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SEDIMENTOLOGY AND DIAGENESIS
OF THE MIDDLE JURASSIC SANDSTONE
IN WELL 6407/1-2, HALTENBANKEN AREA,
OFFSHORE NORWAY

Nicholas B. Harris
Tim K. Lowenstein

TSR No. 1610-780-103-1-83

Technical Service Report

GRADERINGEN GJELDER TIL ________

Conoco Norway Inc.
Stavanger,Norway

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September 1983

Structural and Stratigraphic Research Section
Exploration Research Division
Research and Development Department
Conoco Inc.

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Interoffice Communication

To Distribution

From Richard W. Lahann for Dale E. Miller

Date September 13, 1983

Subject **TECHNICAL SERVICE REPORT NO. 1610-780-103-1-83, "SEDIMENTOLOGY AND DIAGENESIS OF THE MIDDLE JURASSIC SANDSTONE IN WELL 6407/1-2, HALTENBANKEN AREA, OFF-SHORE NORWAY" BY NICHOLAS B. HARRIS AND TIM K. LOWENSTEIN**

This study was made in response to a request for technical assistance from Conoco Norway, Inc. Well 6407/1-2 penetrated a much thicker section of Middle Jurassic sandstone than had been previously encountered in the Haltenbanken area. It was also the first well (in this area) to contain liquid hydrocarbon. This study describes the sedimentology and diagenesis of the the sandstone and interprets the sedimentology in terms of depositional environments.

The authors interpret the sandstone as deposited in a high energy, shallow marine bar complex, but note that the assemblage of sedimentary structures are also compatible with deposition by a sandy braided river system. The core consists entirely of subarkosic to quartzarenite sand, mostly medium to coarse grained. Sedimentary structures are dominantly cross-beds and massive beds.

Porosity in the sandstone was reduced by a combination of quartz overgrowths and pore-filling kaolinite. Permeability has been reduced by authigenic illite and the above minerals. Permeability is greater in coarser grained facies; these facies contain less stylolitization and quartz overgrowth development.

The Middle Jurassic sandstone in the Statoil 6407/1-2 well (3,700 meters) contains more quartz overgrowths than does the same sandstone in two other shallower wells (2,900 meters). This observation suggests that substantial quartz overgrowth development has occurred between 2,900 and 3,700 meters.

Richard W. Lahann for Dale E. Miller, Director
Structural and Stratigraphic Research Section
Exploration Research Division

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John C. Elliott for JBC

Julian B. Coon, Manager
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AUTHORS: N. B. Harris and T. K. Lowenstein

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF PLATES

Conoco Inc.
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Technical Service Report

Number 1610-780-103-1-83

To J. R. Hultman, Conoco Norway, Stavanger

From Nicholas B. Harris and Tim K. Lowenstein, Exploration Research, Ponca City

Date September 14, 1983

Subject SEDIMENTOLOGY AND DIAGENESIS OF THE MIDDLE JURASSIC SANDSTONE IN WELL 6407/1-2, HALTENBANKEN AREA, OFFSHORE NORWAY

SUMMARY

Our study of the Middle Jurassic sandstone (Brent equivalent) cored in the 6407/1-2 well shows that it consists mostly of medium- to coarse-grained subarkosic to quartz arenite sandstone. Sedimentary structures are diagnostic of deposition in a shallow-water, high-energy environment. Such conditions are compatible with a shallow marine bar complex, an interpretation consistent with Eynon (1981) and Aasheim and Larsen (in press). However, based on the suite of sedimentary features observed in core, other depositional environments, particularly that of a sandy braided river complex, cannot be ruled out and should be considered as a possibility in future studies. We suggest that a shallow marine depositional system may be readily distinguished from a braid fluvial system on a seismic section and offer criteria for making this distinction.

The sandstone cored in 6407/1-2 is nearly identical in mineralogy, grain size, and sedimentary structures to Middle Jurassic sandstones cored in two other wells, which occur at the same stratigraphic position: at 2,950 meters in the Saga 6407/2-1 well and at 2,880 meters in the BP 6507/10-1 well. The Saga and BP wells penetrated a substantially thinner section. We suggest that all three units are correlative and that the variations in thickness are either due to variable syndepositional subsidence rates or to differential erosion.

Porosity has been substantially reduced by the formation of quartz overgrowths, which amount to 4 to 10 percent of the rock. They are more abundant in the upper, finer-grained section, where stylolites are more common. Porosity has been further reduced by formation of pore-filling kaolinite, which averages approximately 3 percent of the rock. Dissolution of feldspar, particularly orthoclase, has created additional porosity, averaging 2.8 percent of the rock volume. Calcite cement is generally absent from the sandstone. An exception is a narrow zone at the oil-water contact that contains approximately 8 percent calcite.

Permeabilities are reduced by pore-filling clays, particularly kaolinite and illite. Minor amounts of mixed-layer clays and chlorite are also present.

OBJECTIVES

This study was initiated at the request of Conoco Norway Inc., which had been asked by Statoil to provide technical assistance on Well 6407/1-2 (letter from S. M. Aasheim to John Hultmann, June 17, 1983). The 6407/1-2 well is of interest by virtue of being the first well drilled in the Haltenbanken area that contained liquid hydrocarbon. Also, Aasheim suggested (above reference) that the productive sand might be younger than sands reported from other wells in the Haltenbanken area. A sedimentological study was requested to identify the environment of deposition of the productive sand and to provide petrographic information on it.

CONCLUSIONS

The following conclusions have emerged from our study of the Middle Jurassic sandstone cored in Well 6407/1-2:

1. Deposition occurred in a shallow-water, high-energy environment, most likely, a shallow marine ridge or bar complex. We caution, however, that deposition in a sandy braided river system cannot be ruled out.

2. The sandstone is correlative with thinner Middle Jurassic sandstones cored in two nearby wells.

3. Detrital composition of the sandstone ranges from subarkose to quartz arenite. A mixed granitic and metamorphic source terrain is indicated.

4. Postdepositional alteration (diagenesis) consists of formation of quartz overgrowths and kaolinite (reducing porosity), formation of illite (reducing permeability), and dissolution of feldspar (enhancing porosity).

RECOMMENDATIONS

We recommend examination of core samples of the Middle Jurassic sandstone from other wells in the Haltenbanken area for fossils, burrows, and palynomorphs, in order to confirm our interpretation of a shallow marine depositional environment. Rocks from the Saga 6407/2-1 well are significantly less diagenetically altered, and samples may be more revealing for paleontological and palynological purposes than Well 6407/1-2 is.

We also suggest use of seismic stratigraphy as a means of choosing between a braided river and shallow marine environment. D. W. Huff (personal communication) offers the following suggestions:

To help distinguish braided river from near shore in seismic section, there are two approaches. First, examine the change in continuity and amplitude in the sequence of interest (i.e., seismic facies analysis), and second, analyze the lateral changes in seismic facies.

In a braided river environment, the seismic data should be very discontinuous with variable but generally low-to-moderate amplitudes. Lateral facies relationships may be alluvial fan updip and meandering river or coastal downdip. An alluvial fan should also exhibit discontinuous, variable-amplitude seismic data, but more high-amplitude reflections will be present. Alluvial fans have a rounded external shape and may show prograding. Meandering rivers will have an improvement in continuity relative to braided rivers, and amplitudes will be generally higher.

The nearshore environment will have a discontinuous, variable-amplitude seismic character, but the amplitudes will vary from moderate to high. Lateral seismic facies updip will show a decrease in continuity and lessening of high amplitudes. Downdip, the seismic facies will show improved continuity and more constant amplitudes (i.e., less varying amplitude).

INTRODUCTION: REGIONAL SETTING

The 6407/1-2 well is located on the western edge of the Trondelag Platform (Figure 1) at the margins of the Voring and More Basins (Aasheim and Larsen, in press). This is approximately 500 kilometers northeast of the Viking Graben, the northernmost of the three major intersecting grabens of the North Sea rift system. Numerous faults dissecting the platform show three distinct trends: north/south, northeast/southwest, and northwest/southeast. According to Aasheim and Larsen (their Figure 3a), the north/south- and northeast/southwest-trending faults were active as normal faults during the Jurassic and thus probably influenced deposition of the sandstone cored in 6407/1-2.

The mid-Jurassic (Bajocian-Bathonian) normal faulting on the Trondelag Platform is undoubtedly related to a major rifting event that immediately preceded the onset of sea floor spreading in the north Atlantic (Ziegler, 1981; Eynon, 1981). This pulse most dramatically affected the North Sea, where particularly intense subsidence occurred in the Viking Graben. A major domal uplift centered on the intersection of the Central, Viking, and Witch Ground Grabens shed sediments of the Brent Group into the Viking Graben. Tectonism on the Trondelag Platform appears to have been less intense and less focused than in the North Sea rift system. Aasheim and Larsen (in press; their Figure 3a) suggest that faults with more than 500 meters of displacement were uncommon on the Trondelag Platform.

A paleographic reconstruction during Bajocian-Bathonian times by Eynon (1981) suggests that shallow marine conditions prevailed along the Norwegian coast north of 63°N, including the Haltenbanken area. Within the North Sea grabens to the south, deltaic or continental sediments were deposited. Aasheim and Larsen (in press) likewise suggest that nearshore shallow marine conditions prevailed.

RESULTS: SANDSTONE MINERALOGY AND SEDIMENTOLOGY

Summary

The middle Jurassic sandstone penetrated in Well 6407/1-2 is 113 meters thick. A detailed lithologic log, together with porosity and permeability data for the core, is given in Plates 1a, 1b, and 1c. It is bounded above and below, perhaps unconformably, by shale. The cored interval comprises the upper 58 meters of the sandstone. It is medium- to coarse-grained and subarkosic to quartz arenite in composition, with sparse fine-grained sand and micaceous and conglomerate layers near the top. No siltstone or shale is present.

Sedimentary structures are dominantly massive sand beds or low-angle tangential (trough) cross-beds. Planar tabular cross-beds, ripple cross-lamination, horizontal lamination, vertical burrows, and scoured surfaces are also present. This assemblage of sedimentary structures is diagnostic of deposition in a shallow, high-energy environment with strong current activity. Such conditions are commonly attained in a shallow offshore marine bar complex. The lack of fossils and only sparse burrows make such a marine setting likely but not definite. Thus the possibility of a nonmarine braided river complex as a suitable environmental analogue cannot be entirely eliminated at this point.

Sedimentology

The sandstone cored in 6407/1-2 contains a similar assemblage of sedimentary structures throughout, suggesting that it was deposited under relatively uniform conditions. Several examples of sedimentary structures seen in core are given in Appendix A. Sands are generally medium- to coarse-grained, moderately sorted, and very clean (no silt or clay present anywhere). Micaceous laminae represent quiescent depositional conditions in an otherwise sand-dominated, high-energy environment. Structures are dominantly massive sand beds or low-angle tangential (trough) cross-beds. Other common structures include planar cross-bedding, steep tangential cross-bedding, planar lamination, ripple cross-lamination, burrows, and erosional surfaces. Some burrows resemble those of Ophiomorpha, a marine burrow, but we do not consider this identification as definitive. Small amounts of reworked coal and terrestrial palynomorphs are found (data from Statoil).

Two general associations characterize the cored interval. Facies A consists of massive or tangentially cross-bedded medium- to coarse-grained sandstone (Plate 1). Horizontal layering occurs locally; ripple cross-lamination and burrows are rarely seen. Grain size within this association shows little bed-to-bed variation. Distinct fining or coarsening-upward sequences are generally absent in this facies. Facies A characterizes most of the core below 3,680 meters. One zone, from 3,684.0 to 3,686.5 meters, is clearly different and falls into Facies B (below).

Facies B, characterizing the core from 3,661 to 3,680 meters, consists of fine- to coarse-grained sandstone with some conglomerate beds. Massive sandstones are uncommon. Dominant sedimentary structures include low-angle tangential cross-bedding, horizontal lamination, climbing ripple cross-lamination, planar tabular cross-bedding, and burrows. Reactivation surfaces are common within cross-bedded intervals. Scoured bases occur at the base of a few conglomerate or coarse sand layers; other conglomerate beds have gradational, nonerosive bases. Micaceous partings are common, and micaceous laminae greater than 2 to 3 millimeters are present.

Grain size variations define distinct beds in Facies B, unlike Facies A. Coarse-grained sandy to conglomeratic beds are most numerous at about 3,670 meters. Above this depth are several 0.5- to 1.0-meter-thick, coarsening-upward cycles; below this depth are several fining-upward cycles of similar thickness.

Both Facies A and B were deposited in shallow water under the influence of currents. Facies B represents more variable flow conditions than does Facies A.

The highest permeabilities measured in the cored interval occur in Facies A (Plate 1). This is largely a grain size effect, since Facies A tends to be coarser-grained than Facies B.

Environment of Deposition

The 6407/1-2 cored interval contains a thick sequence of current-deposited sandstones. Eynon (1981) has projected stratigraphically equivalent Middle Jurassic sandstones along the Norwegian Coast as marine. Aasheim and Larsen (in press) studied the 6407/1-2 cored interval, interpreted the sequence as marine, and suggested "a regressive fan delta building out into fairly shallow waters, with decreasing wave influence and increasing fluvial processes towards the top."

We generally concur with these interpretations and infer a shallow marine sand ridge or bar complex composed of large-scale bedforms developed under the influence of strong current activity. Analogous modern shallow marine systems described by Reineck and Singh (1980), contain sedimentary structures dominated by cross-bedded sand with subordinate small-scale ripple cross-lamination and parallel lamination. The patchy burrow structures seen in the 6407/1-2 core, tentatively identified as Ophiomorpha, add weight to this interpretation.

We add a word of caution: the association of sedimentary structures seen in the 6407/1-2 core, together with the lack of fossils and sparse burrows, makes it impossible to rule out a nonmarine "fluvial influence," as suggested by Aasheim and Larsen (in press), or even an entirely nonmarine origin. Deposition in modern sandy braided rivers, for instance, is by sand bar migration; cross sections through such sediments are dominated by trough and planar tabular cross-beds (Cant and Walker, 1976 and 1978; Miall, 1977). Ripple cross-laminated and parallel-laminated sands and mud drapes are superimposed on larger-scale bedforms under waning flood conditions or during the final stages of channel filling. Burrows have been documented in such an environment (Stanley and Fagerstrom, 1974).

Mineralogy

The sandstone is very quartz-rich with minor amounts of feldspar (plagioclase, orthoclase, and microcline), mica, and sparse rock fragments (Figure 2 and Table 1). Samples below 3,696.0 meters are quartz arenites or subarkoses; samples from above 3,696.0 meters are subarkoses (terminology from McBride, 1963).

Rock fragments are mostly of metamorphic origin, either quartzite (see Appendix B, Figure B5) or quartz-muscovite schist. Granitic and volcanic rock fragments are present in small amounts. Heavy mineral grains include garnet (dominant), apatite, zircon, rutile, tourmaline, and monazite. The tourmaline is bright pink and very obvious in core and cuttings.

Both strained single crystals and polygonized quartz grains were noted occasionally (less than 5 percent). This, combined with the observations on rock fragments and heavy minerals, indicates a mixed granitic and metamorphic source terrain.

RESULTS: SANDSTONE DIAGENESIS

Summary

Sandstone porosity has been reduced by a combination of grain compaction and formation of authigenic minerals, particularly quartz overgrowths. A small amount of porosity has been created by framework grain dissolution. Permeability is reduced by the formation of authigenic clays, especially kaolinite and illite.

Mineralogy and Paragenesis

The sequence of diagenetic events is summarized in Figure 3. Several examples of diagenetic minerals and paragenetic relations are shown in Appendix B. Mica, rock fragments, and clay clasts present have undergone grain compaction (Figure 4 and Figure B6, Appendix B). This has contributed little to porosity loss because of the quartz-rich nature of the sandstone.

The formation of feldspar overgrowths is an early diagenetic phenomenon, preceding formation of quartz overgrowths. Such authigenic feldspar is volumetrically insignificant, amounting to much less than 1 percent of the rock volume (Table 1). Authigenic feldspar rims are commonly dissolved, leaving a skeletal clay residue and, remarkably, sometimes a pristine core.

Quartz overgrowths comprise an average of 5.6 percent of the rock volume (Figure 4 and Table 1), ranging from about 4 percent in the coarser-grained lower sands up to 10 percent in the finer-grained upper sands. Formation of quartz overgrowths spanned a significant part of the paragenetic sequence (Figure 3). They began to form after mechanical compaction of deformable detrital grains, kaolinization of mica, and formation of feldspar overgrowth rims and continued to grow after the beginning of authigenic clay formation.

The dissolution of feldspar has increased porosity an average of 2.8 percent of the rock volume. This figure represents 35 percent of the original feldspar content of the rock. K-feldspar appears to be more vulnerable to dissolution than plagioclase (Figure 5), and orthoclase is preferentially leached over microcline. Dissolution of feldspar apparently took place over a significant time span. In general, dissolved feldspars are not filled by clays (Figures 4 and 5), indicating dissolution followed formation of clays. Contrary examples exist, however, where kaolinite, illite, and minor amounts of chlorite partially fill voids once occupied by feldspar grains.

Authigenic clays consist of kaolinite, illite, chlorite, and smectite (Table 2). Kaolinite is ubiquitous and most abundant. One variety consists of randomly oriented books that may completely fill pore spaces (Figures 4 and 6). A second variety occurs as an alteration product of muscovite and biotite. This variety forms dense masses up to 0.3 millimeters long that pack tightly against pore walls (Figure B14, Appendix B). The kaolinite content averages 3.2 percent and does not vary systematically in the cored interval.

Illite occurs in small amounts (average 0.9 percent) in most of the cored interval (Figure 7 and Figures B16 and B17 in Appendix B). It appears to have formed both during and after formation of kaolinite. It has a fibrous form and has grown on top of detrital grains, quartz overgrowths, and kaolinite crystals. Where abundant, fibers may completely bridge pores.

Chlorite and mixed-layer clay were noted in variable but minor proportions in X-ray analysis of clay separates. Chlorite-like crystals were observed in SEM examination intergrown with illite. Mixed-layer clays occur as pore-bridging crystals. These are composed of 35 percent expandable clays (R. W. Lahann, personal communication).

One narrow interval is heavily cemented by calcite (3,707.6 to 3,708.1 meters) (Figure 8). Porosity drops to approximately 7 percent, and permeabilities are correspondingly decreased. The calcite-cemented zone occurs at the oil-water contact, suggesting that carbonate is derived from decarboxylation of oil. A carbon isotope analysis of the calcite ($\delta^{13}C_{PDB}$ = -12.2 ± 0.03 °/oo; $\delta^{18}O_{SMOW}$ = +12.9 ± 0.09 °/oo) indicates that the carbonate is organic in origin. Calcite precipitated late in the paragenetic sequence, postdating quartz overgrowths and incorporating earlier-formed kaolinite. The calcite has since been partially dissolved ("decemented"), leaving in places ragged, embayed crystals and isolated islands of optically continuous crystals.

Stylolites are common in fine-grained lithologies of the upper portion of the cored interval. They appear generally to have formed as an overprint on primary sedimentary micaceous laminae. They consist of concentrations of mica, pyrite, and coally matter in various proportions. Quartz grains show extreme amounts of solution within or contiguous to the stylolite seam (Figure 9). Little evidence of intense dissolution of detrital quartz grains is found elsewhere away from stylolites. The larger number of stylolites, together with the greater volume of quartz overgrowths in Facies A, suggests that silica dissolved along stylolites was locally redistributed as nearby quartz overgrowths.

As indicated earlier, higher permeabilities are found in Facies A. This corresponds to rocks of coarser grain size; it also corresponds to rocks with fewer stylolites and fewer quartz overgrowths.

Potential Production Problems

The abundance of pore-filling kaolinite presents a potential production problem because of migration of fines. No other clays appear to be present in sufficient quantity to cause problems.

DISCUSSION: COMPARISON TO OTHER WELLS

Core from two other wells in the Haltenbanken area was examined briefly at the GECO facility. These are the Saga 6407/2-1 and the BP 6507/10-1 wells (locations in Figure 1). Both wells penetrate a clean sand in the same stratigraphic position as that in the Statoil 6407/1-2 well. In the Saga well, it is 43 meters thick; in the BP well, it is 14 meters thick. Despite the thickness variation between the three wells, the sandstone is similar in composition and sedimentary structures. It is almost certainly correlative. The difference in thickness is perhaps due in part to differential erosion.

The upper section of core from the Saga well contains coarse-grained, quartz-rich sandstone. Trace amounts of pink tourmaline are present. Bedding is indistinct, but some cross-bedding and burrows are apparent. The rock is indistinguishable from Facies A in the 6407/1-2 well. The lower section is fine- to medium-grained sandstone with ripple cross-lamination and planar tabular cross-bedding with numerous reactivation surfaces. It is locally bioturbated. very quartz-rich, and contains some coally and micaceous laminae. It is similar, but not identical, to Facies B in the 6407/1-2 well.

Core from the BP well contains medium-to-very-coarse, quartz-rich sandstone. Minor feldspar and sparse metamorphic rock fragments and mica are present. Trace amounts of pink tourmaline are present. Bedding is generally indistinct, but cross-beds are apparent. This unit, too, is indistinguishable from Facies A in the 6407/1-2 well.

The sandstones cored in these wells contain substantially fewer quartz overgrowths than in the 6407/1-2 well (at a depth 850 meters shallower). If one compares the Facies A units from each well, the BP well has more quartz overgrowths than the Saga well; this results in poorer porosities and permeabilities.

METHODS

Core was described at a scale of 1:10 at the GECO facility in Forus. Noted in the core description were lithology, sedimentary structures, grain size, detrital and diagenetic mineralogy, and stylolites. Core samples were routinely examined with a binocular microscope. Hydrochloric acid was used to test the sandstone for the presence of calcite.

We studied thin sections using standard optical microscopy techniques. Twenty-seven thin sections were point-counted using an average of 600 points per section.

The clay fractions (<5 microns) of 17 samples were analyzed by X-ray diffraction. Nine of these samples with expandable clays were then glycolated to determine the fraction of expandable clays.

Eleven samples were studied with a scanning electron microscope to elucidate clay mineralogy and the relative timing of diagenetic features.

The calcite cement of one sample was analyzed for its carbon and oxygen isotopic composition.

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TABLE 1

COMPOSITION OF SANDSTONES FROM STATOIL WELL 6407/1-2, DETERMINED BY OPTICAL POINT COUNT OF PETROGRAPHIC THIN SECTIONS

	Average (Percent)	Minimum (Percent)	Maximum (Percent)
Quartz	67.1	55.6	76.4
K-feldspar	3.5	2.1	4.9
Plagioclase	1.6	0.5	3.1
Muscovite	0.7	0.0	3.4
Biotite	0.2	0.0	1.4
Chert	0.1	0.0	0.5
Metamorphic rock fragments	0.04	0.0	0.2
Unidentified rock fragments	0.2	0.0	1.0
Garnet	0.1	0.0	0.7
Opaques	0.4	0.0	0.8
Quartz overgrowths	5.6	2.8	10.0
Kaolinite	3.2	1.3	5.6
Authigenic clay	0.9	0.0	1.8
Feldspar overgrowths	0.03	0.0	0.3
Intergranular porosity	13.1	9.1	16.9
Dissolution porosity	2.8	0.8	4.9

TABLE 2

RELATIVE ABUNDANCE OF CLAYS (<5 MICRONS) IN SAMPLES FROM STATOIL WELL 6407/1-2, DETERMINATION BY X-RAY DIFFRACTION ANALYSIS

Sample Number	Depth (Meters)	Mineralogy*
1	3,661.15	KAOL, illite, (chlorite)
7	3,663.40	KAOL, illite, (chlorite)
19	3,667.40	KAOL, (chlorite), (illite)
24	3,669.10	KAOL, (illite), (chlorite)
25	3,669.60	KAOL, illite, (chlorite), (mixed-layer clay)
37	3,673.40	KAOL, (illite)
45	3,676.40	KAOL, illite, (chlorite), (mixed-layer clay)
46	3,676.70	KAOL, (illite), (smectite), (chlorite)
67	3,684.80	KAOL, (chlorite), (illite), (mixed-layer clay)
76	3,688.05	KAOL, (illite), (chlorite)
91	3,693.00	KAOL, chlorite, illite, (mixed-layer clay)
97	3,695.00	KAOL, (illite), (chlorite)
103	3,697.00	KAOL, illite (chlorite), (mixed-layer clay)
109	3,699.00	KAOL, (illite), (chlorite)
128	3,706.30	KAOL, (illite)
148	3,713.10	KAOL, (illite)
160	3,717.35	KAOL, (illite)

*Minerals in capital letters are major phases, in lower-case letters are minor phases, and in parentheses are trace phases.

Note--Discrete smectite was found in several other samples, but except where noted above, it was 100 percent expandable and thus was like introduced from drilling mud.

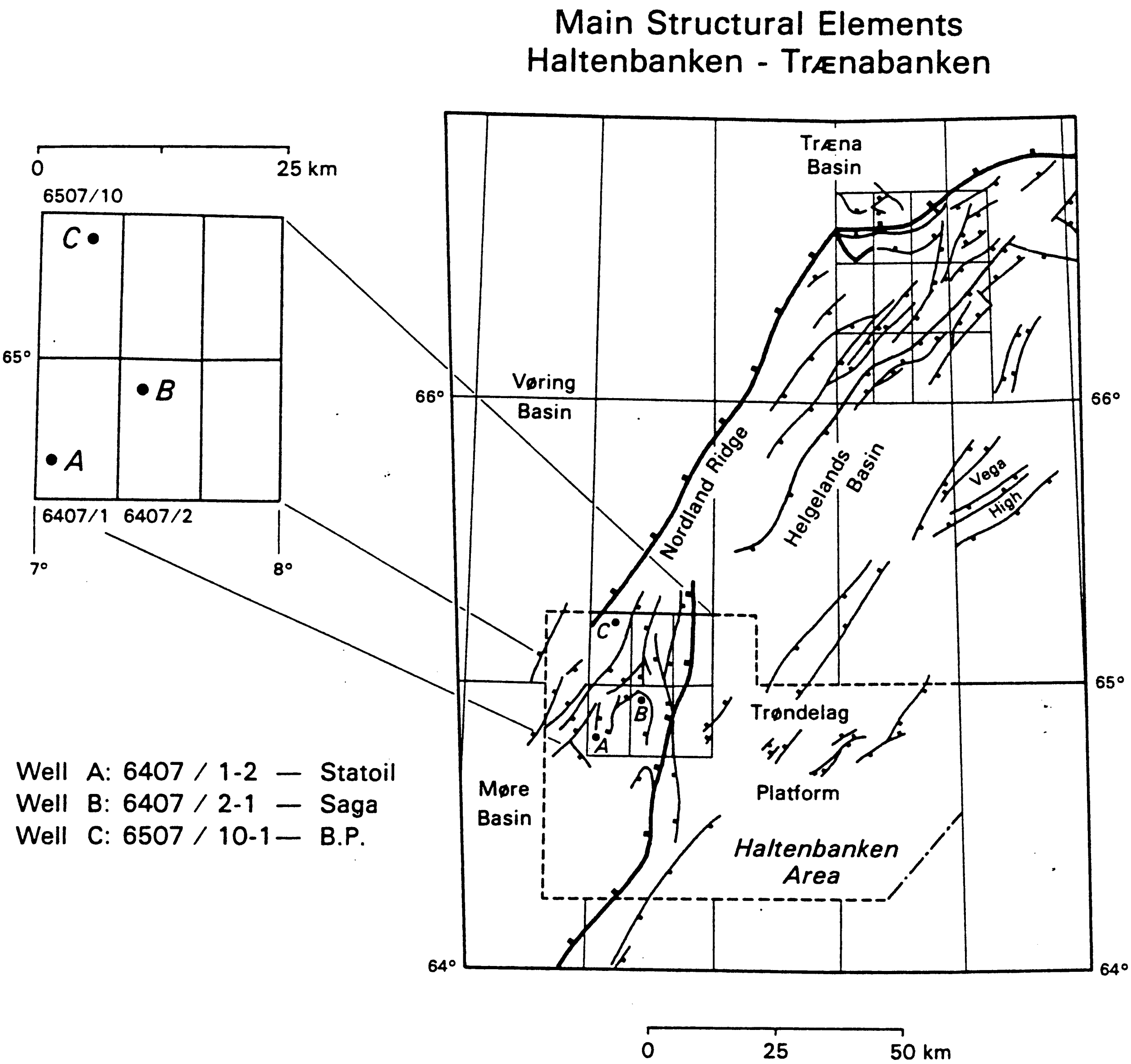


Figure 1. Major structures in the Haltenbanken area, offshore Norway, showing location of wells discussed in this report. Downthrown side of faults is indicated by tick marks. Displacement rarely exceeds 500 meters. Modified after Aesheim and Larsen (in press).

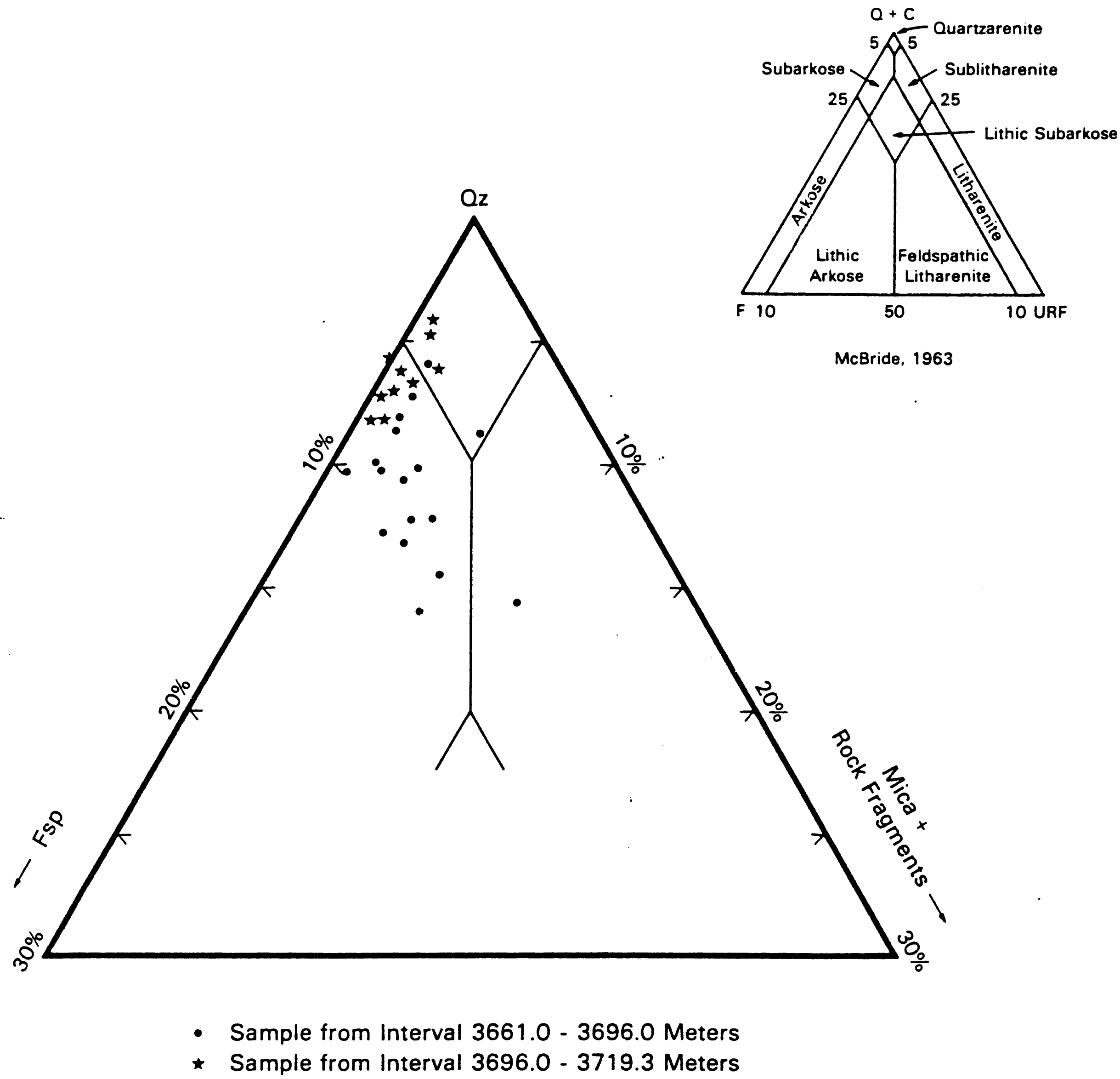


Figure 2. Composition of sandstone from the 6407/1-2 well determined by petrographic point counting. Data plotted represent an average of 600 points per sample.

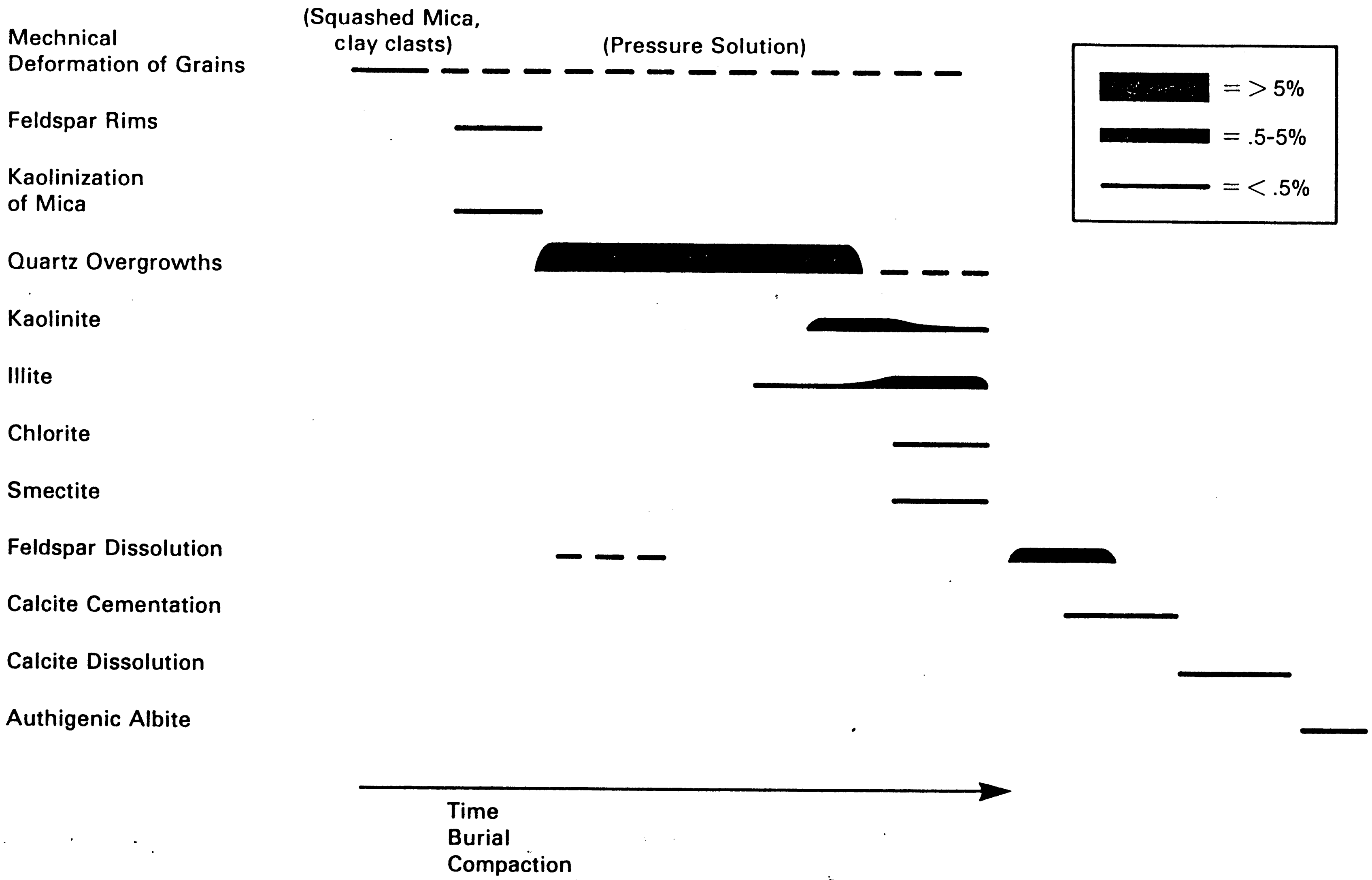


Figure 3. Sequence of diagenetic events. Volume contribution to porosity is indicated by the height of the bar.

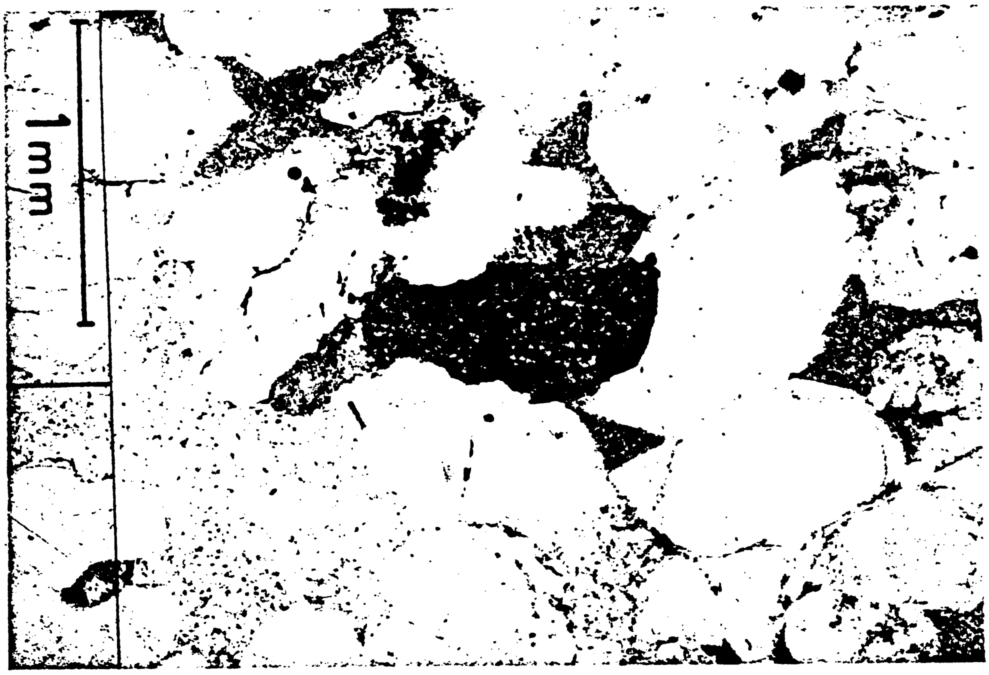


Figure 4. Photomicrograph of sample from 3717.35 meters. Quartz overgrowths are abundant. Squashed grain in center is volcanic rock fragment. Note abundant kaolinite filling pores. Dissolved feldspars (2) just above rock fragment and right center.

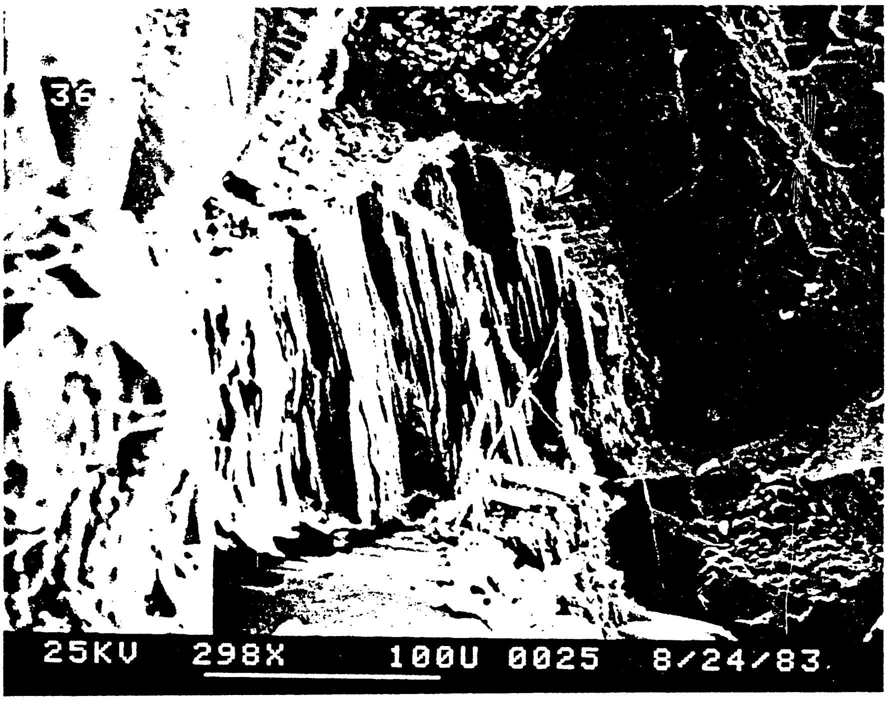


Figure 5. SEM photograph of dissolved K-feldspar grain from 3673.4 meters. Quartz overgrowths on right and illite at bottom.

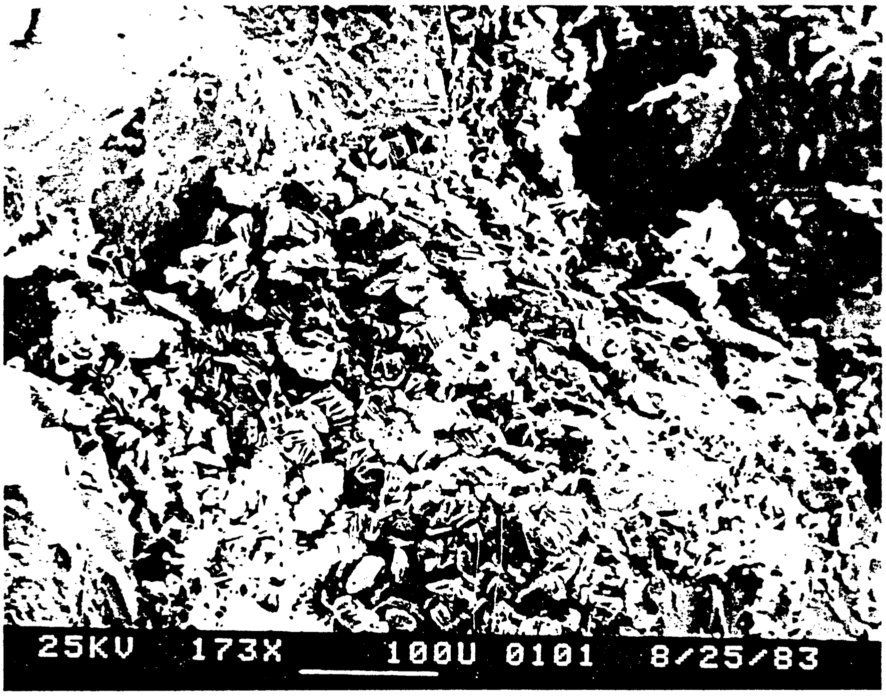


Figure 6. Pore-plugging kaolinite from 3717.35 meters.

Figure 7. Pore-bridging illite. Note that illite interferes with partially formed quartz overgrowth, indicating illite formed during formation of quartz overgrowths. From 3661.15.

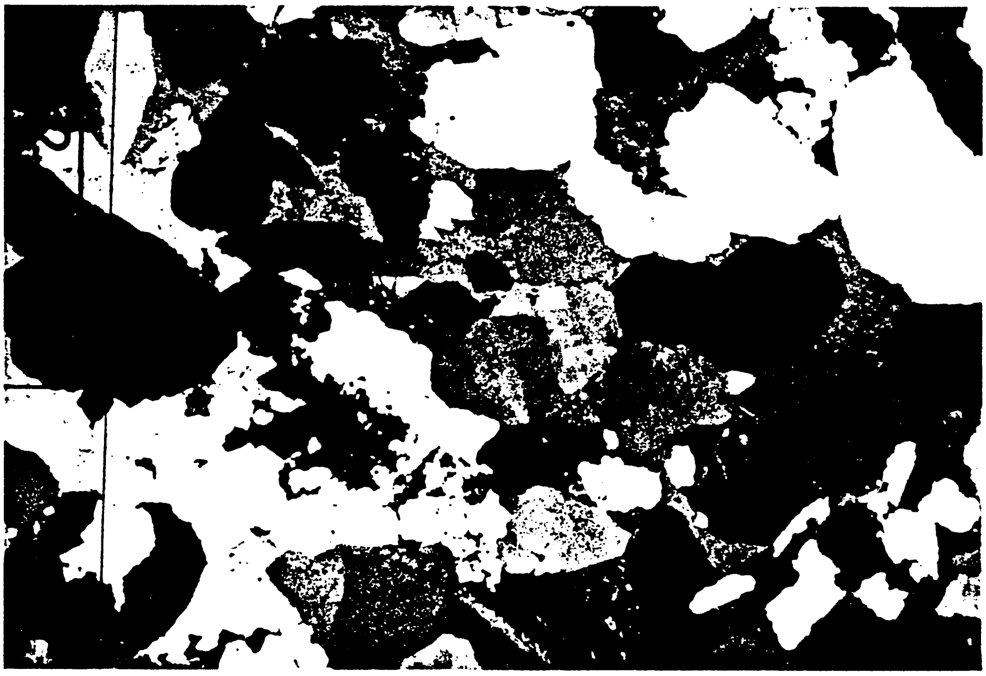


Figure 8. Poikilotopic calcite cementing sandstone, from 3708.00 meters. Note dissolution of calcite just below and left of center. Quartz overgrowths are numerous and predate calcite, as indicated by straight grain edges.

Figure 9. Stylolite, from 3677.75 meters. Note the extreme interpenetration of quart grains, indicative of dissolution. Fine-grained material includes mica and pyrite.

APPENDIX A

EXAMPLES OF SEDIMENTARY STRUCTURES, WELL 6407/1-2

This section presents examples of several types of sedimentary structures described in the text and in Plate 1 (lithologic log). These examples are arranged by depth (shallowest to deepest).

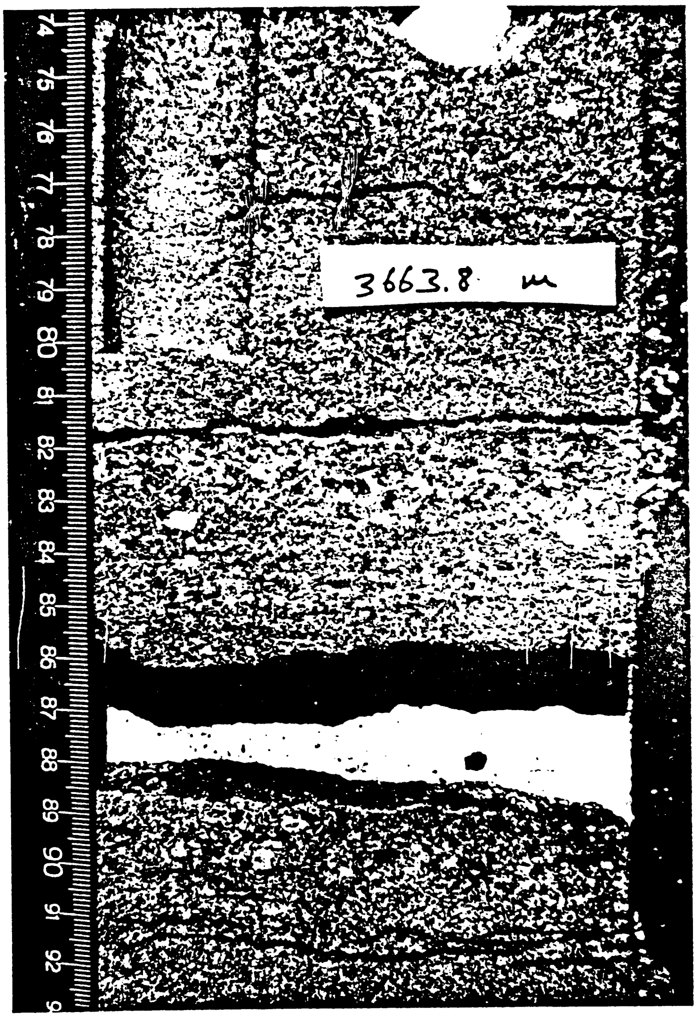


Figure A1. Gravel layers in medium grained horizontally bedded sequence. Stylolites at 3663.77 and 3663.91 meters. Scale on the left in this and following photographs is in centimeters. Number on core is depth in meters.

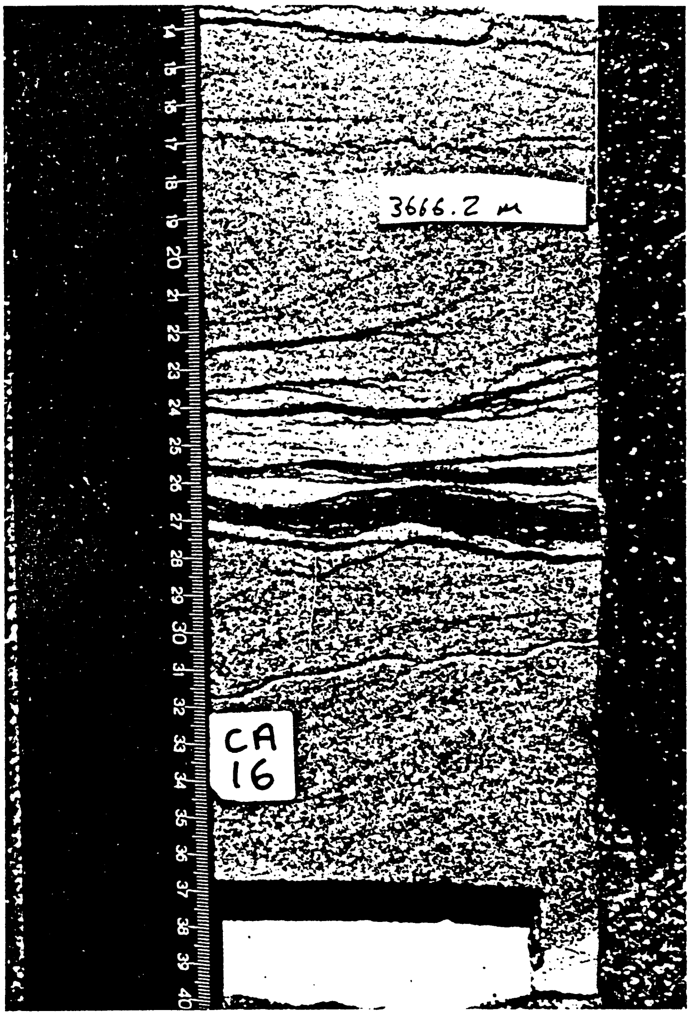


Figure A2. Medium grained, low angle tangentially cross-bedded sand with micaceous laminae 3666.22 to 3666.29 meters. Climbing ripple cross-lamination at 3666.20-3666.24 meters.

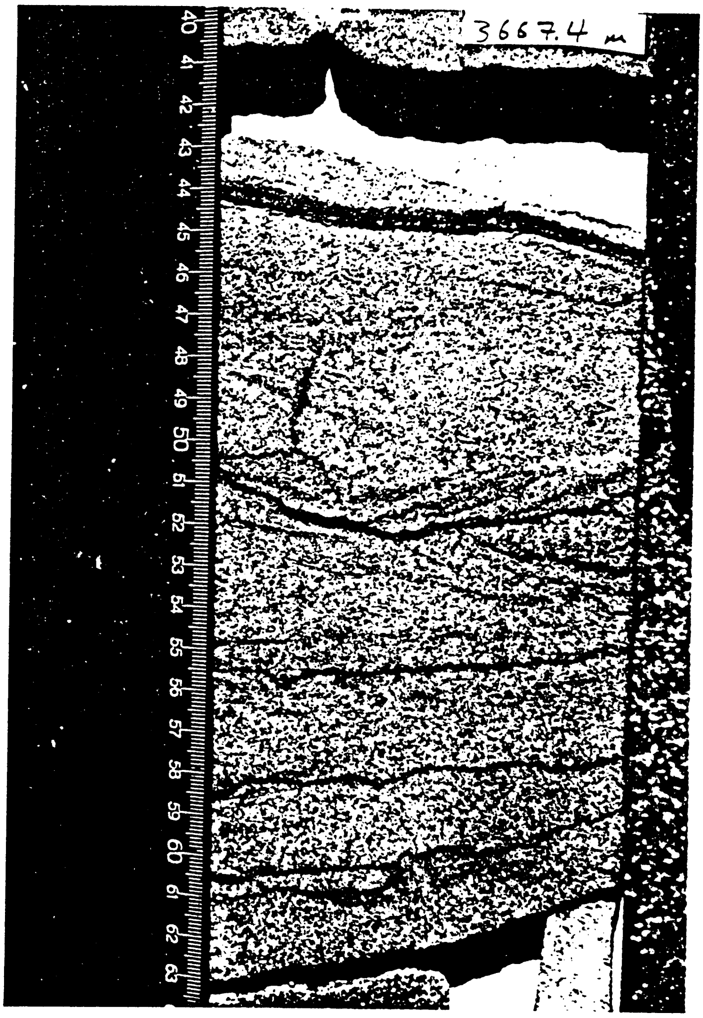


Figure A3. Five sets of low angle tangential cross-beds. Present thickness ranges from 1 to 7 cm. Micaceous lamina at 3667.44. Note several stylolites. Sand is medium grained.

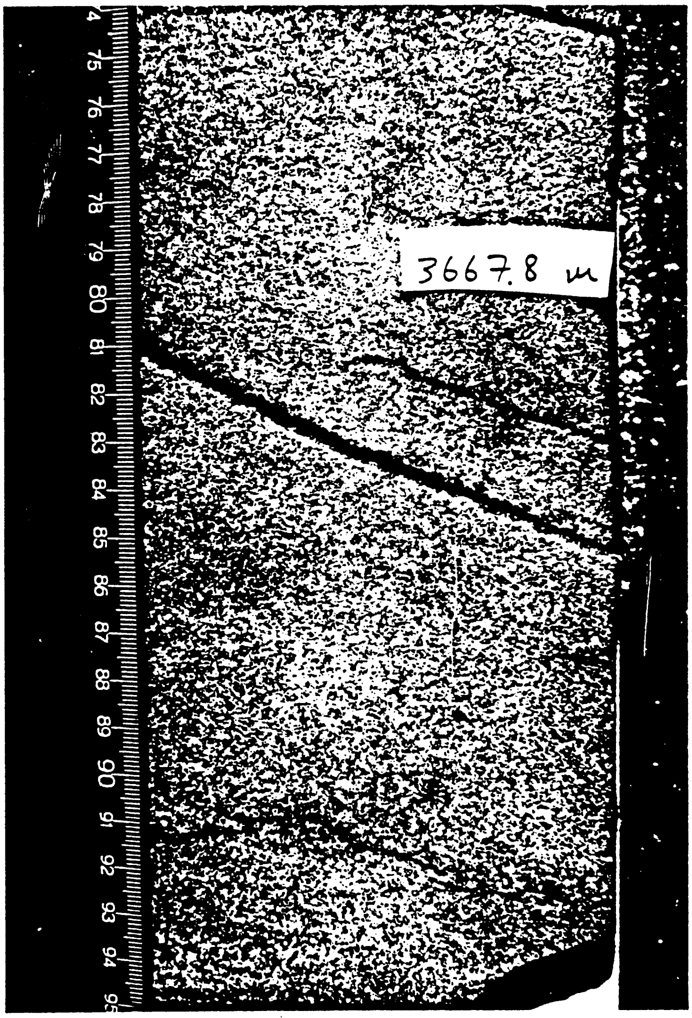


Figure A4. Steeply inclined tangential cross-beds in medium grained sandstone. Present thickness is 25 cm, eroded top (not shown).

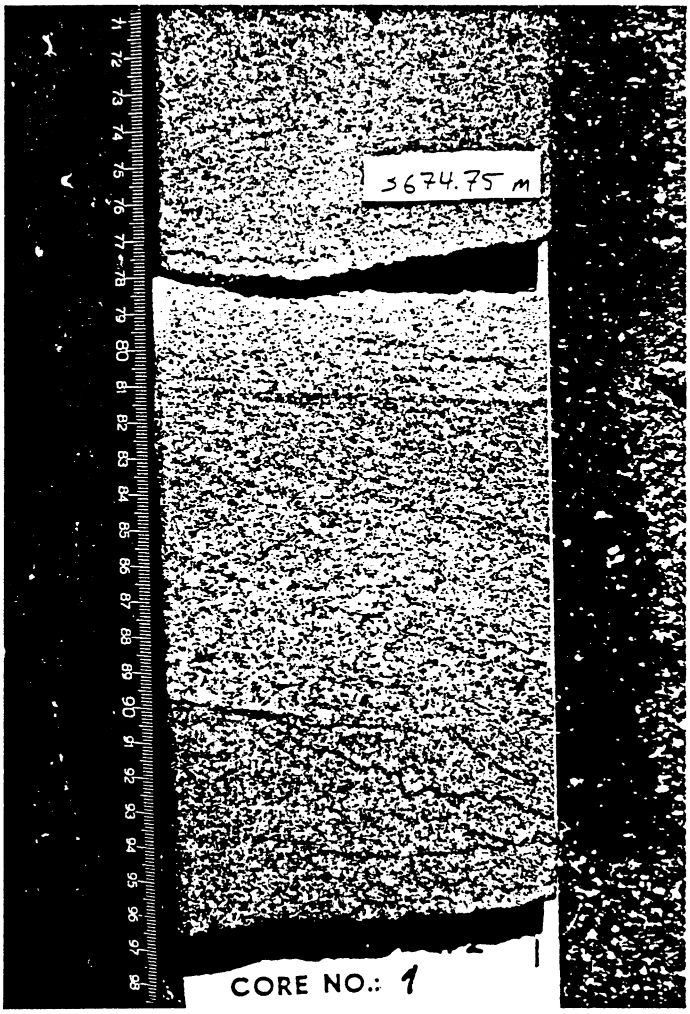


Figure A5. Planar tabular cross-bedding in medium grained sandstone. Note alternating coarse and finer grained layers from 3674.85 to 3674.90 meters. Reactivation surfaces at 3674.81 and 3674.90 meters. Truncated burrow on the lower surface. Coally material at 3674.89 meters.

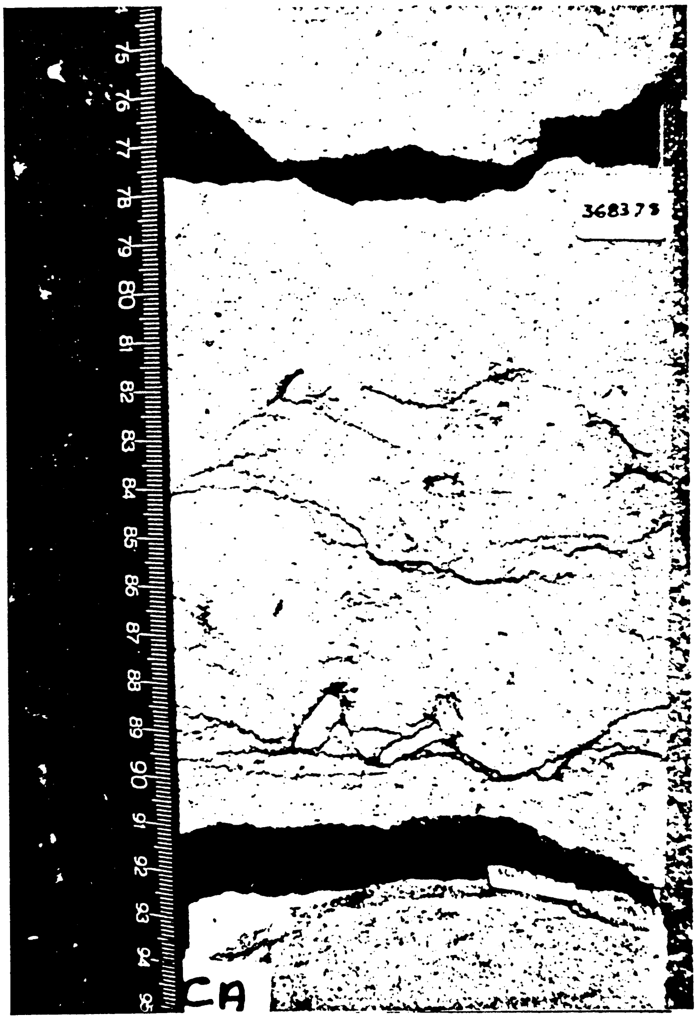


Figure A6. Burrows, modified by stylolitization. Much of the dark material is coally detritus. Sandstone is fine to medium grained.

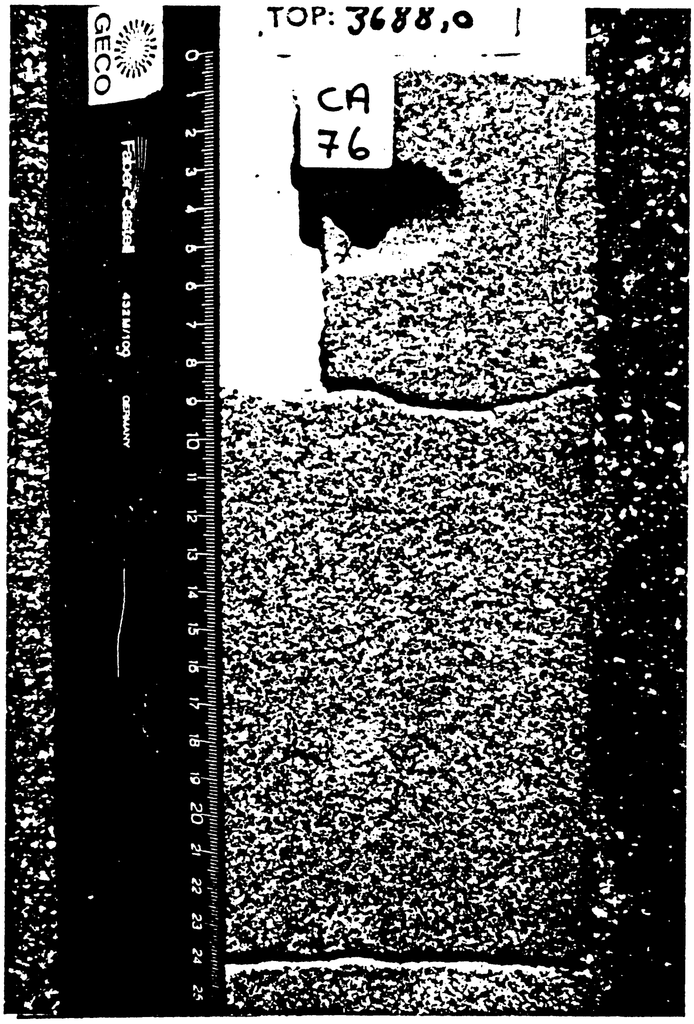


Figure A7. Massive, medium to coarse grained sandstone. Depth is 3688.0 meters.

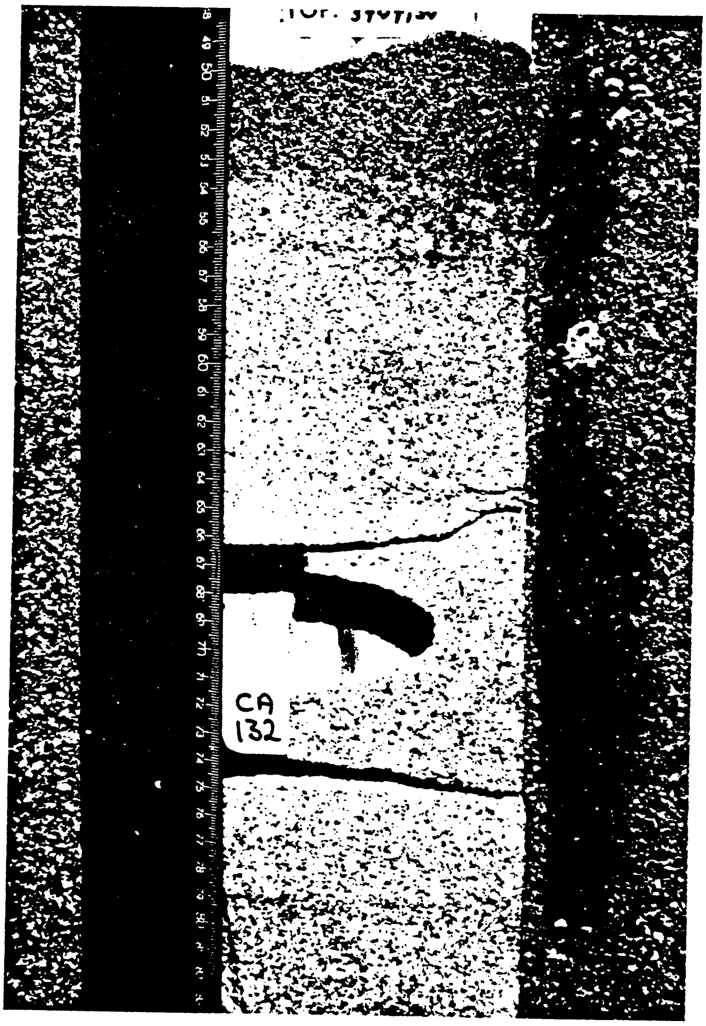


Figure A8. Coarse to very coarse grained sandstone, locally showing faint horizontal bedding. The sandstone is calcite cemented from 3707.56 meters to bottom of photograph.

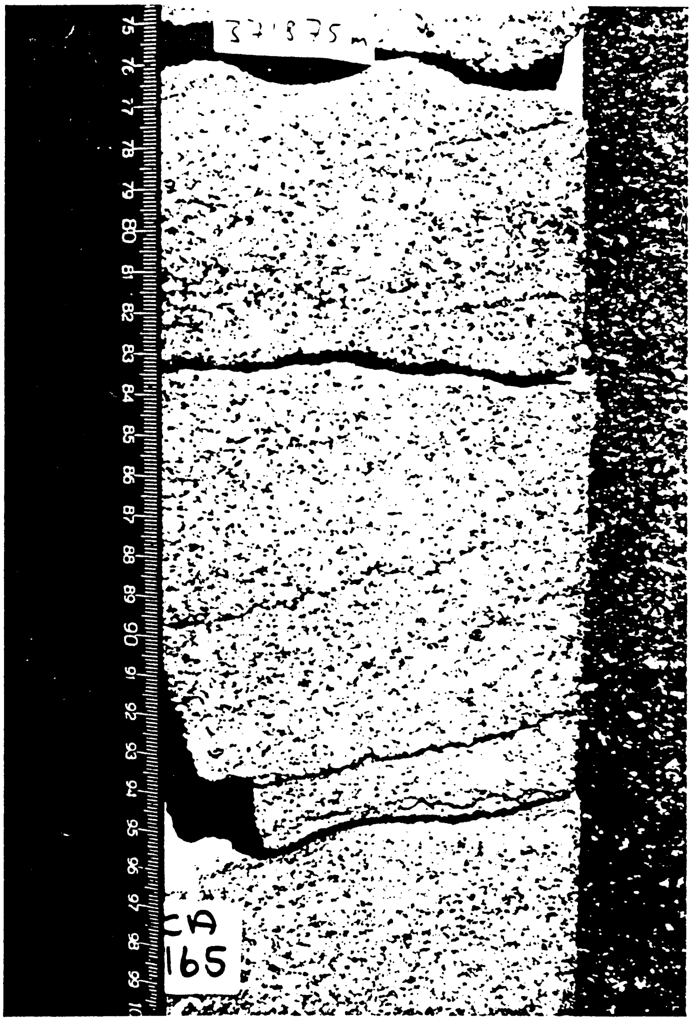


Figure A9. Coarse grained sandstone, with low angle tangential cross-bedding. The lightest layers contain no feldspar; elsewhere a small amount of feldspar is present.

TSR No. 1610-780-103-1-83

APPENDIX B

EXAMPLES OF SANDSTONE MINERALOGY AND DIAGENESIS, WELL 6407/1-2

This section presents examples of sandstone mineralogy and diagenesis, illustrated by photomicrographs and scanning electron microscope photographs. Figures B1 to B4 illustrate variations in gram size and its effect on pore throats. Figures B5 to B7 illustrate detrital components of the sandstone. Figures B8 to B20 illustrate diagenetic features, following the order in which they are presented in the text.

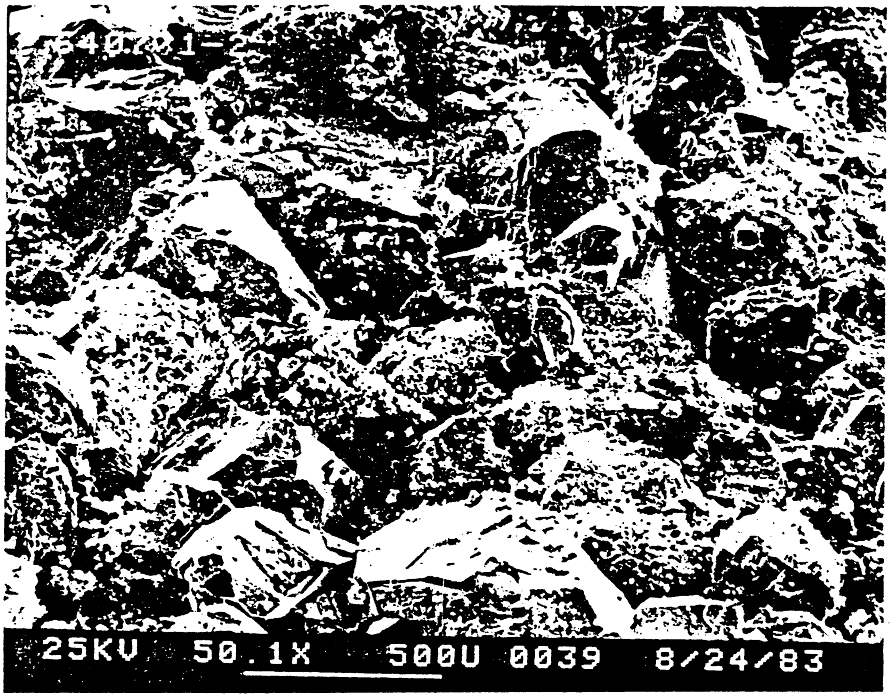


Figure B1. Overview. Note development of euhedral quartz overgrowths and authigenic clay. Pore throats are relatively small. Permeability of this sample is 265 millidarcies. From 3667.4 meters.

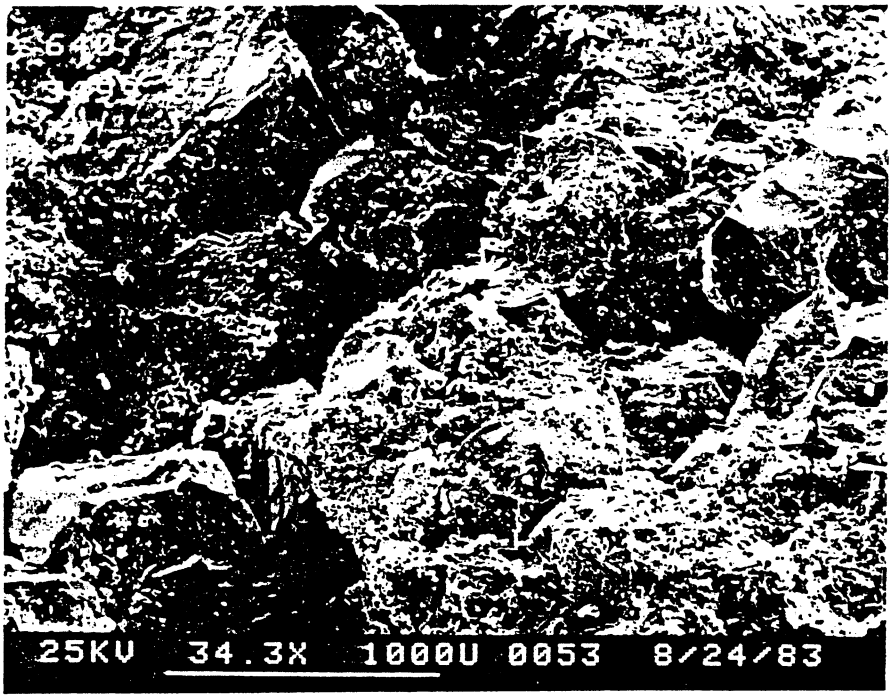


Figure B2. Overview. Quartz overgrowths and authigenic clay are present. Permeability of this sample is 119 millidarcies. From 3699.35 meters.

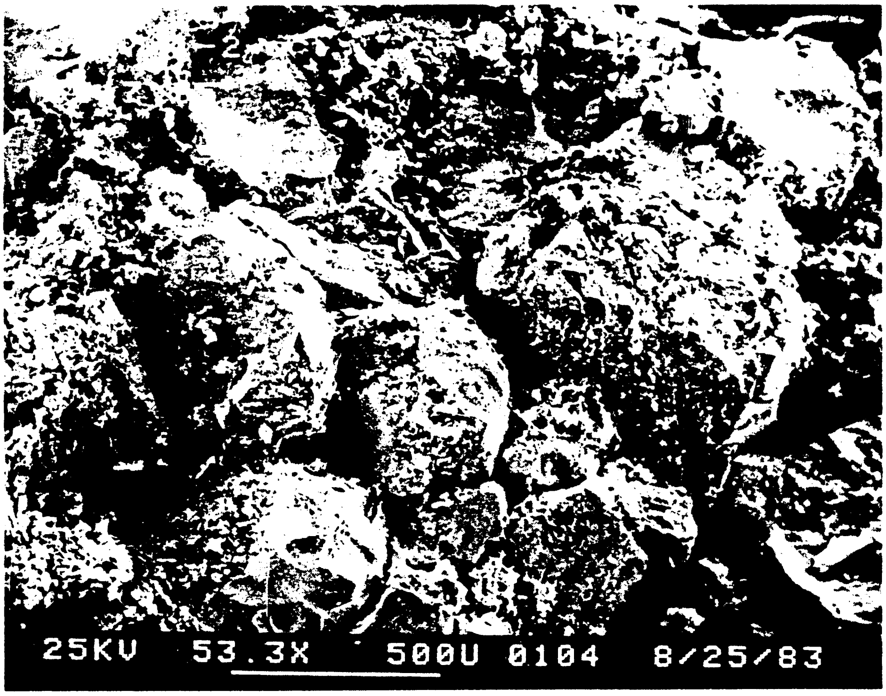


Figure B3. Overview. Note large grain size and relative lack of quartz overgrowths. Larger, more open pore throats are present. Permeability is 168 millidarcies. From 3717.35 meters.

Figure B4. Overview. Note large grains, large open pores. Dissolved feldspar in upper center part of photograph. From 3717.35 meters, permeability given above.

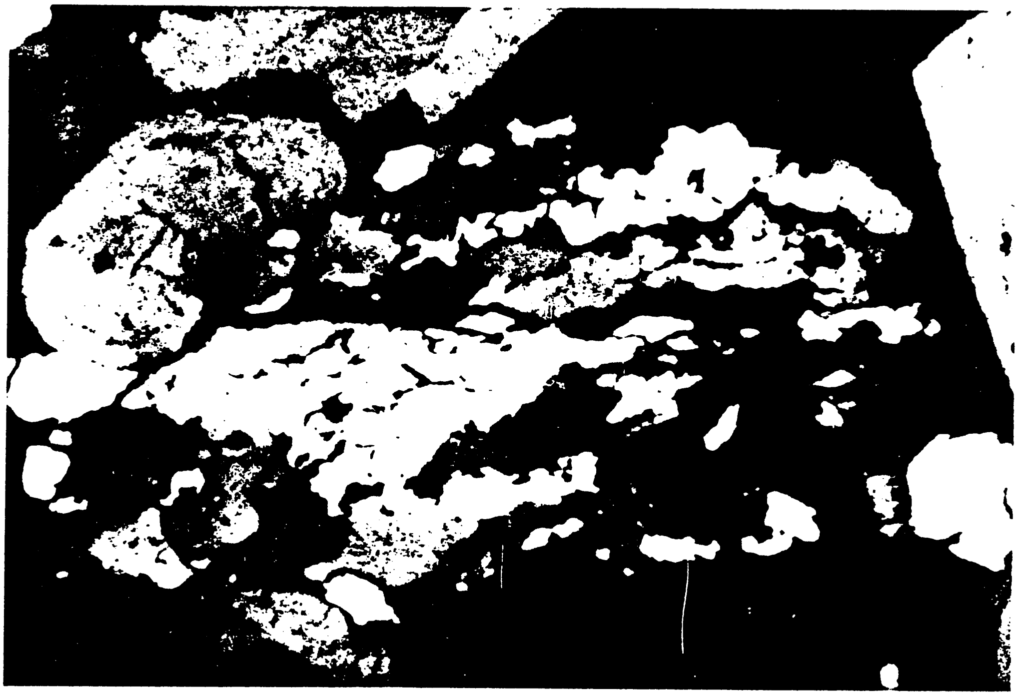


Figure B5. Metamorphic rock fragment from 3718.3 meters. Crossed nicols. Field of view is 1. 6 mm.

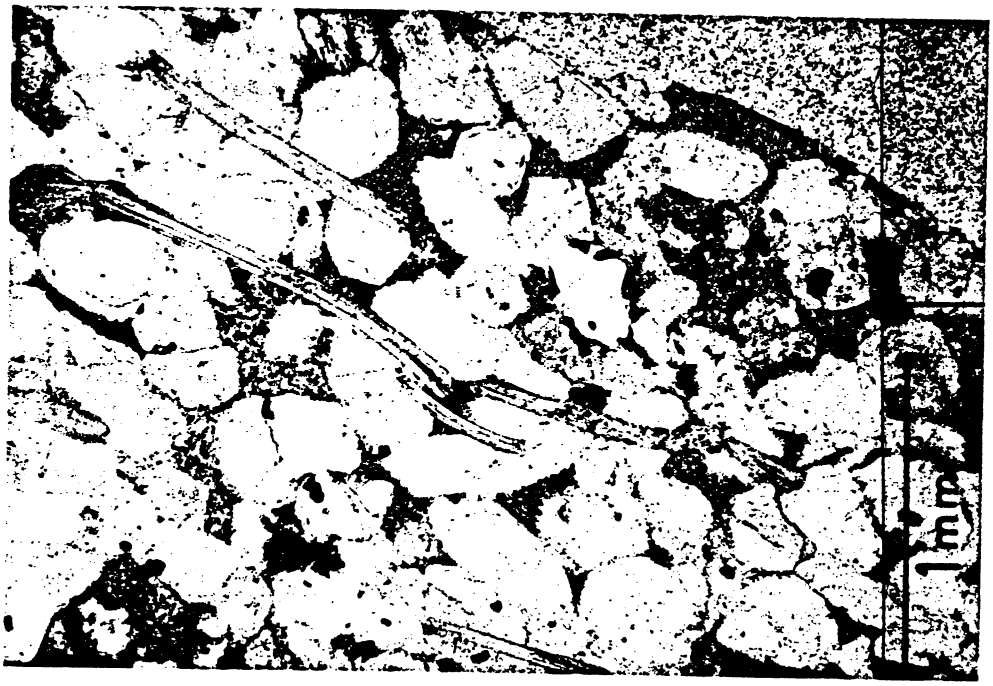


Figure B6. Compacted muscovite grains, from 3673.4 meters. Also note presence of quartz overgrowths and pore-filling kaolinite cement.

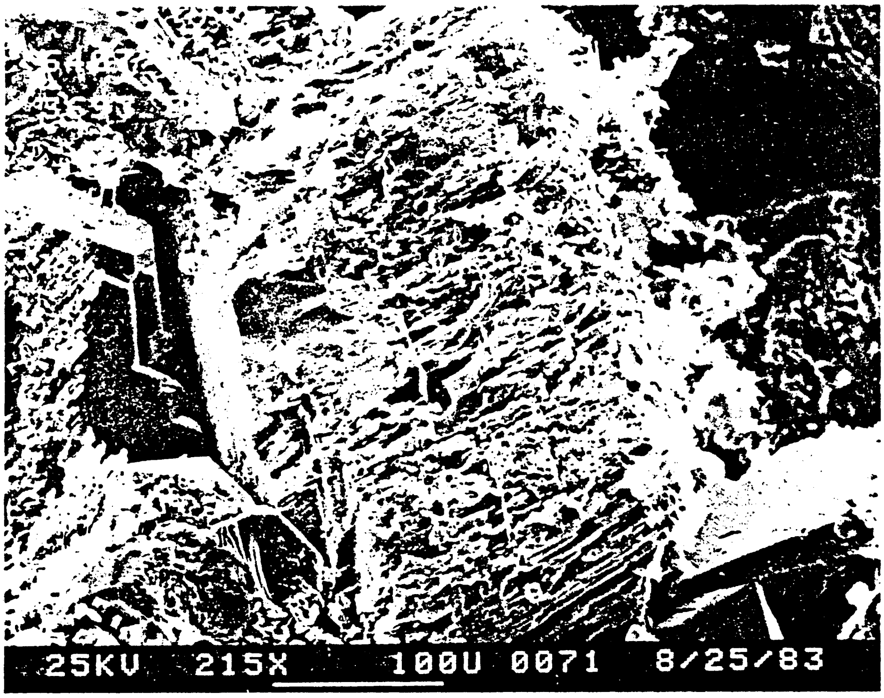


Figure B9. Dissolved K-feldspar grain, overgrown by wispy kaolinite and chlorite flakes. Kaolinite in lower left. From 3693.0 meters.

Figure B8. Abundant quartz overgrowths. Dissolved feldspar just below center. Squashed mica in lower right. From 3673.4 meters.

Figure B9. Dissolved K-feldspar grain, overgrown by wispy kaolinite and chlorite flakes. Kaolinite in lower left. From 3693.0 meters.

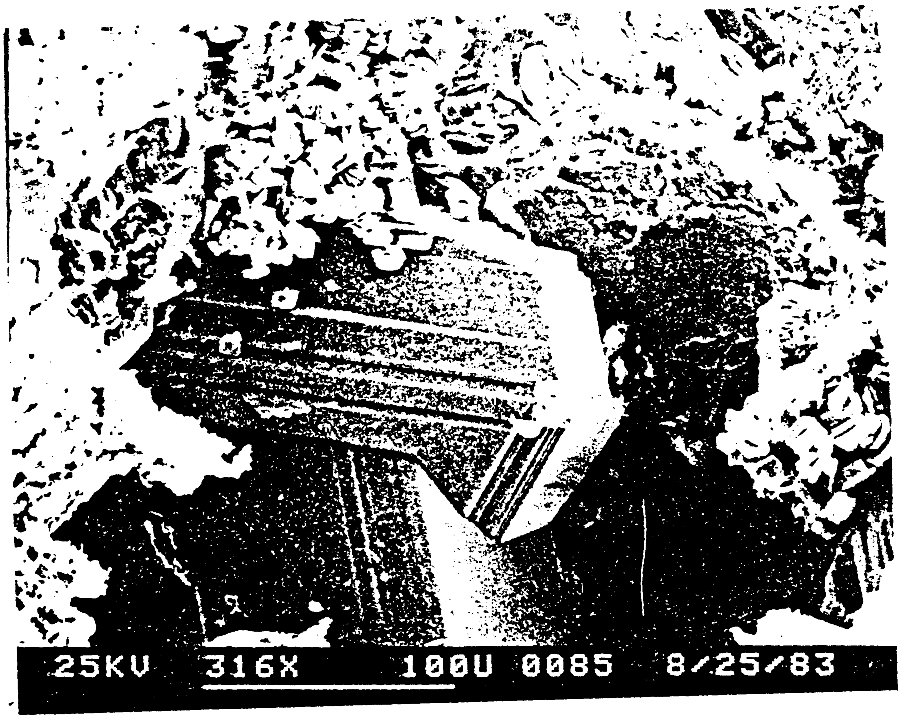


Figure B10. Authigenic plagioclase. Kaolinite above and to right. From 3661.15 meters.

Figure B11. Dissolved authigenic rim on K-feldspar. Note that quartz overgrowths stop at edge of the remnant rim, indicating feldspar rim formed earlier. Field of view is 0.5 mm.

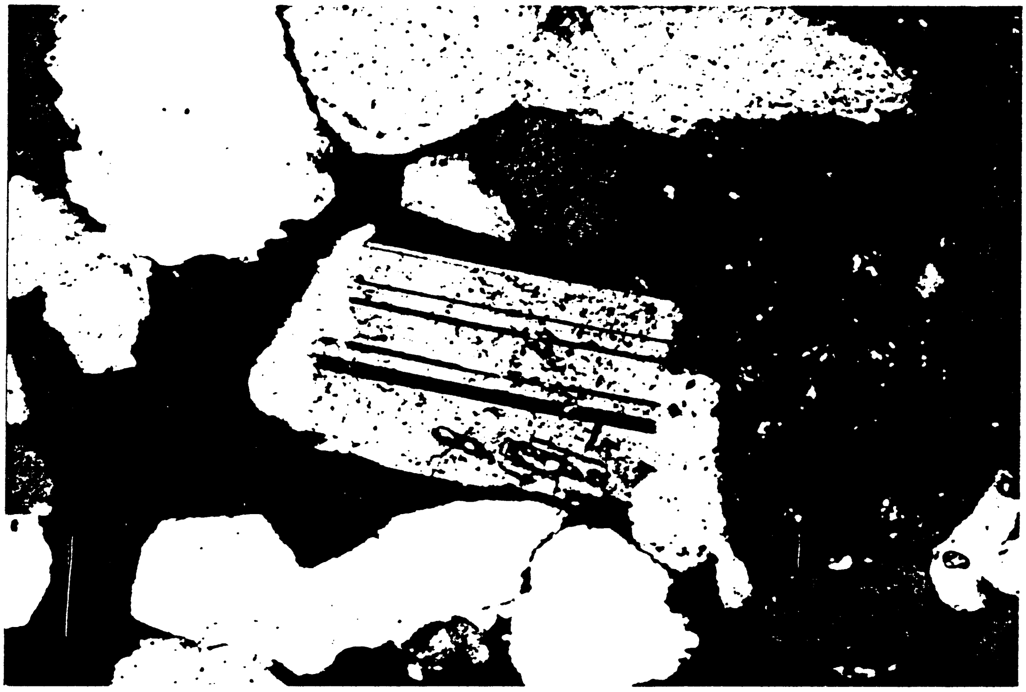


Figure B12. Authigenic rim (untwinned) on detrital plagioclase. From 3676.70 meters. Field of view is 1.0 mm.

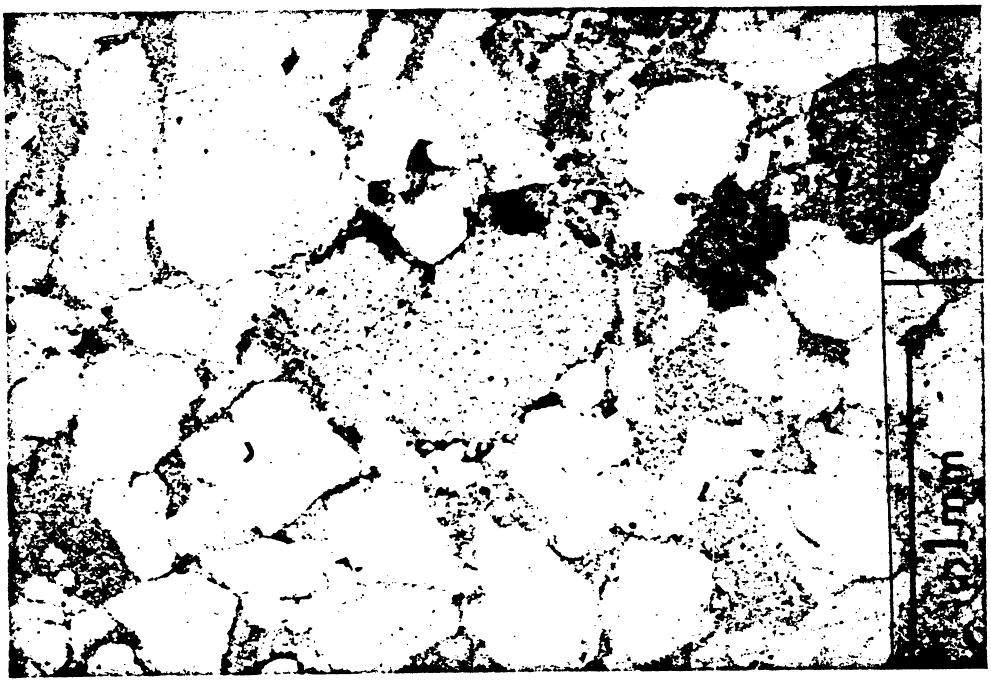


Figure B13. Kaolinite filling pores, including oversize pore left by dissolved framework grain. From 3706.0 meters.

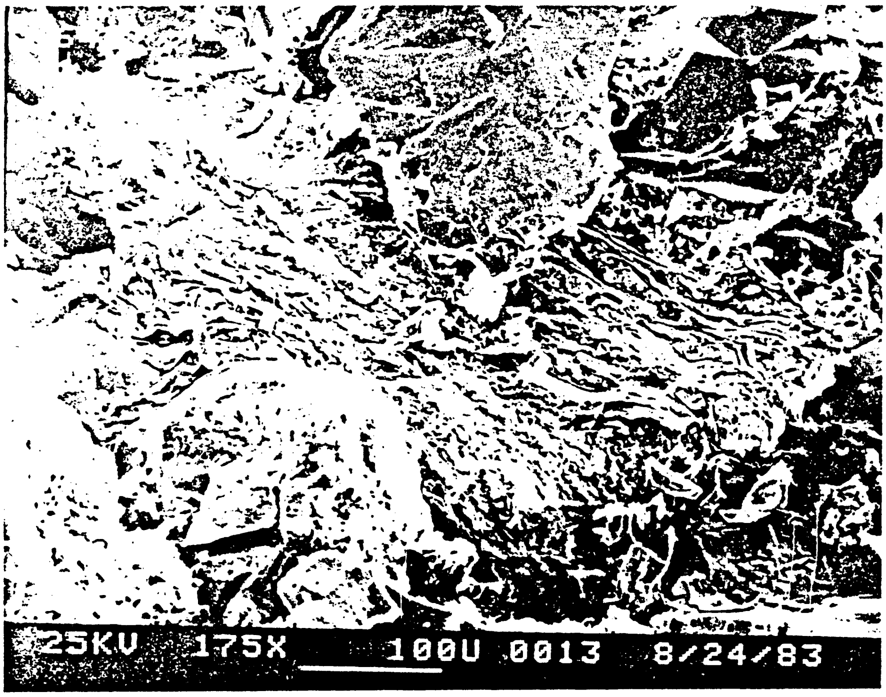


Figure B14. Kaolinite formed by alteration of mica. From 3684.8 meters.

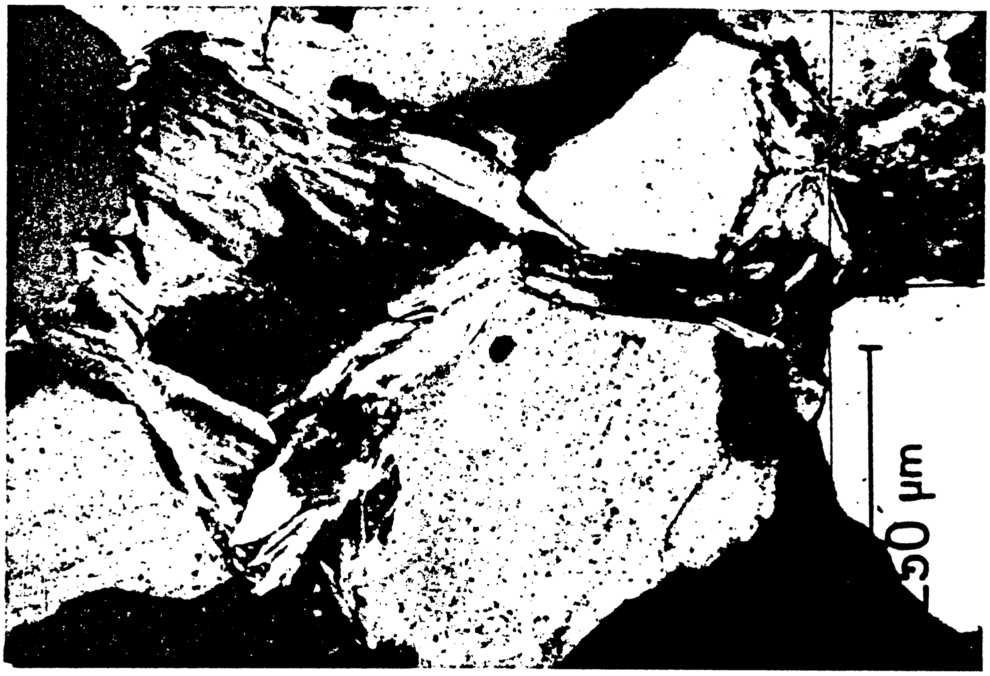


Figure B15. Muscovite alternating to kaolinite. Note that quartz overgrowths do not form against edge of kaolinite, indicating that kaolinite formed before quartz overgrowths. From 3661.15 metes. Field of view is 0.8 mm.

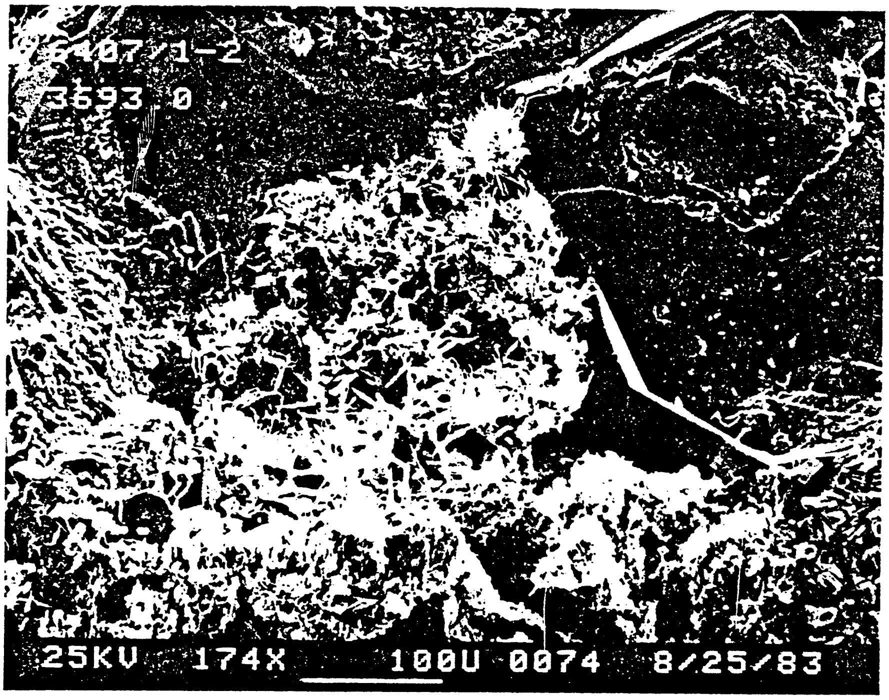


Figure B16. Fibrous illite growing on quartz overgrowths. From 3693.0 meters.

Figure B17. Fibrous illite filling pore. From 3684.8 meters.

Figure B18. Illite replacing dissolved feldspar grain. From 3684.8 meters.

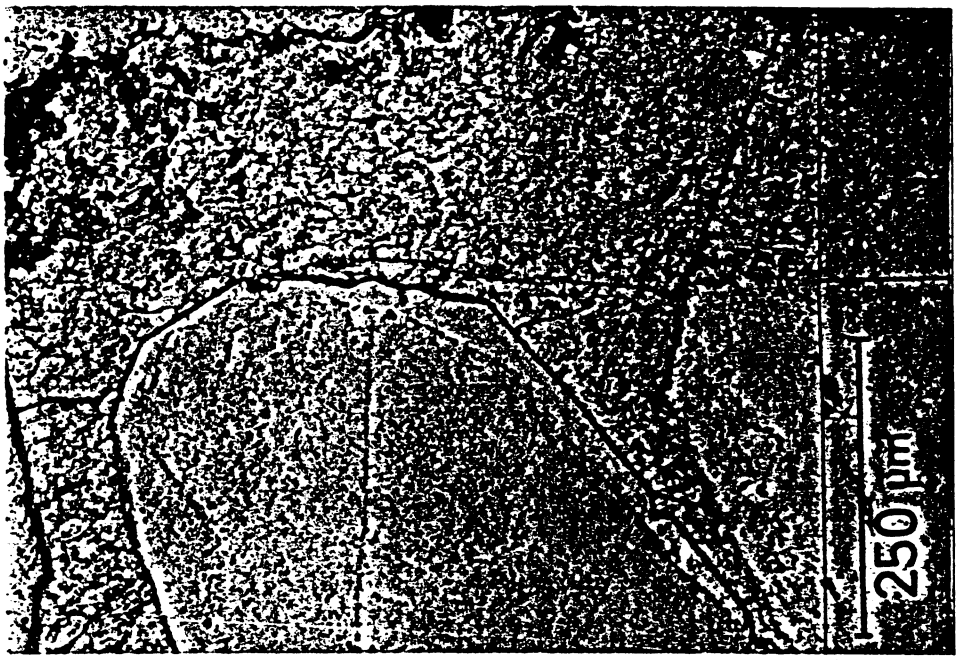


Figure B19. Poikilotopic calcite cement surrounding quartz grain with quartz overgrowth, indicating that calcite formation post-dated quartz overgrowth. From 3708.00 meters.

Figure B20. Carbonate crystals, probably siderite, filling pore left by dissolved feldspar. From 3703.05 meters. Kaolinite partially fills surrounding pores. Field of view is 1.0 mm.

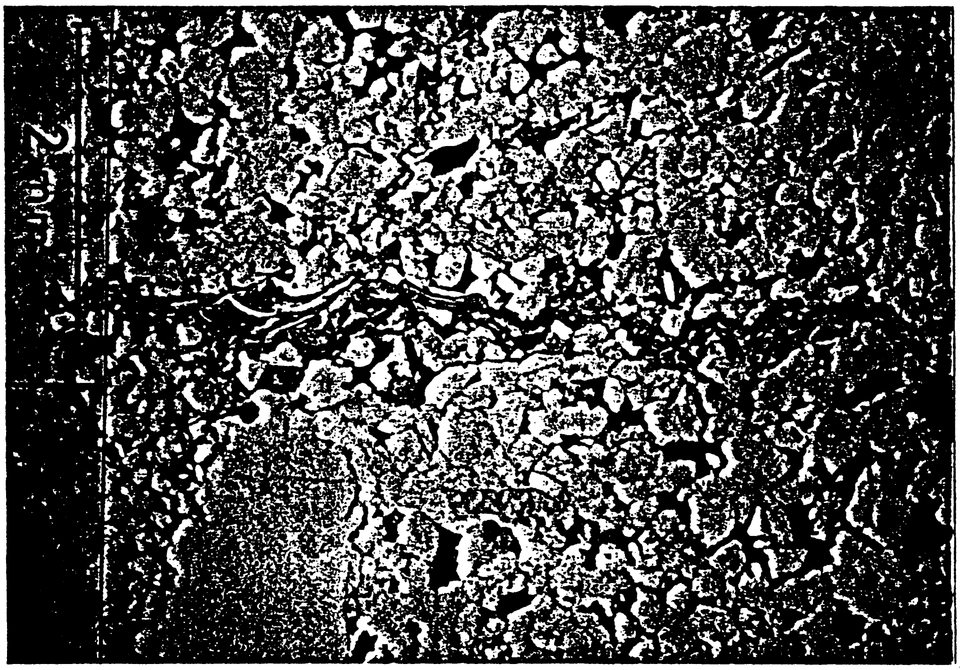
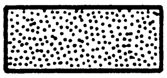
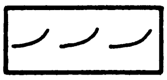
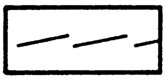
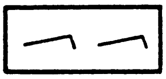
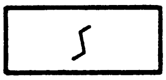
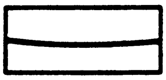
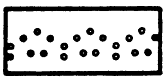


Figure B21. Stylolite, with accumulated mica, sulfide, and organic matter. Note poor sorting indicted by large grain in lower left. From 3675.4 meters.

Key to Sedimentary Structures
(To Accompany Plate 1)

1		Massive
2		Low Angle Tangential Cross-Bedding
3		Horizontal Bedding
4		Planar Tabular Cross-Bedding
5		Ripple Cross-Laminations
6		Steep (Angle of Repose) Tangential Cross-Beds
7		Burrows
8		Erosional Truncation
9		Sandy Conglomerate

Facies A is Characterized by Dominance of Sedimentary Structures 1-4. Facies B is Characterized by all Types of Structures Listed Above. (See Text for Details).

Plate 2