom No. 14) drilled by the Geological Survey of Queensland, has been studied. The 5 samples from this well all showed kaolinite as the dominant mineral in the fine fraction X-Ray Diffraction analysis, with mica, illite and chlorite occurring in smaller concentrations.

Surat Basin (Table 1E and Table 3)

A total of 9 wells were studied in the basin. Except for one sample from the Mitchell No. 2 well, the dominant, fine fraction material is again kaolinite which occurred in 13 of the 14 samples examined. Smectite occurred in smaller concentrations in some of these samples, as did some of the mixed layer clays and chlorite.

The Amadeus Basin (Table 3)

The Pacoota sandstone in the Amadeus Basin is generally regarded as an interval of low clay content; accordingly, separate test results were included in this study for comparative purposes, particularly with respect to possible damage characteristics exhibited where the clay content of rocks is limited. Of 14 samples examined for clay content in 4 wells (Pacoota sandstone, Mereenie field), 12 indicated that quartz was the dominant fine fraction mineral (-5 um). Only 2 samples from one well showed that illite was the dominant fine fraction mineral (Table 3).

BENZIDINE REACTION AND Qv VALUE

EROMANGA BASIN Tables 4A to 4C.

Charleville Area (Table 4A) Out of 11 samples from this area (Eastern Central Eromanga Basin) there were 10 positive benzidine reactions observed, indicating the presence of smectite.

The average Qv value was rather high at 0.29 me/cu cm. According to Neasham (1977) these formations would be classified as slightly to very shaley.

Bodalla Area (Table 4B) Sample evaluation in this region (west of the Charleville area) indicated that smectite is less prevalent than in the Charleville area. However, 5 out of 8 samples from the Bodalla area indicate the presence of smectite.

The average Qv value is 0.09 me/cu cm. According to Neasham these samples are classified as clean to slightly shaley.

Jackson Area (Table 4C) This area is west and south of the above areas; from the 12 samples examined, only one indicated the presence of smectite (trace only) during benzidine tests.

The average Qv value is 0.07 me/cu cm. According to Neasham these samples are classified as clean to slightly shaley.

Gidgealpa Area: Only 2 samples from this area (west of Jackson) were examined; both resulted in negative benzidine reactions indicating the absence of smectite.

The average Qv value is 0.10 me/cu cm. According to Neasham these samples are classified as clean to slightly shaley.

BOWEN BASIN Table 4D

The only samples examined from this area were all from the GSQ well, Taroom No. 14. Of 9 samples examined only one resulted in a positive benzidine reaction.

The average Qv value is 0.13 me/cu cm. According to Neasham classification these samples are classified as slightly shaley.

SURAT BASIN Table 4E

Ten samples from Alton Nos. 1, 3, 4, 5 and 8 wells and 6 samples from the GSQ Mitchell No. 2 well were examined of which eight (mainly from Mitchell No.2) indicated the presence of smectite when subjected to the benzidine test.

Individual Qv values varied considerably from 0.02 me/cu cm in the Alton No.5 well to 0.40 me/cu cm in one Mitchell No. 2 sample. The average Qv value for all samples was 0.10 me/cu cm. According to Neasham these samples are classified as slightly shaley.

AMADEUS BASIN

Four samples from 4 wells penetrating the Pacoota sandstone were tested for the presence of smectite; all gave negative results. The average Qv value for these sampales was 0.05 me/cu cm. According to Neasham these samples are classified as clean.

FRESH WATER INDEX (FWI)

EROMANGA BASIN Tables 4A to 4C.

Charleville Area (Table 4A) Of the 12 samples from 2 wells (Quilpie No 1 and Charleville No 1) tested for FWI, 5 collapsed when subjected to water saturation or flow; the FWI for these samples must be recorded as zero. The FWI for 6 of the remaining samples varied from 3% to 30% and one other indicated an FWI of 88%. An average taken for all samples was 21% indicating a high sensitivity to fresh water.

The fact that these zones are water sensitive is confirmed by the widespread presence of smectite detected by benzidine tests and the relatively high Qv values obtained.

Bodalla Area (Table 4B). The FWI was determined on 7samples from this area, all from the Bodalla South Nos. 1 and 2 wells.

Values of FWI varied from 55% to 100% in 6 samples, the other sample exhibited a low 17% FWI. The average FWI for all the samples was 75%, much higher than for the Charleville area. From the high FWI values, the lower concentration of smectite and the relatively low Qv values, it is suggested that in this area the Hutton Sandstone and Basal Jurassic are not particularly water sensitive.

In a special test, twin plugs from 1592.3 m and 1593.8 m in Bodalla No. 2 well were treated with a clay stabilising compound before being subjected to the FWI test. Results are shown in Table 4B where, for the former sample, the FWI has been increased from 55% in the untreated sample to 95% in its twin which was treated with the clay stabiliser. The latter twin plugs exhibited little change. Clay stabilisation tests on other samples are shown in the next section.

Jackson Area (Table 4C). Twelve samples from 4 wells were tested for sensitivity to fresh water; the resultant FWI values ranged from 49% to 100% (average 79%) indicating that the formations investigated are only slightly water sensitive.

Smectite in these zones was virtually non-existent and the average Qv value was a low 0.07 me/cu cm.

Gidgealpa Area. No FWI values were determined on the 2 samples available from this area.

BOWEN BASIN Table 4D.

No FWI determinations were made on samples from this area.

SURAT BASIN Tables 4E.

Ten samples from 5 Alton wells were the only ones tested for FWI in this area. FWI values varied from 14% to 85% with an average of 78%. The relatively high FWI value is indicative of formations that are not very water sensitive.

The Alton samples showed only traces of smectite during the benzidine test and the Qv values were low, confirming that water sensitivity is not a problem in this area.

AMADEUS BASIN

In a separate comparative investigation the Pacoota sandstone exhibited a higher FWI than any samples reported above.

SURGE TESTING AND CLAY STABILISATION

Most of the samples flow tested under a surge pressure procedure exhibited some type of clay movement. In some cases, clays were displaced from the sample; accordingly, permeability was sometimes reduced and sometimes enhanced, depending on the character of the clay movement. However, the actual change in permeability, whether positive or negative, is the value that has been recorded since it is the movement of fines which is thought to be the major contributing factor in degrading reservoir permeability.

Short length plugs may tend to allow mobile clays to be ejected from the sample rather than becoming trapped in pore throat restrictions, but it is probable these clays would have eventually plugged passages, reducing permeability, had their journey through the test plugs been of greater length (eg. as in an actual reservoir). Some test results of longer samples (7.5 cm) from the Bodalla area support this conclusion by generally exhibiting a reduced permeability after surging.

EROMANGA BASIN Tables 5A to 5D.

Charleville Area. Table 5A. Eight samples covering the 2 wells from this area were subjected to the surge testing procedure; changes in permeability, after the surge had been applied, varied from 4% to 100% of the permeability before surge testing occurred.

Even though smectite occurs in this area it is probable that permeability changes which occurred were due to clay movement, rather than clay swelling, as the flowing fluid was 30 000 ppm NaCl which would inhibit smectite swelling.

No clay stabilisation testing of samples from this area was carried out.

Bodalla Area. Table 5B. Four samples from Bodalla South Nos. 1 and 2 were used for surge testing and exhibited variable changes in permeability due to surging; changes ranged from 9% to 135%.

Twin samples to the 4 used above were tested with clay stabiliser before surge testing, resulting in permeability changes of only 3% to 16% indicating the effective application of the stabiliser.

Jackson Area. Table 5C and 5D. Sixteen samples from the 4 wells in the Jackson area indicated changes in permeability from 0% to 90% after surge testing. Four twin samples to the above were treated with clay stabiliser before surging, and this resulted in considerable stability being effected as the permeability change, after surging, was only from 1% to 17%.

Gidgealpa Area. No surge or clay stabilisation testing of samples from this area was carried out.

BOWEN BASIN Table 5E

Four samples from the GSQ Taroom No. 14 well were tested and changes in permeability after surge testing ranged from 32% to 82%. However, twin samples treated with a clay stabiliser exhibited a change in permeability after surging of only 4% to 25%, again showing the effective application of clay stabilisers in reducing the movement of fines in the samples.

SURAT BASIN Table 5F

Only the Alton field samples were used for surging tests, with the change in permeability after surging ranging from 1% to 73%. Smectite was indicated in some of these samples, but the use of 30 000 ppm Na Cl in the flow tests would inhibit clay swelling in the samples. Therefore, permeability changes subsequent to surge tests were most likely a result of movement of loosely attached clays rather than any clay swelling effects.

No clay stabilisation testing of samples from this area was carried out.

AMADEUS BASIN (For comparison)

Surge tests carried out on the Pacoota sandstone indicated permeability changes, due to surging, to be lower than any recorded in the above tests. This is a characteristic of samples with a minimum amount of clay fines in the pore space.

CONCLUSIONS

Although the number of samples which have been studied from the Mesozoic section in the Queensland basins is limited, some trends do appear from 14
the results of this study which indicate variations both within and between basins.

The Eromanga Basin is characterised by formations in the eastern part (Charleville area) which show a common presence of smectite and kaolinite, with low fresh water index (FWI) and generally high Qv values (high clay indications). These formations are highly susceptible to formation damage, particularly if contacted with fresh water. In the central part of the Eromanga Basin (Bodalla area, Jackson area), formations are generally less fresh water sensitive with high FWI and low Qv values, and with kaolinite as the dominant clay. The Bodalla area samples, however, are more sensitive to damage than those from the Jackson area (particularly resulting from fresh water contact) probably due to the slightly higher smectite content of the former. Limited tests on Hutton sandstone samples from the Gidgealpa area indicate clean formations with low Qv values but with some chlorite as the fine fraction clay.

In the Bowen Basin the samples examined indicated that authigenic kaolinite was prevalent, as was the case with the samples from the three Surat Basin wells which were studied. However, the Qv values in each case were not particularly high. The limited tests carried out on samples from the two basins indicate that neither area is particularly susceptible to formation damage.

The Amadeus Basin samples provided comparative tests on essentially clay free quartz sandstones. These samples were the least sensitive to formation damage of all the samples tested, with low Qv values, high FWI and only very limited effects from surge pressure tests.

Surge pressure testing was characterised by permeability reduction in the majority of samples subjected to these tests. Although no particular trends in this type of damage were seen across the basin(s), its general prevalence indicates that caution should be exercised with any downhole operations where high differential pressures may occur around the wellbore. Further detailed comments on this aspect are beyond the scope of this paper and will be covered in a future publication by the author.

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APPENDIX 1

Clay Mineral assemblages

Scanning electron photomicrographs of typical clay mineral assemblages in the areas studied.

Plate A. Euhedral quartz growths
Little clay

Plate B. Margin of pore space
Chlorite and smectite
Extending into pore

Plate C. Kaolinite and fibrous illite lining a pore space

Plate D. Authigenic illite lining a pore space. Note microporosity

Plate E. Authigenic quartz, chlorite and kaolinite

Plate F. Porefill of chlorite between euhedral quartz growths.

APPENDIX 2

TESTING PROCEDURES

Sample Preparation:

For the majority of the tests only plugs perpendicular to the core axis, (parallel to bedding plane), were used. These were cut using either a 2.54 cm or 4.81 cm diamond core bit, depending on core size. The ends of the plugs were trimmed to give a symmetrical cylinder of from 3 cm to 8 cm in length. Where material was in short supply, some plugs were obtained by drilling parallel to the core axis. In some tabulated results, it will be seen that two plugs, taken from the same depth, vary greatly in permeability values; this is due to one being a "horizontal" plug, the other "vertical".

After extracting with toluene for 12 hours the plugs were oven dried at 105°C for 18 hours, then cooled in a desiccator.

Conventional Porosity and Permeability:

The effective porosity at atmospheric conditions was determined using an accurate, mercury pycnometer for bulk volume and a helium porosimeter for grain volume. From these measurements and the weight of the sample, effective porosity, apparent grain density and dry bulk density were obtained.

Permeabilities of the cleaned and dried plugs were measured by flowing dry nitrogen through them as they were confined in a rubber sleeved, Hassler cell. Sample dimensions were measured, a differential pressure applied, the rate of flow of nitrogen observed and from these values the permeability was calculated.

Benzidine Reaction:

For this test a small piece of the sample was taken from near the centre of the core segment so that any contamination by bentonite from the drilling fluid was minimised.

The selected piece was crushed and placed in a test tube with an equal amount of benzidine powder and the test tube shaken to intimately mix the two powders. The test tube was then half filled with water and the resulting mixture shaken vigorously and allowed to settle. After 24 hours the mix was examined.

A blue colouration appearing in the solids was indicative of the presence of montmorillonite, the swelling component of bentonite. It has been found in our investigations that some forms of illite, particularly degraded illite, also gives this colouration.

Depending on the strength of the blue colouration, results were recorded as very strong, strong, medium, light, trace or nil.

Cation Exchange Capacity (CEC) and Qv Values

Samples for this test were taken from the centre of the core and lightly crushed before simmering in a complex phosphate solution, then placed in a sonic bath to disperse clays and expose all cation exchange sites.

After cooling, the mixture was titrated with a standard methylene blue solution to an end point where the clay component was saturated with and would not absorb further methylene blue. The CEC was then calculated as milliequivalents of cation exchangeable material per 100 g of sample. Qv values were determined using the Waxman and Smits formula.

Fresh Water Index (FWI)

For this determination the cleaned and dried plugs were evacuated before saturating with a relatively high concentration brine (30 000 ppm NaCl). Permeability to this brine was then determined with the plug confined in a rubber sleeved Hassler cell.

While still in the Hassler cell the plugs were subjected to flushing with evacuated fresh water and allowed to stand overnight in this water before the permeability to fresh water was obtained.

All waters used in these and other tests were treated with mercuric chloride to prevent growth of bacteria, and also filtered using 3 um millipore papers before use.

The FWI was then determined using the following formula:

$$\text{Fresh water index (\%)} = \frac{\text{Permeability to fresh water} \times 100}{\text{Permeability to 30 000 ppm NaCl}}$$

Simulated Down-Hole Pressure Surge Tests

As clays were known to be present in the pore space of most of the sandstones examined, a test was designed to discover if such clays could be dislodged during turbulent flow such as might occur during down hole operations.

The permeabilities of separate plugs, to 30 000 ppm NaCl brine, were determined in an overburden pressure cell. Flowing pressures were maintained below 70 kPa, with triaxial confining pressure of 14 000 kPa.

Next a "surge" flowing pressure of 3 500 kPa was applied to each of the samples and a 50 ml volume of 30 000 ppm NaCl brine was passed through each plug at this pressure. The surge pressure was then removed and the permeability re-measured at the same flowing pressure as was used before the surge.

During surging the effluent was collected and, in some cases, the filtrate ejected was subjected to a scanning electron microscopic examination.

Clay Stabiliser Testing

To ascertain the efficiency of a commercial clay stabiliser, additional pairs of plugs, taken as close as possible to each other, were drilled from core segments. All plugs were evacuated and saturated with 30 000 ppm NaCl solution.

One plug from each pair was then confined in a Hassler cell and subjected to flooding with a 5% KCL solution containing 1% of a clay stabilising compound. The other plugs from each pair were not treated with the clay stabiliser.

All plugs, both treated and untreated, were next subjected to a flow of 30 000 ppm NaCl at 70 kPa flowing pressure and 14 000 kPa confining pressure (overburden pressure cell) before surging with the brine at a pressure of 3 500 kPa. After surging, the permeability to brine at 70 kPa flowing pressure was re-determined. Comparisons of permeability changes were made between the untreated plugs and those that had been treated with the clay stabiliser.

TABLE - 1A

EROMANGA BASIN

X-Ray Diffraction Characteristics

Well Name & No.	Depth m.	Horizon	X-Ray Diffraction Dominant Mineral: Bulk Sample	X-Ray Diffraction Dominant Mineral: -5um Fraction	Other Minerals Present
Augathella No.3(BMR)	24.62	Hooray	Quartz	Kaolinite	M/I.
"	40.70	"	"	"	M/I.
Balfour No.1	955.69	Precipice	Quartz	Kaolinite	M/I.
Bodalla South No.1	1468.2	Hutton	Quartz	Kaolinite	M.
"	1469.1	"	"	"	M.
Bodalla South No.2	1449.7	Hutton	Quartz	Kaolinite	C. I/Sm.
"	1453.9	"	"	"	M.I/Sm.
"	1459.9	"	"	"	M.
"	1468.0	"	"	Quartz Kaolinite	K.
"	1592.3	Basal Jurassic	"	Quartz	K.C.
"	1593.8	"	"	"	K.C.
Budgerygar No.1	1511.95	Birkhead	Quartz	Quartz	M/I.K.
Canaway No.1	1331.71	Hutton	Quartz	Kaolinite	M/I.F.C.
Charleville No.1	164.60	Wallumbilla	Feldspar	Berthierine?	Sm. clinop-tilolite
"	454.49	Cadna Owie	Quartz	Kaolinite	M/I.
"	562.14	Hooray	"	"	M/I.
"	640.80	"	"	"	F.Sm.
"	784.73	Adori	"	"	F.Sm.
"	843.62	Hutton	"	Smectote	F.K.
"	1043.11	"	"	Kaolinite Smectite	M/I.
Chandos No.1	1606.10	Birkhead	Quartz Feldspar	Smectite Illite	C.K.
"	1635.67	"	Quartz	Quartz	M/I.K.Sm

M-Mica, I-Illite, C-Chlorite, K-Kaolinite, S-Siderite, B-Barite, Sm-Smectite, F-Feldspar, An-Anhydrite, Do-dolomite, Ca-Calcite

TABLE - 1B

EROMANGA BASIN

X-Ray Diffraction Characteristics

Well Name & No.	Depth m.	Horizon	X-Ray Diffraction Dominant Mineral: Bulk Sample	X-Ray Diffraction Dominant Mineral: -5um Fraction	Other Minerals Present
Coongie No.1	1746.95	Adori	Quartz	Quartz	K.Sm.
Cumbroo No.1	1767.89	Birkhead	Quartz	Smectite/ Illite Kaolinite	F.C.
Eromanga No.1	862.4	Hooray	Quartz	Kaolinite	M/I.
"	921.3	"	"	"	Sm.B.
"	1027.6	Adori	"	Quartz	K.M/I.C. Sm.
"	1152.7	Hutton	"	Kaolinite	M/I.
"	1204.8	"	"	Chlorite	M/I.K.
"	1249.7	Precipice	"	Mica/Illite Kaolinite	Sm.
"	1255.1	"	"	Quartz	M/I.K.Sm.
Fairlea No.1	916.11	Birkhead	Quartz	Kaolinite	F.C.
"	1111.43	Hutton	"	Chlorite	M/I.F.
Galway No.1	2418.1	Triassic	Quartz Barite	Barite	M/I.
Gidgealpa No.1	2158.91	Hutton	Quartz	Chlorite	M/I.F.K.
Gilmore No.1	3700.2	Etonvale	Quartz	Illite/ Smectite	M/I.F.
Jackson No.1	1115.82	Cadna-Owie	Quartz	Kaolinite	F.C.
"	1333.82	Westbourne	"	"	M/I.F.Sm. Siderite
"	1343.01	"	"	"	M/I.F.I/Sm. Siderite
"	1440.90	Hutton	"	"	M/I.Sm.
"	1447.56	"	"	Smectite	M/I.K.I/Sm. Siderite
Merrimelia No.1	2156	Hutton	Quartz	Kaolinite	M/I.Do. Siderite

M-Mica, I-Illite, C-Chlorite, K-Kaolinite, S-Siderite, B-Barite, Sm-Smectite, F-Feldspar, An-Anhydrite, Do-Dolomite, Ca-Calcite

TABLE - 1C

EROMANGA BASIN

X-Ray Diffraction Characteristics

Well Name & No.	Depth m.	Horizon	X-Ray Diffraction Dominant Mineral: Bulk Sample	X-Ray Diffraction Dominant Mineral: -5um Fraction	Other Minerals Present
Mt Howitt No.1	1874.7	Nappamerri	Quartz	Dickite siderite	M/I.
Murterie No.1-A	1535.06	Hutton	Quartz	Dickite	M/I.Sm/I.
Naccowlah South No.4	1696.80	"	Quartz	Kaolinite	M/I.I/Sm.
"	1696.80	"	"	Dickite	M/I.I/Sm.
Newlands No.1	1165.85	Hooray	Quartz	Kaolinite Quartz	M/I.C.
Quilpie No.1	621.40	Cadna-Owie	Quartz	Kaolinite	M/I.F.
"	667.60	"	Feldspar Smectite	Smectite	K.
"	728.47	Hooray	"	"	K.
"	772.78	"	Quartz	Kaolinite Smectite	F.B.
"	803.61	Westbourne	"	Smectite	F.K.Ca.C.
"	852.03	"	"	"	C.B.K.
"	897.96	Adori	"	Kaolinite	F.C.Sm.
"	908.22	"	"	"	M/I.F.C.
"	961.02	Birkhead	Quartz Kaolinite Feldspar	Illite/ Smectite Kaolinite	-
"	987.88	"	Quartz	Smectite	K.C.
"	1029.80	Hutton	"	M/I.	
'	1098.68	"	"	M/I.C.	
Weena No.1	1250.30	Blythesdale	Quartz	Quartz Kaolinite	M/I.Sm.
Wilson No.1	1364.13	Westbourne	Quartz	Kaolinite siderite	M/I.Sm.
Yanda No.1	1509.29	Cadna-Owie	Quartz	Kaolinite	M/I. I/Sm. siderite
Yongala No. 1	1917.13	Hutton	Quartz	Quartz	M/I.K.
Yongala No.2	1809.15	Hutton	Quartz	Calcite	Ca.S.C.

M-Mica, I-Illite, C-Chlorite, K-Kaolinite, S-Siderite, B-Barite, Sm-Smectite, F-Feldspar, An-Anhydrite, Do-Doloimite, Ca-Calcite

TABLE - 1D

BOWEN BASIN

X-Ray Diffraction Characteristics

Well Name & No.	Depth m.	Horizon	X-Ray Diffraction Dominant Mineral Bulk Sample	X-Ray Diffraction Dominant Mineral -5um Fraction	Other Minerals Present
Taroom No.14	20.61	Moolayember	Quartz	Kaolinite	F.Ca.C.
"	521.23	"	"	"	F.M/I.C.
"	610.35	Clematis	"	"	F.M/I.C.
"	987.77	"	"	"	M/I.C.
"	1121.83	Rewan	"	"	F.C.M/I. Ca.

M-Mica, I-Illite, C-Chlorite, K-Kaolinite, S-Siderite, B-Barite, Sm.Smectite, F-Feldspar, An-Anhydrite, Do-Dolomite, Ca-Calcite

TABLE 1E

SURAT BASIN

X-Ray Diffraction Characteristics

Well Name & No.	Depth m.	Horizon	X-Ray Diffraction Dominant Mineral: Bulk Sample	X-Ray Diffraction Dominant Mineral: -5um Fraction	Other Minerals Present
Alton No.1	1862	Precipice	Quartz	Kaolinite	I/Sm.C.
Alton No.3	1851	Precipice	Quartz	Kaolinite	I/Sm.
Alton No.4	1858	Precipice	Quartz	Kaolinite	I/Sm.
Alton No.5	1864	Precipice	Quartz	Kaolinite	C.
Alton No.8	1859	Precipice	Quartz	Kaolinite	Ca.
Mitchell No.2	374.70	Westbourne	Quartz	Smectite	F.C.K.
"	715.84	Hutton	"	Kaolinite	F.C.
"	818.90	"	"	"	F.C.M/I.
"	844.66	Evergreen	"	"	Sm.
"	853.86	"	"	"	M/I.
"	932.69	Precipice	"	"	M/I.Sm.C.
Moonie No.1	1776.8	Precipice	Quartz	Kaolinite	F.M/I.
Moonie No.2	1770.1	Precipice	Quartz	Kaolinite	F.M/I.
Moonie No. 3	1773.2	Precipice	Quartz	Kaolinite	F.M/I.

M-Mica, I-Illite, C-Chlorite, K-Kaolinite, S-Siderite, B-Barite, Sm-Smectite, F-Feldspar, An-Anhydrite, Do-Dolomite, Ca-Calcite

TABLE - 2

CLAY MINERAL CONTENT

Percent Dominant Mineral in X-Ray Analysis of -5um Fraction

(A) EROMANGA BASIN, MESOZOIC (64 samples)

	Percent
Kaolinite	59
Smectite	16
Quartz	15
Illite	6
Chlorite	5

(B) EROMANGA BASIN, MESOZOIC, SEPARATED INTO HORIZONS

Horizon	No. of Samples	Kaolinite (Dickite)	Smectite	Quartz	Illite	Chlorite
Cadna Owie	5	80	20	-	-	-
Hooray	9	83	11	6	-	-
Westbourne	5	60	40	-	-	-
Adori	5	60	-	40	-	-
Birkhead	7	29	29	29	13	-
Hutton	23	68	12	7	-	13
Precipice/Basal Jurassic	5	30	-	60	10	-

TABLE - 3

CLAY MINERAL CONTENT

Percent Dominant Mineral In X-Ray Analysis of -5um Fracture

BOWEN BASIN (5 samples)

Kaolinite	100	
Smectite	0	
Quartz	0	Insufficient samples to separate into horizons
Illite	0	
Chlorite	0	

SURAT BASIN (14 samples)

Kaolinite	93	
Smectite	7	
Quartz	0	Insufficient samples to separate into horizons
Illite	0	
Chlorite	0	

AMADEUS BASIN For comparison (14 samples)

Kaolinite	0
Smectite	0
Quartz	86
Illite	14
Chlorite	0

BENZIDINE REACTION - Qv - FRESH WATER INDEX

EROMANGA BASIN | **TABLE - 4A**

Charleville Area

Well Name & No.	Depth m.	Porosity Percent of Bulk Volume	Benzidine Reaction	Qv m.e./cu cm pore space	Permeability md. (K) Nitrogen	30 000 ppm NaCl	Fresh Water	Fresh Water Index (FWI) K fresh / K 30 000 ppm NaCl percent
Charleville No.1 (G.S.Q.)	164.60	35	Nil	0.18	231	99	87	88
"	454.49	35	Medium	0.94	Plug disintegrated			0
	562.14	32	Strong	0.37	640	109	Plug disintegrated	0
"	640.80	35	Medium	0.22	827	188	"	0
"	784.73	33	Light	0.08	Plug disintegrated			0
"	1043.11	28	Trace	0.14	434	105	3.3	3
Quilpie No.1 (G.S.Q.)	621.40	30	Light	0.12	161	88	4.2	5
"	667.60	28	Very Strong	0.95	30	0.68	Plug disintegrated	0
"	897.96	31	Trace	0.05	671	469	140	30
"	908.22	32	"	0.03	2677	1709	290	17
"	1029.80	29	-	-	6238	3727	924	25
"	1098.68	23	Trace	0.07	59	43	9.1	21

BENZIDINE REACTION - Qv - FRESH WATER INDEX

EROMANGA BASIN — **TABLE - 4B**

Bodalla Area

Well Name & No.	Depth m.	Porosity Percent of Bulk Volume	Benzidine Reaction	Qv m.e./cu cm pore space	Permeability md. (K): Nitrogen	Permeability md. (K): 30 000 ppm NaCl	Permeability md. (K): Fresh Water	Fresh Water Index (FWI): K fresh / K 30 000 ppm NaCl percent
Bodalla South No.1	1468.2	19	Medium	0.13	65	25	4.3	17
"	"	20	-	-	80	37	36	97
"	1469.1	19	Light	0.04	279	168	111	66
'	"	19	-	-	304	182	190	100
Bodalla South No.2	1449.7	16	Medium	0.31	0.35	Not determined		-
"	1453.9	15	"	0.30	0.74	0.12	0.09	75
"	1459.9	19	Nil	0.02	148	Not determined		-
"	1468.0	19	Trace	0.06	1477	"	"	-
"	1592.3*	17	Nil	0.01	653	241	230	95
"	"	17	-	-	603	257	141	55
"	1593.8*	17	Nil	0.01	115	33	24	73
"	"	17	-	-	761	324	241	74

* Treated with clay stabiliser before FWI test.

BENZIDINE REACTION - Qv - FRESH WATER INDEX

EROMANGA BASIN

TABLE - 4C

Jackson Area

Well Name & No.	Depth m.	Porosity Percent of Bulk Volume	Benzidine Reaction	Qv m.e./cu cm pore space	Permeability md. (K) Nitrogen	30 000 ppm NaCl	Fresh Water	Fresh Water Index (FWI) K fresh / K 30 000 ppm NaCl percent
Jackson No. 1	1115.34	21	Nil	0.06	125	97	123	100
"	1115.82	20	"	0.04	94	75	80	100
"	1333.82	19	Trace	0.07	256	197	136	69
"	1343.01	20	Nil	0.07	21	15	16	100
"	1440.90	21	"	0.04	332	233	132	57
"	1447.56	21	"	0.08	413	330	218	66
Naccowlah South No. 4	1694.87	17	"	0.04	328	284	251	88
"	1696.80	17	"	0.11	178	152	138	91
Wilson No. 1	1364.13	18	"	0.10	5.7	9.8	4.8	49
"	1364.41	16	"	0.08	6.8	4.8	3.4	71
Yanda No. 1	1508.26	13	"	0.07	107	83	74	89
"	1509.29	"	"	0.05	176	146	118	

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BENZIDINE REACTION - Qv - FRESH WATER INDEX

BOWEN BASIN

TABLE - 4D

Well Name & No.	Depth m.	Porosity Percent of Bulk Volume	Benzidine Reaction	Qv m.e./cu cm pore space	Permeability md. (K) Nitrogen	30 000 ppm NaCl	Fresh Water	Fresh Water Index (FWI) K fresh / K 30 000 ppm NaCl percent
Taroom No.14 (GSQ)	20.61	12	Nil	0.34	0.01	Not determined		
"	521.23	16	"	0.15	0.35	"		"
"	610.35	22	"	0.06	11	"		"
"	689.35	21	"	0.03	192	"		"
"	802.97	18	Light	0.04	266	"		"
"	870.16	26	Nil	0.02	228	"		"
"	924.61	21	"	0.09	18	"		"
"	987.77	12	"	0.05	1.6	"		"
"	1121.83	11	"	0.37	0.01	"		"

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BENZIDINE REACTION - Qv - FRESH WATER INDEX

SURAT BASIN **TABLE - 4E**

Well Name & No.	Depth m.	Porosity Percent of Bulk Volume	Benzidine Reaction	Qv m.e./cu cm pore space	Permeability md. (K) Nitrogen	30 000 ppm NaCl	Fresh Water	Fresh Water Index (FWI) K fresh / K 30 000 ppm NaCl percent
Alton No. 1	1862	15	Nil	0.09	6.2	2.4	1.6	67
"	1863	14	"	0.12	74	28	9.0	32
Alton No. 3	1851	16	"	0.06	270	266	184	69
"	1852	18	"	0.05	398	378	300	79
Alton No. 4	1858	18	"	0.06	834	792	677	85
"	1859	13	Trace	0.14	10	2.4	0.84	35
"	1869	16	"	0.11	318	214	102	48
Alton No. 5	1863	20	Nil	0.02	418	397	339	85
"	1864	17	Trace	0.03	222	200	170	85
Alton No. 8	1856	17	"	0.05	30	7.9	1.1	14
Mitchell No. 2 (GSQ)	374.70	30	Very Strong	0.40	676	Not Determined		
"	715.84	26	Trace	0.06	1018	"	"	
"	818.90	22	"	0.08	969	"	"	
"	844.66	17	"	0.10	105	"	"	
"	853.86	20	Nil	0.05	197	"	"	
"	932.69	22	Masked	0.09	4500	"	"	

SURGE PRESSURE TESTING AND EFFECT OF CLAY STABILISER

EROMANGA BASIN — TABLE - 5A

Charleville Area

Well Name & No.	Depth m.	Samples saturated with 30 000 ppm sodium chloride only. Permeability to brine at low flowing pressure. md.				Samples saturated with 30 000 ppm NaCl. then flushed with clay stabiliser in KCl. Permeability to brine at same low flowing pressure. md.			
		Before surge pressure of 3500 kPa	After surge pressure	Change in permeability		Before surge pressure of 3500 kPa	After surge pressure	Change in permeability	
				md.	percent			md.	percent
Charleville No. 1 (GSQ)	164.60	19	Sample Collapsed	19	100	Not Determined			
"	1043.11	173	317	144	83	"	"		
Quilpie No. 1 (GSQ)	621.40	110	180	70	64	"	"		
"	772.78	1127	1086	41	4	"	"		
"	897.96	349	303	46	13	"	"		
"	908.22	1136	891	245	22	"	"		
"	1029.80	1879	1546	333	18	"	"		
"	1098.68	25	18	7	28	"	"		

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SURGE PRESSURE TESTING AND EFFECT OF CLAY STABILISER

EROMANGA BASIN **TABLE - 5B**

Bodalla Area

Well Name & No.	Depth m.	Samples saturated with 30 000 ppm sodium chloride only. Permeability to brine at low flowing pressure. md.				Samples saturated with 30 000 ppm NaCl. then flushed with clay stabiliser in KCl. Permeability to brine at same low flowing pressure. md.			
		Before surge pressure of 3500 kPa	After surge pressure	Change in permeability		Before surge pressure of 3500 kPa	After surge pressure	Change in permeability	
				md.	percent			md.	percent
Bodalla South No. 1	1468.2	29	20	9	31	38	32	6	16
"	1469.1	166	36	130	78	173	165	8	5
Bodalla South No. 2	1459.9	74	67	7	9	67	62	5	7
"	1468.0	420	986	566	135	30	29	1	3

SURGE PRESSURE TESTING AND EFFECT OF CLAY STABILISER

EROMANGA BASIN **TABLE - 5C**

Jackson Area

Well Name & No.	Depth m.	Samples saturated with 30 000 ppm sodium chloride only. Permeability to brine at low flowing pressure. md.				Samples saturated with 30 000 ppm NaCl. then flushed with clay stabiliser in KCl. Permeability to brine at same low flowing pressure. md.			
		Before surge pressure of 3500 kPa	After surge pressure	Change in permeability		Before surge pressure of 3500 kPa	After surge pressure	Change in permeability	
				md.	percent			md.	percent
Jackson No. 1	1115.34	66	64	2	3	Not Determined			
"	1115.82	89	79	10	11	"	"		
"	1333.82	184	220	36	20	"	"		
"	"	435	664	229	53	317	320	3	1
"	1343.01	14	13	1	7	Not Determined			
"	1440.90	223	173	50	22	"	"		
"	"	189	212	23	12	271	251	20	7
"	1447.56	297	563	266	90	Not Determined			
"	"	362	452	90	25	304	357	53	17

SURGE PRESSURE TESTING AND EFFECT OF CLAY STABILISER

EROMANGA BASIN — **TABLE - 5D**

Jackson Area (cont'd)

Well Name & No.	Depth m.	Samples saturated with 30 000 ppm sodium chloride only. Permeability to brine at low flowing pressure. md.				Samples saturated with 30 000 ppm NaCl. then flushed with clay stabiliser in KCl. Permeability to brine at same low flowing pressure. md.			
		Before surge pressure of 3500 kPa	After surge pressure	Change in permeability		Before surge pressure of 3500 kPa	After surge pressure	Change in permeability	
				md.	percent			md.	percent
Naccowlah South No. 4	1694.87	77	68	9	12	Not Determined			
"	1696.80	119	66	53	45				
"	"	115	98	17	15	101	90	11	11
Wilson No. 1	1364.08	220	207	13	6	Not Determined			
"	1364.41	132	129	3	2	"	"		
Yanda No. 1	1508.26	4.8	4.8	0	0	"	"		
"	1509.29	3.9	3.7	0.2	5	"	"		

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SURGE PRESSURE TESTING AND EFFECT OF CLAY STABILISER

BOWEN BASIN **TABLE - 5E**

Well Name & No.	Depth m.	Samples saturated with 30 000 ppm sodium chloride only. Permeability to brine at low flowing pressure. md.				Samples saturated with 30 000 ppm NaCl. then flushed with clay stabiliser in KCl. Permeability to brine at same low flowing pressure. md.			
		Before surge pressure of 3500 kPa	After surge pressure	Change in permeability		Before surge pressure of 3500 kPa	After surge pressure	Change in permeability	
				md.	percent			md.	percent
Taroom No. 14 (GSQ)	689.35	37	54	17	46	85	82	3	4
"	802.97	61	111	50	82	137	144	7	5
"	870.16	84	111	27	32	114	129	15	13
"	924.61	6.9	4.7	2.2	32	12	9	3	25

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SURGE PRESSURE TESTING AND EFFECT OF CLAY STABILISER

SURAT BASIN **TABLE - 5F**

Well Name & No.	Depth m.	Samples saturated with 30 000 ppm sodium chloride only. Permeability to brine at low flowing pressure. md.				Samples saturated with 30 000 ppm NaCl. then flushed with clay stabiliser in KCl. Permeability to brine at same low flowing pressure. md.			
		Before surge pressure of 3500 kPa	After surge pressure	Change in permeability		Before surge pressure of 3500 kPa	After surge pressure	Change in permeability	
				md.	percent			md.	percent
Alton No. 1	1862	4.3	3.0	1.3	30	Not	Determined		
Alton No. 3	1851	232	201	31	13	"	"		
"	1852	194	150	44	23	"	"		
Alton No. 4	1858	193	113	80	41	"	"		
Alton No. 5	1863	407	455	48	12	"	"		
"	1864	184	182	2	1	"	"		
Alton No. 8	1856	22	6.4	16	73	"	"		

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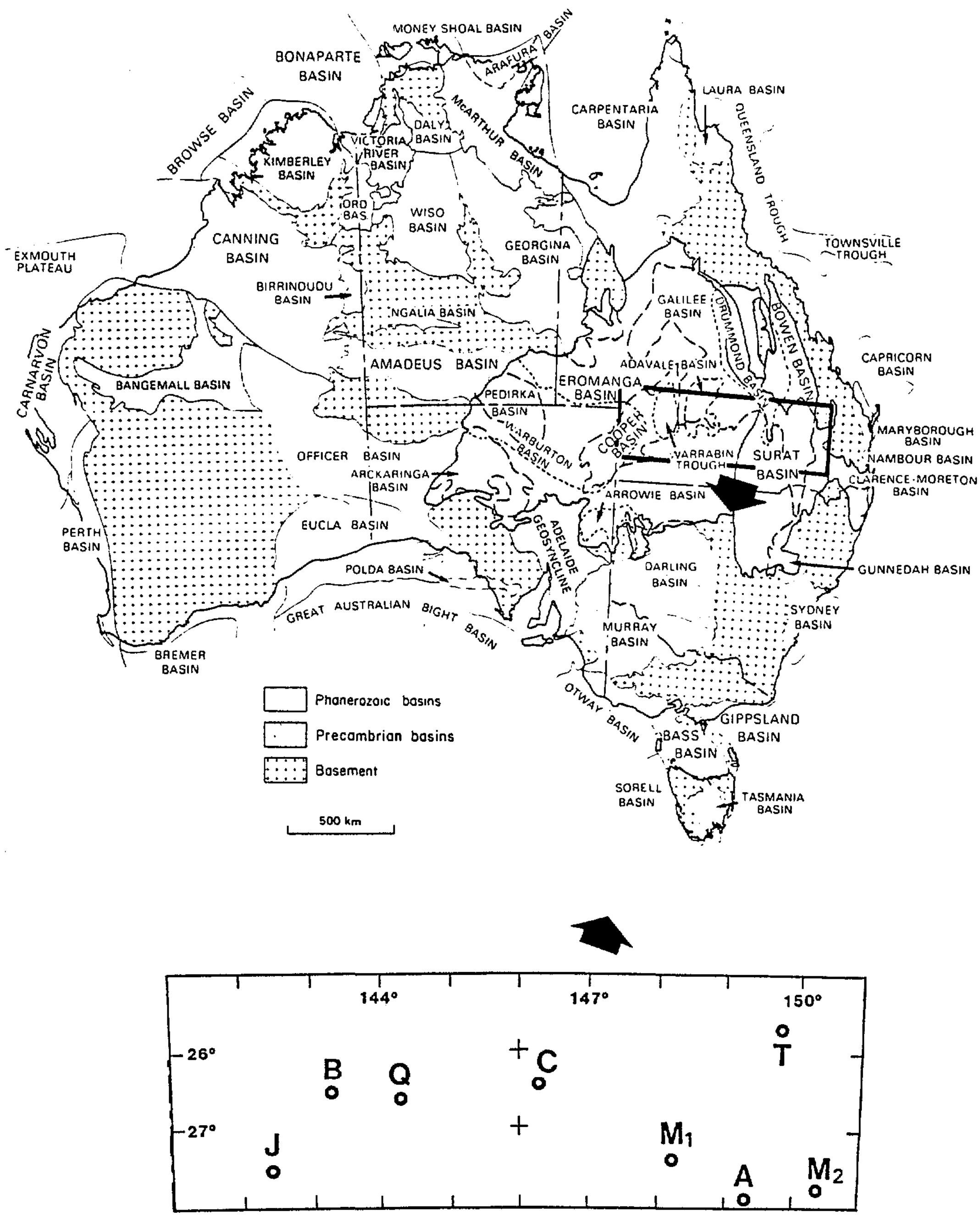
Figure 1 - Principal Areas of Investigation



A —*Alton Area (Surat)*

B —*Bodalla Area (Eromanga)*

C —*Charleville Area (Eromanga)*

J —*Jackson Area (Eromanga)*

M_1—*Mitchell Area (Surat)*

M_2—*Moonie Area (Surat)*

Q —*Quilpie Area (Eromanga)*

T —*Taroom Area (Bowen)*

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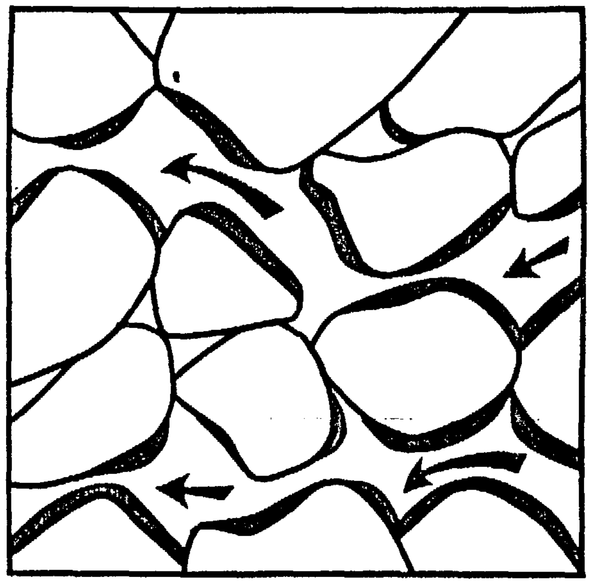
PORE PLUGGING THROUGH CLAY SWELLING



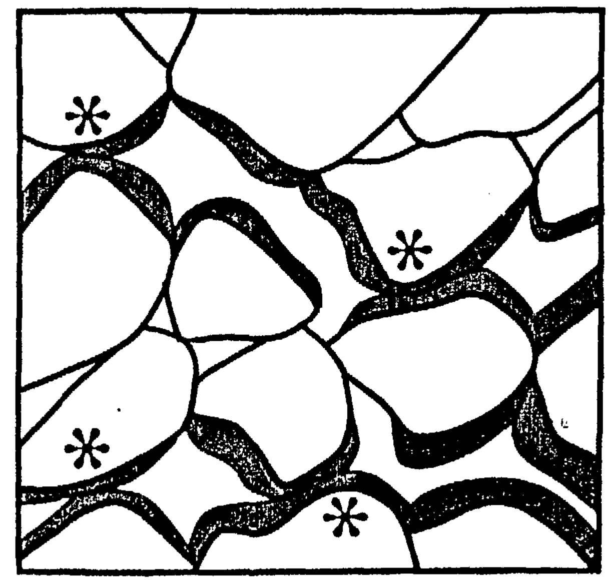


Fig. 2.

CLAY MOVEMENT THROUGH PRESSURE SURGING

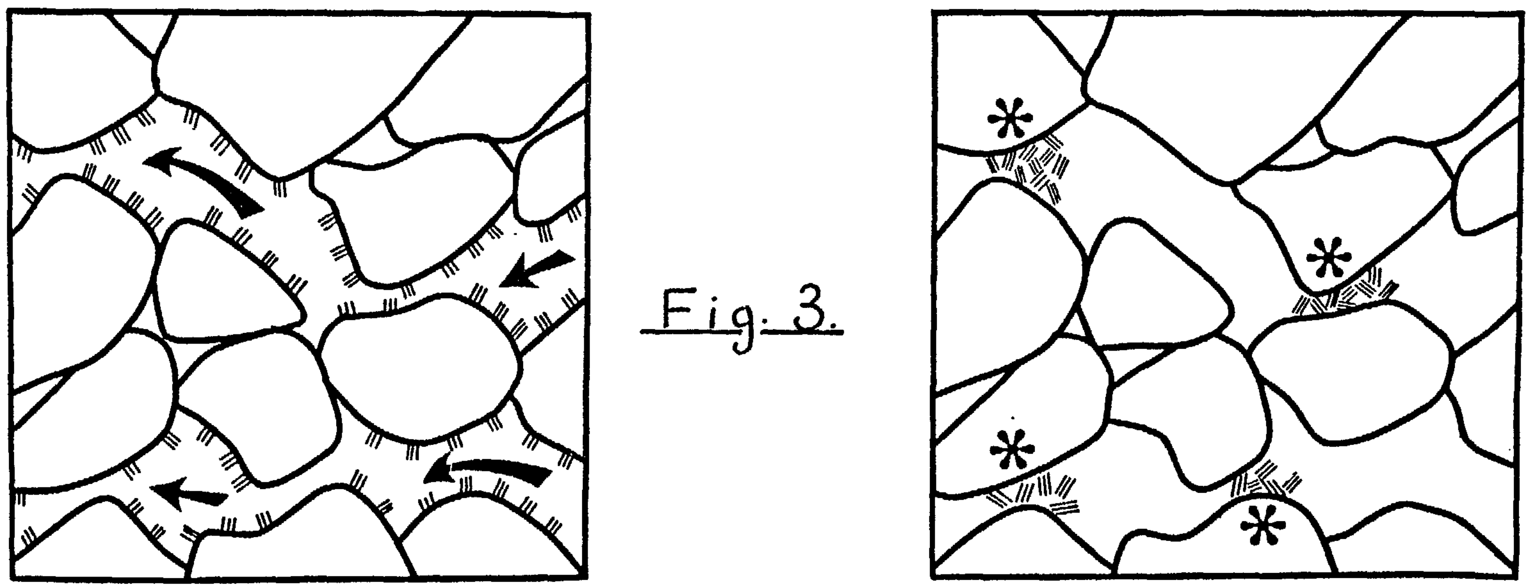


Fig. 3.

DRILL STEM TEST

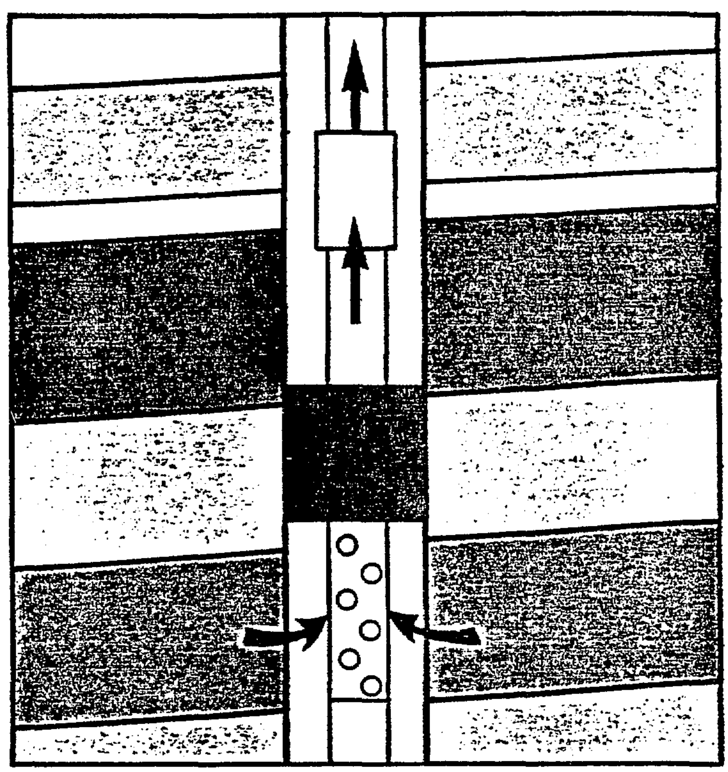


Fig. 4.

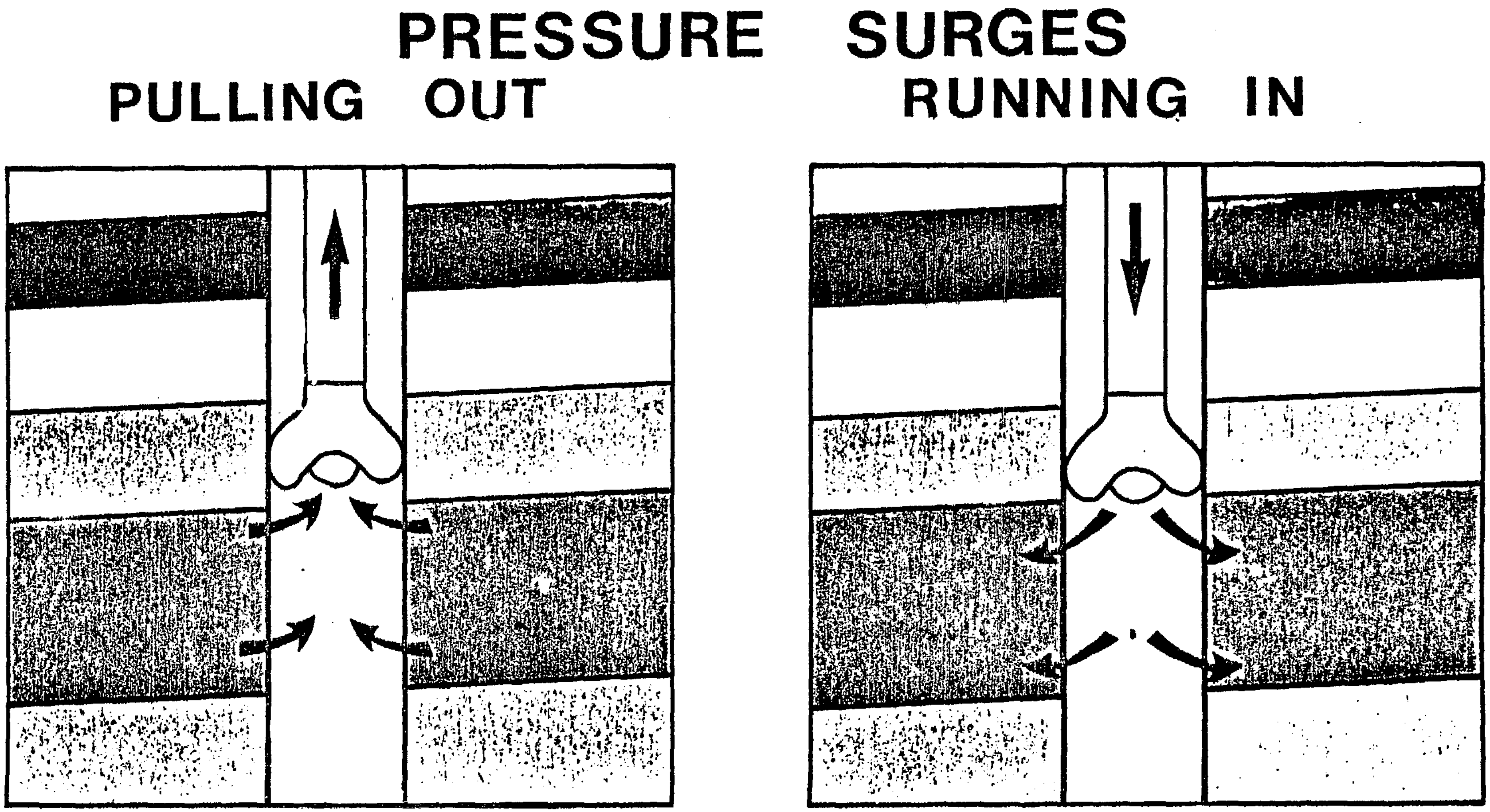


Fig. 5.

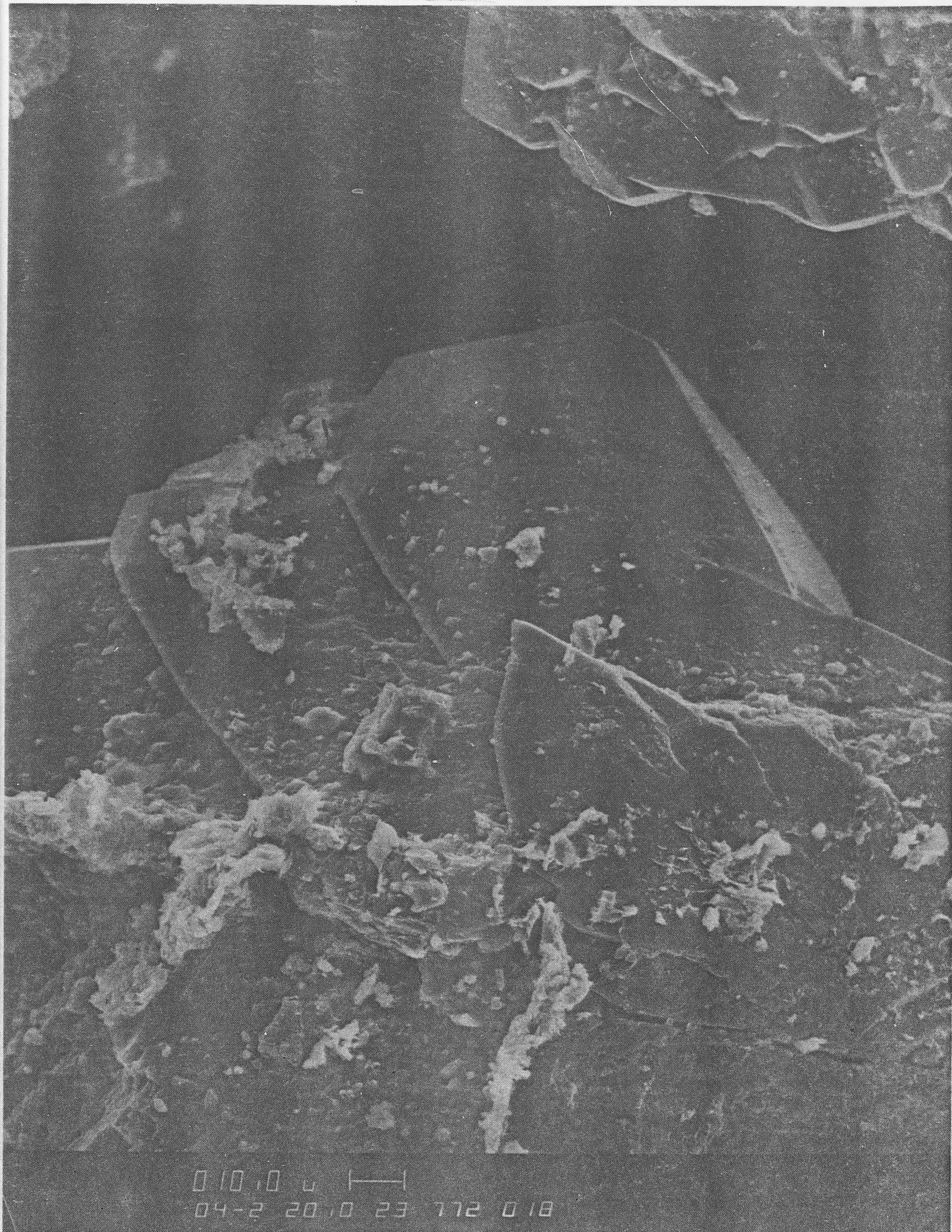


Fig. 8 Sample Q772

Fig. 8 Sample Q772 PLATE A

Enlargement of euhedral quartz overgrowths extending into pore space. Note the irregular clays at lower left.

PLATE B

Fig. 17 Sample Q897

Margin of a pore space with fine euhedral quartz (q), and some chlorite (c) and ?smectite (sm) extending into the pore.

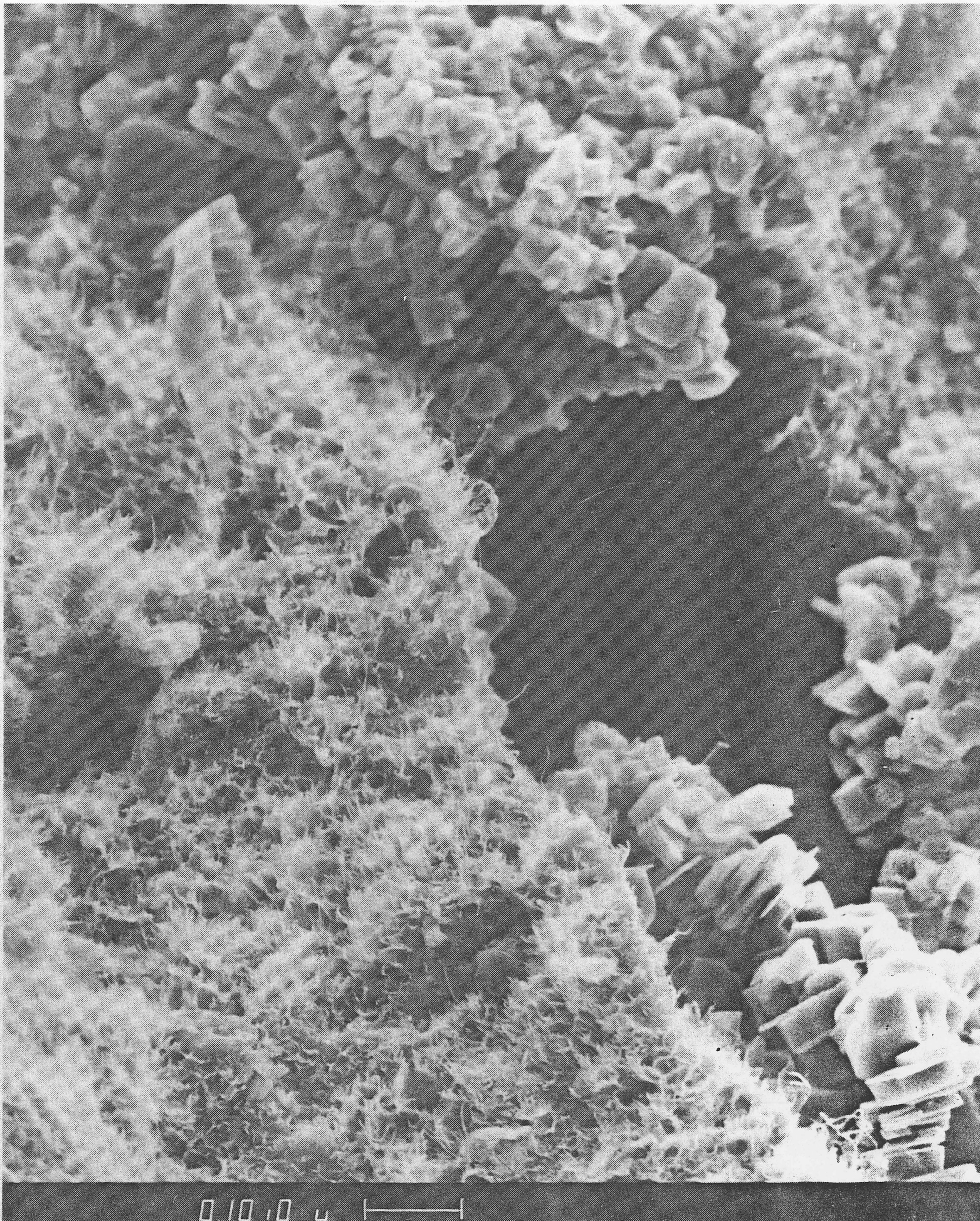


PLATE C

[redacted] CV57

This plate shows authigenic kaolinite and 'hairy' illite lining a pore space in this sandstone.

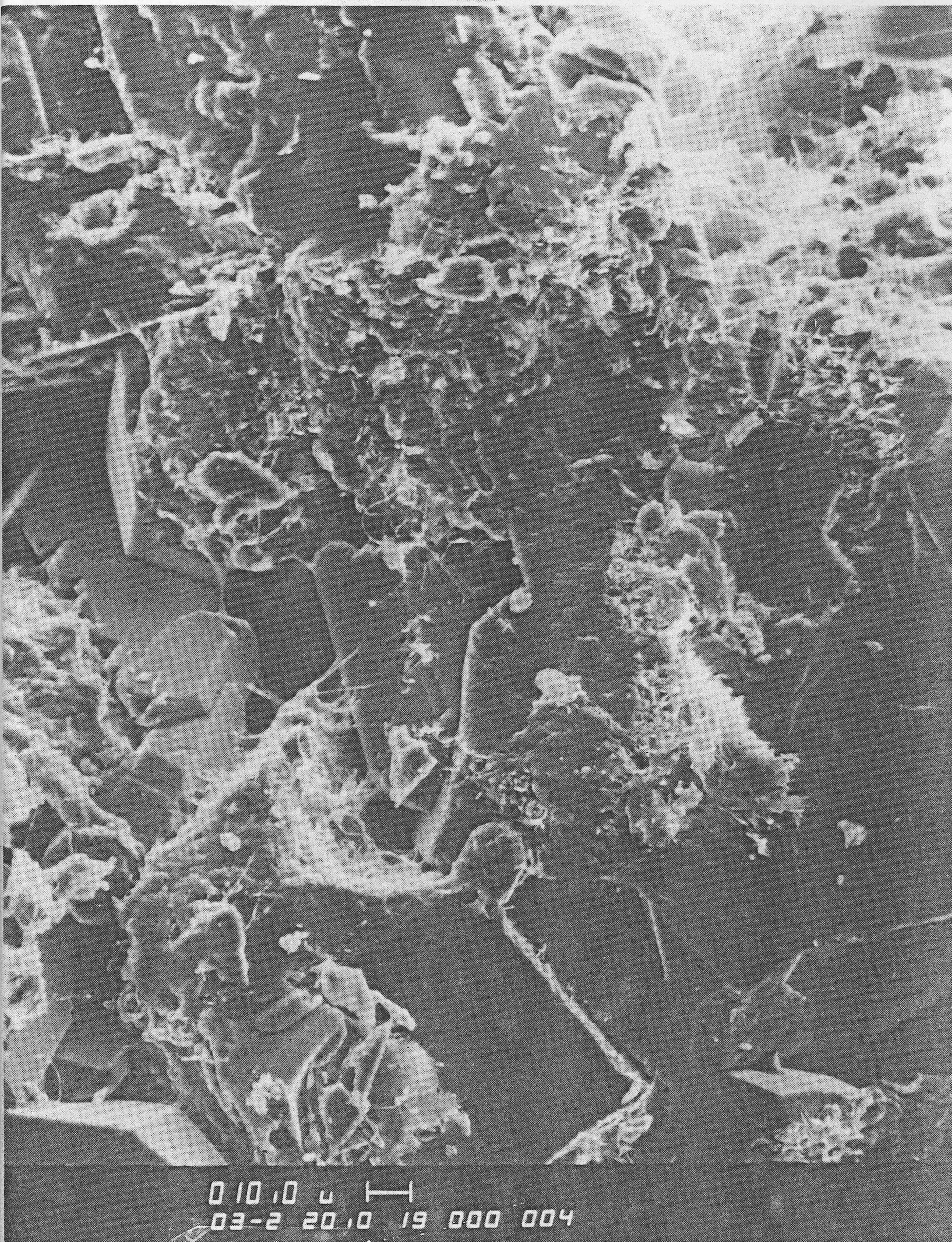


PLATE D

PLATE 3: EM7-G

Quartz crystals in this sandstone are not quite as intergrown as in sample EM7-F. The pore spaces in this sample are lined with authigenic illite.

PLATE E

Fig. 25 Sample Q1029

Enlarged view showing irregular intergrowths of authigenic quartz (q) and chlorite (c), with well formed kaolinite (k) adjacent. Scale is 1 μm.

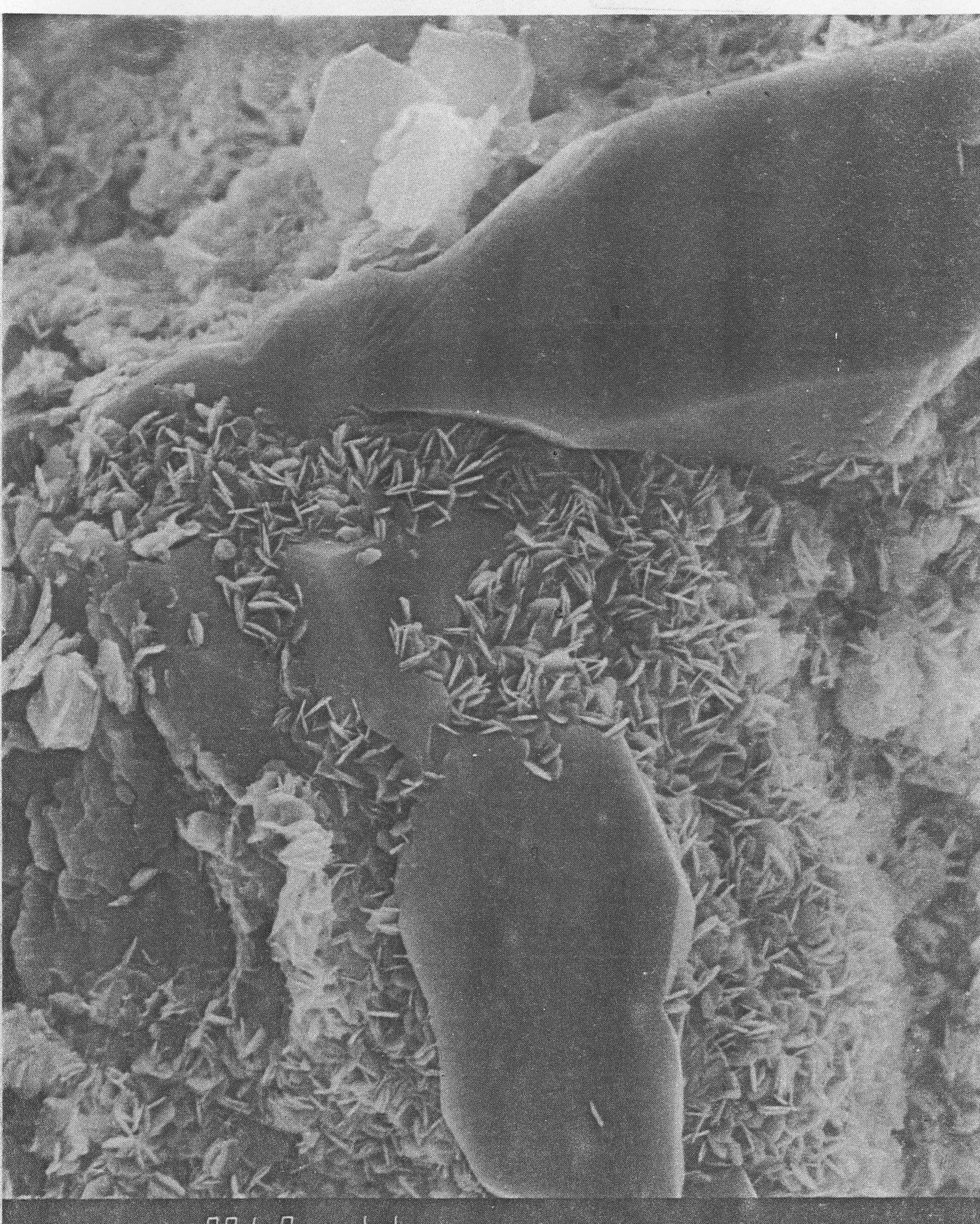


PLATE F

Fig. 19 Sample Q908

Enlarged view of surface of framework grain showing chlorite (c) and euhedral quartz (q) intergrowths.