SEDIMENTATION AND DIAGENESIS IN SANDSTONES OF THE MANNVILLE GROUP (LOWER CRETACEOUS), SOUTHEASTERN ALBERTA

SEDIMENTATION AND DIAGENESIS IN SANDSTONES OF THE MANNVILLE GROUP (LOWER CRETACEOUS), SOUTHEASTERN ALBERTA

by

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A Thesis
Submitted to the Department of Geology
in Partial Fulfilment of the Requirements
for the Degree
Bachelor of Science

McMaster University

May, 1981

BACHELOR OF SCIENCE (1981) | McMASTER UNIVERSITY

(Geology) | Hamilton, Ontario

TITLE: Sedimentation and Diagenesis in Sandstones of the Mannville Group (Lower Cretaceous), Southeastern Alberta.

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SUPERVISOR: Professor G. V. Middleton

NUMBER OF PAGES: ix, 61

ABSTRACT

Lower Cretaceous Mannville Group sandstones of Alberta were deposited in non-marine and marginal environments. A shallow sea transgressed several times over the study area and left evidence of tidal action. The proportion of rock fragments increases from Lower Mannville to Upper Mannville sandstones due to the uplifting of strata to the west.

Observed petrographic and SEM textures indicate that authigenic pyrite, quartz and calcite cements were precipitated in that order followed by the dissolution of carbonate material and feldspar grains with the simultaneous precipitation of kaolinite and quartz. The secondary (or dissolution) porosity is the result of an influx of acidic pore waters. This secondary porosity is best developed in the Ellerslie Sandstone because its remnant intergranular porosity and permeability are superior to the porosity and permeability in the overlying sandstones. The present degree of diagenesis in the sandstones is largely controlled by the permeability of the rock.

ACKNOWLEDGEMENTS

The author is very grateful to Dr. G. V. Middleton for his expert supervision of the project and editing of the thesis. Dr. Monti Lerand of Gulf Canada Resources, Inc. suggested the topic and was most helpful during the important initial stages of the project.

Mike Moore of the Electron Microscopy Unit of the McMaster University Medical Center, Gary O'Farrell of Electron Optics Unit of McMaster University's Metallurgy Department and Ania Kamienska of Gulf Canada Resources, Inc. are all thanked for technical assistance with the various scanning electron microscopes.

Thanks are also due to Jack Whorwood for developing the micrographs and to Margaret Kavanagh for typing the final manuscript.

Marlene West provided expert assistance and encouragement throughout the project.

Dr. Middleton and the Department of Geology, McMaster University provided the necessary funding. Gulf Canada Resources, Inc., Calgary, Alberta prepared thin sections and allowed the author the time and material to study the cores used in this thesis.

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CHAPTER I

INTRODUCTION

In recent years, the scanning electron microscope (SEM) has given the sedimentologist an extremely clear view of some of the microtextures possible in sediments and sedimentary rocks (Scholle and Schluger, 1979; Whalley, 1978). Such a tool has become increasingly useful in the petroleum industry as the search for more subtle stratigraphic traps intensifies and the development of poorer clastic reservoirs becomes feasible.

Lower Cretaceous sediments in Alberta have been the subject of many geological investigations due to economic interest in their coal, oil and gas bearing members. The Mannville Group consists of Lower Cretaceous sediments in the plains of central Alberta and Saskatchewan. This project is a study of the facies and diagenesis of some of the sandstones in the Mannville Group. More precisely, it is a study of the facies and diagenesis as shown in three cores from separate wells in southeastern Alberta (Fig. 1) representing a discontinuous stratigraphic interval from the top of the Lower Mannville to the middle of the Upper Mannville. The stratigraphic nomenclature of the Mannville Group used in this study is shown in figure 2.

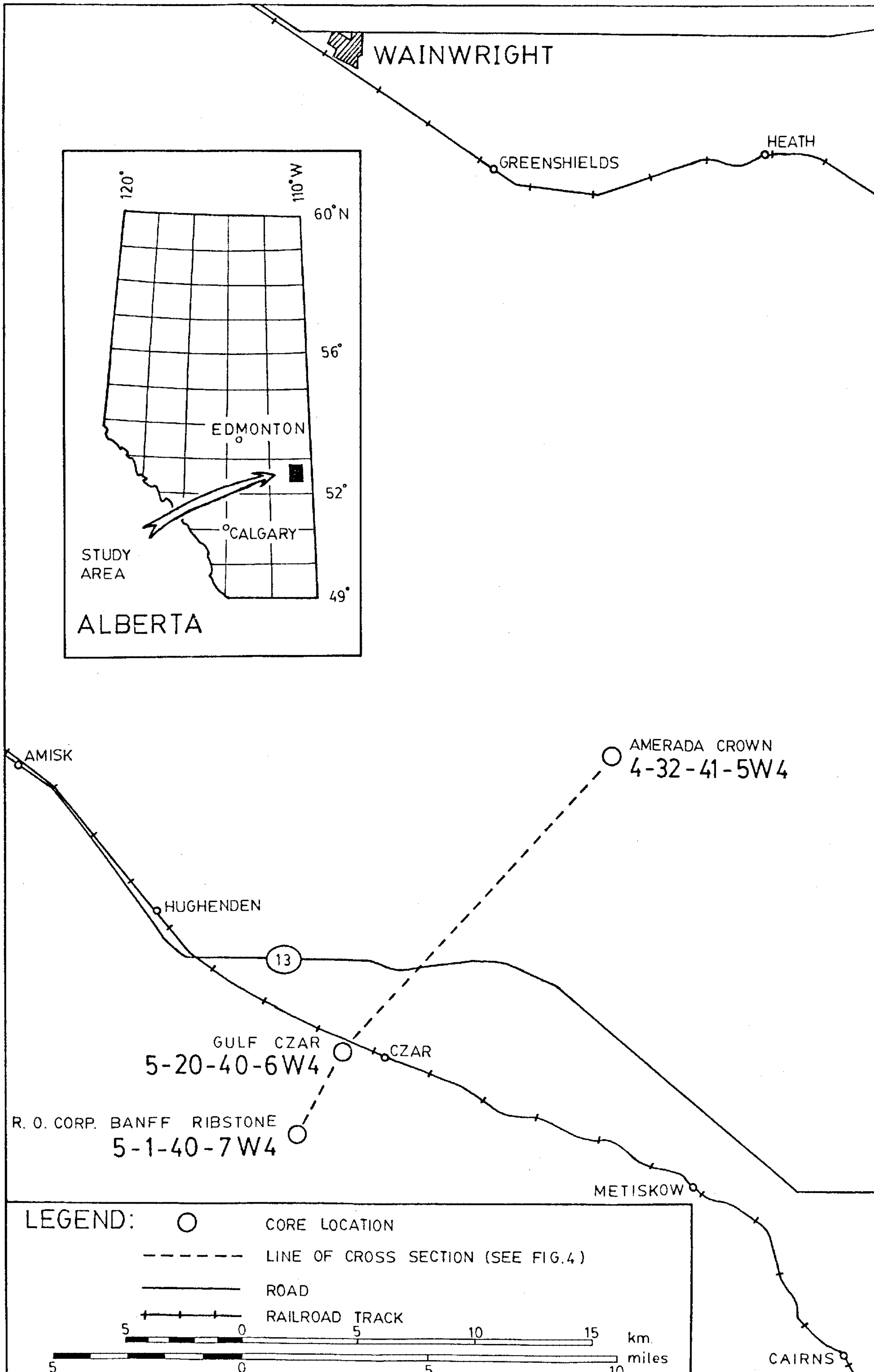


Fig. 1 Location map.

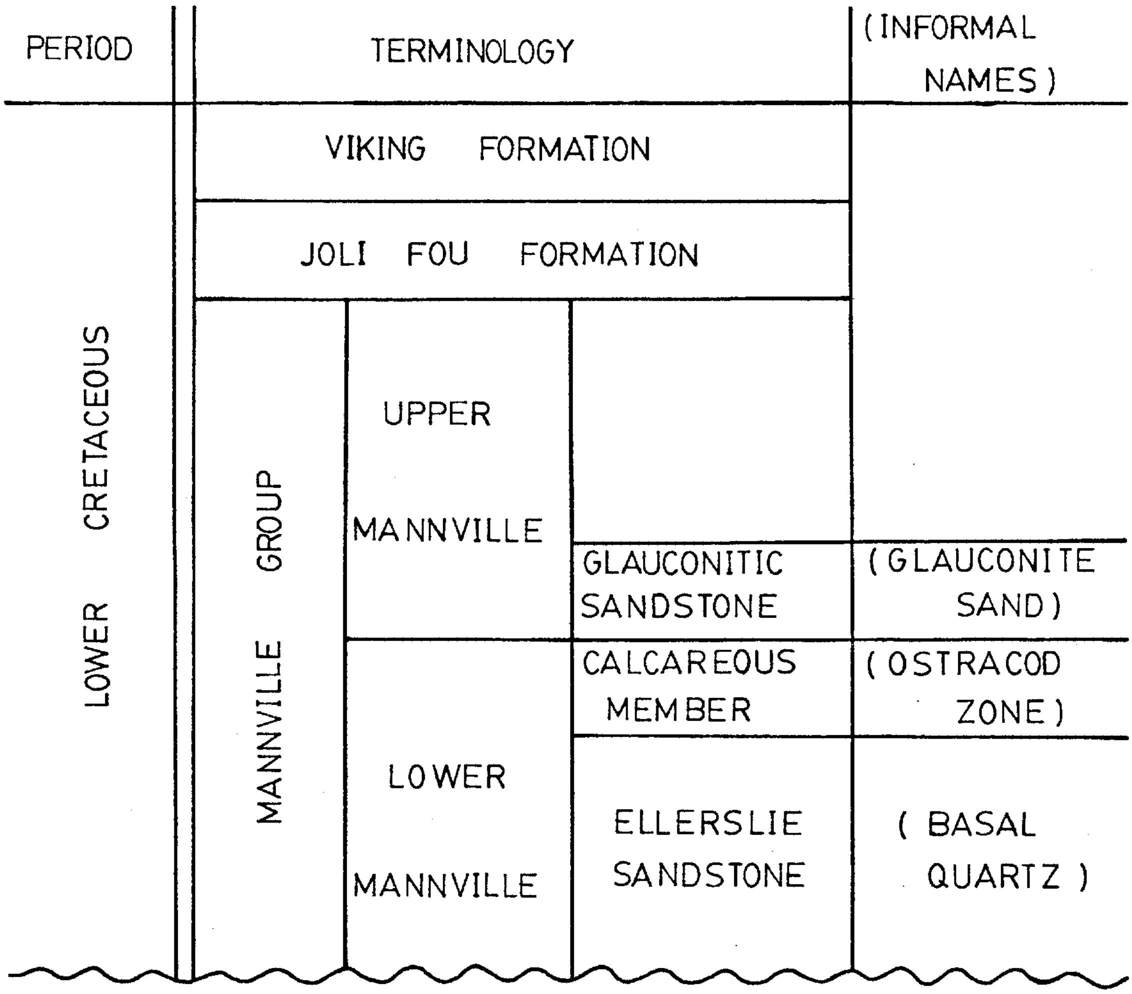


Fig. 2 Lower Cretaceous stratigraphy of the Central Alberta Plains (after Glaister, 1959).

CHAPTER II

METHODOLOGY

Sample Collection

Initially, all the cores were examined and described with the aid of a binocular microscope.

The 5-20-40-6W4 core was sampled and studied more intensely than the other cores. Samples were taken from the center of the core to avoid contamination from the drilling mud. Twenty-five samples of the sandstones in this core had their porosity and permeability accurately determined by Core Laboratories Canada Ltd. Thin sections were cut from these and other samples. Specimens for the SEM were also taken from six of these locations so that petrographic, porosity and permeability data would be available for the SEM specimens. Five shale samples were taken in order to determine the detrital clay mineralogy by X-ray diffraction (XRD) analysis.

The 4-32-41-5W4 and the 5-1-40-7W4 cores had seven and two thin sections made from their sands respectively. SEM samples were taken from a thin section location in each of these wells. No shale samples were taken from these wells.

Sample Preparation and Analysis

All thin sections were impregnated with a blue epoxy to indicate porosity. The composition of the sandstones was estimated by taking 300 point counts on 12 of the thin sections. The standard deviations of these values were computed from the means of 6 traverses of 50 point counts on each thin section.

Oil-stained samples to be observed under the SEM were washed with acetone to remove the oil. SEM samples were then mounted on stubs and given a conductive gold coating for viewing under the SEM. A Mark 2A Cambridge SEM with a Kevex X-ray energy dispersive attachment was occasionally used to identify questionable minerals but a Phillips SEM 501 was used for the vast majority of SEM observations.

Shale samples were prepared for XRD analysis using a method similar to that of Vermuri (1967). Approximately 20 grams of each of the shale samples was crushed with a mortar and pestle and dispersed in a blender for 6 to 8 minutes with distilled water. This solution was transferred to a one litre cylinder, diluted to volume with distilled water, stirred and allowed to settle for 225 minutes. The top 200 ml. of this solution should contain the less than 2μ size particles and was carefully siphoned off using a pipette. The clay was finally recovered by filtering the solution under a vacuum using a Millipore 0.45μ filter. These filters were then taped to glass slides. The orientation of the basal plane of clay minerals should be maintained approximately parallel to the slide using this method.

Clay slides were run at 1° 2θ per minute from 5° to 40°

2θ on a Philips X-ray diffractometer. Copper radiation with a graphite 002 monochromator was used at a setting of 60 kv. and 20 ma.

Only the kaolinite/illite ratio was determined because of the lack of significant amounts of other clay minerals and the problems associated with obtaining a semi-quantitative estimate of the clay mineralogy. This kaolinite/illite ratio was determined by measuring the areas under the peaks of the basal planes for these minerals (i.e. the 7.17 Å and 10.0 Å basal d spacings for kaolinite and illite respectively).

CHAPTER III

FACIES AND DEPOSITIONAL ENVIRONMENTS

The Mannville Group

General review

The Lower Cretaceous stratigraphic nomenclature used by various authors for the Central Alberta Plains is shown in figure 3. Glaister's (1959) terminology is used in this report.

The Mannville Formation was named by Nauss (1945). It included marine and non-marine facies overlying the Paleozoic unconformity and below the Lloydminster Shale (Colorado Group) in the Vermilion area of east-central Alberta. The formation was believed to be Lower Cretaceous in age and was tentatively correlated with outcrops of the McMurray, Clearwater and Grand Rapids Formations to the north along the Athabasca River Valley.

Badgley (1952) studied the Lower Cretaceous subsurface stratigraphy of Central Alberta and raised the Mannville to a group status. He included the McMurray, Clearwater and Grand Rapids Formations in the Mannville Group.

Glaister (1959) separated the Mannville Group into lower and upper portions at the top of the Calcareous Member and successfully correlated the Mannville Group with the Blairmore Group of the Alberta foothills.

Williams (1963) studied the paleogeomorphology,

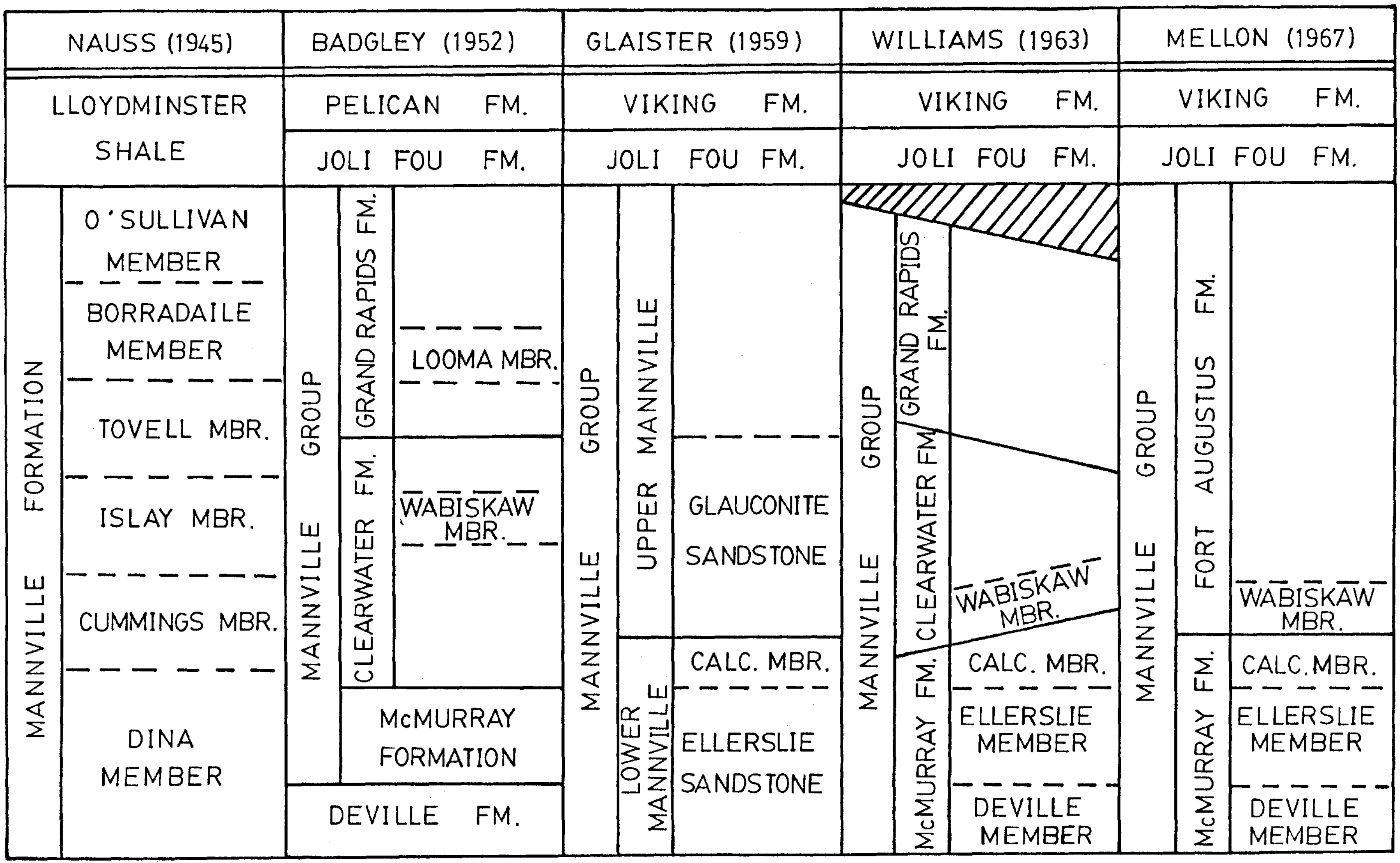


Fig. 3 Lower Cretaceous stratigraphy of the Central Alberta Plains by various authors (after Mellon, 1967)

stratigraphy and petrography of the Mannville Group. From isopach maps of Lower Cretaceous strata he interpreted that a series of northwesterly-flowing rivers drained southern and central Alberta prior to and at the beginning of Mannville time. Petrographically he concluded that the Lower Mannville sandstones were quartz-rich lithic sandstones while sandstones of the Upper Mannville ranged from lithic sandstones at the base to arkoses at the top.

The stratigraphy and petrology of the Lower Cretaceous sediments of the Alberta foothills and plains have been discussed in a comprehensive report by Mellon (1967). He proposed that the Lower Mannville and the Upper Mannville be renamed the McMurray Formation and the Fort Augustus Formation, respectively (Fig. 3).

Jardine (1974) presented a depositional framework for the Lower and Upper Mannville times in western Canada and discussed the origin and occurrence of oil in the oil sands of these sediments.

Facies

Mannville strata unconformably overlie Devonian and Mississippian carbonates in the central Alberta Plains (Williams, 1963). The Lower Mannville varies in thickness from 0 to over 100 meters depending on the topography of the underlying Paleozoic rocks (Mellon, 1967).

The Lower Mannville consists of two or three members

(Fig. 3). The lowermost of these members is the Deville Member which only occurs locally varying in thickness from 0 to 30 meters. It consists of green, brown and red shales, chert fragments and siderite pellets that grade upwards into brown shale interbedded with poorly sorted siltstone and fine-grained sandstone (Mellon, 1967).

The Ellerslie Sandstone is the middle member of the Lower Mannville and has a gradational contact with the Deville Member below it. It is the main facies of the Lower Mannville and may attain a thickness of over 60 meters. The Ellerslie is composed of fine-grained, kaolinitic quartz sandstone, laminated siltstone and silty shale. Fish scales, pelecypod fragments and carbonized plant remains may rarely be found (Mellon, 1967).

The upper member (the Calcareous Member) has a gradational contact with the Ellerslie Sandstone. It varies in thickness from 3 to 9 meters and consists of hard, calcareous shale, siltstone and sandstone. These beds often contain abundant remains of gastropods, pelecypods and/or ostracods of fresh and brackish water origin which may form coquinas up to 1 meter thick. The Calcareous Member is a highly correlative lithological unit throughout most of central and southern Alberta (Mellon, 1967; Williams, 1963).

The lower contact of the Upper Mannville is generally sharp. The formation varies in thickness between about 100 and 200 meters. The basal member of the formation is known as the Glauconitic Sandstone and ranges from less than 8 meters to more than 40 meters in thickness. This member is ideally glauconitic or sandy shale grading into fine-grained glauconitic sandstone interbedded with argillaceous sandstone having clay pockets and partings. The amount of glauconite in this member varies considerably (Mellon, 1967).

The Glauconitic Sandstone grades upwards into the rest of the Upper Mannville which is composed of laminated shale and siltstone and fine to medium-grained, feldspathic sandstone. These sandstone beds may attain a thickness of 10 meters. Normally the soft, kaolinitic sandstones have hard, thin, calcareous layers with many siderite pellets. Thin coal beds and plant fossils can sometimes be found near the top of the formation. The top of the formation is abrupt where shales of the Joli Fou Formation appear over the Mannville sandstones (Mellon, 1967; Williams, 1963).

Depositional environments

During late Jurassic time, western Canada was uplifted and an erosional period began (Jardine, 1974). Northwesterly-flowing rivers created an average relief of over 100 meters on the pre-Cretaceous unconformity. The trend of these major river systems was largely dictated by the underlying geology (Williams, 1963). Emplacement of the Nelson and Cassier-Omineca batholiths of the Cordilleran region occurred at about this time. Continued uplift of the Cordilleran region and concurrent emergence of the Canadian Shield provided westerly and easterly sources of sediment for Lower Mannville deposits. The Lower Mannville is generally fluvial-deltaic deposits that filled in the valleys left on the pre-Cretaceous erosional surface. In northwestern Alberta thin marine shales were deposited at this time as the Arctic sea transgressed southward (Jardine, 1974).

The lowermost member of the Lower Mannville (the Deville Member) is interpreted as residual detritus caused by the weathering of the carbonates beneath them (Mellon, 1967). The Ellerslie Member can be interpreted as a deltaic complex moving into a standing body of water or as the infilling of a channel (M.M. Lerand, personal communication, 1981).

The Calcareous Member was deposited under non-marine and near-marine conditions which coincided with the start of the southward transgression of the Arctic (Clearwater) Sea (Mellon, 1967; Williams, 1963).

Upper Mannville time began with the continued southward transgression of the Arctic Sea which reworked older sediments and deposited the basal Glauconitic Sandstone. Also, the Gulfian Sea transgressed northward into southern Alberta during Upper Mannville time. Both seas transgressed repeatedly over most of the province during this period but central Alberta and the foothills remained dominently non-marine (Jardine, 1974). The end of Mannville time was marked by widespread transgression as the Arctic and Gulfian Seas formed an epicontinental sea in which the shaly rocks of the Lower Cretaceous Colorado Group were subsequently deposited (Jardine, 1974).

The Study Area

Figure 1 shows the location of cores used, while figure 4 correlates the cores in a cross section using spontaneous-potential (SP) logs. Figures 6 to 8 summarize the facies of the 3 cores.

Facies

The 5-20-40-6W4 core was studied in great detail. Photographs of the core appear in the appendix for comparison with the following facies descriptions and figure 6. The other two cores could not be easily divided into meaningful facies and large portions of these cores have questionable facies names or are unlabeled.

Facies are defined on the basis of lithology, sedimentary structures and fossils. The following are descriptions of the various facies.

Facies CC: Coal.

This facies normally consists of only black coal but shaly interbeds are sometimes found.

Facies CS: Coaly shale and siltstone.

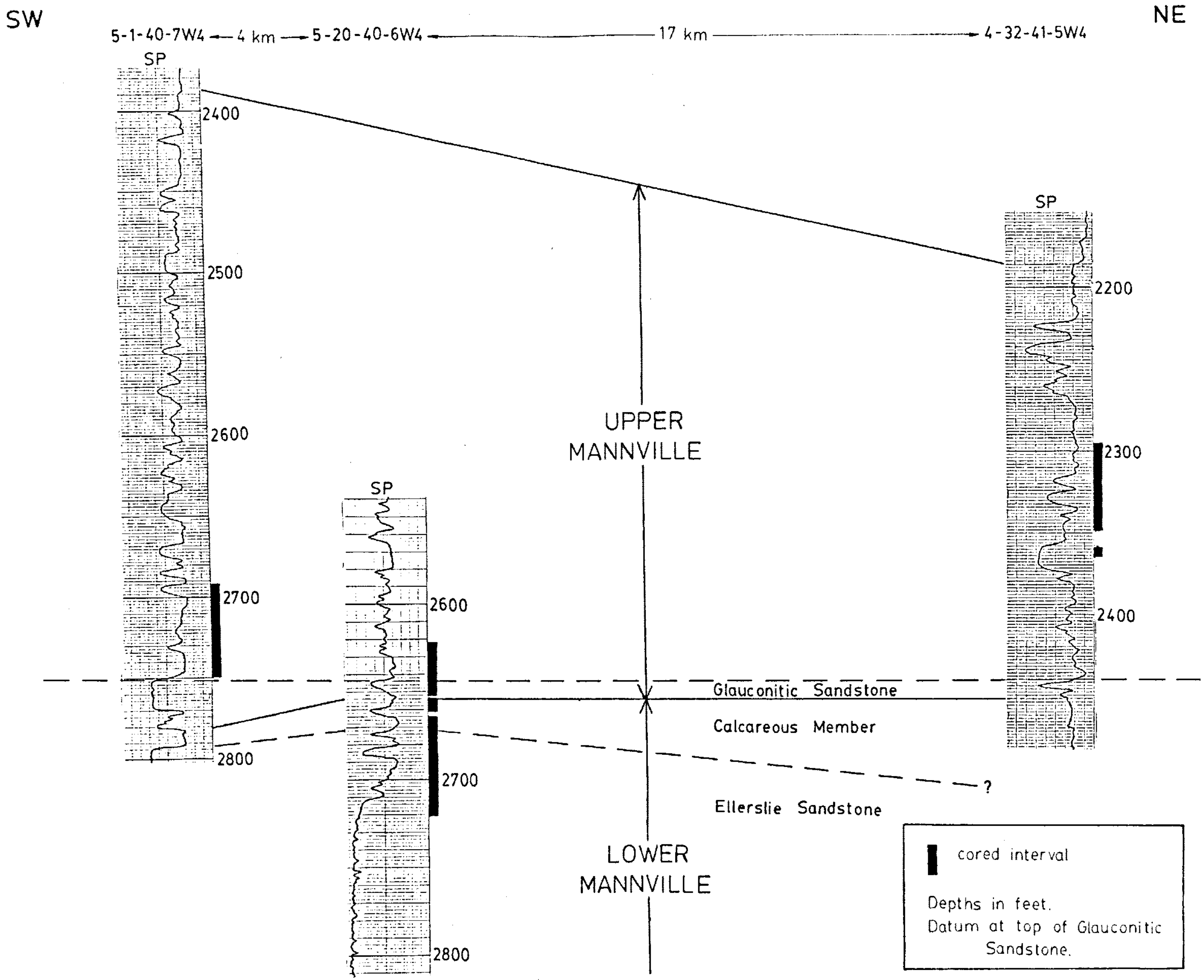


Fig. 4 Correlation of the cores using SP logs.
Well locations are shown on figure 1.

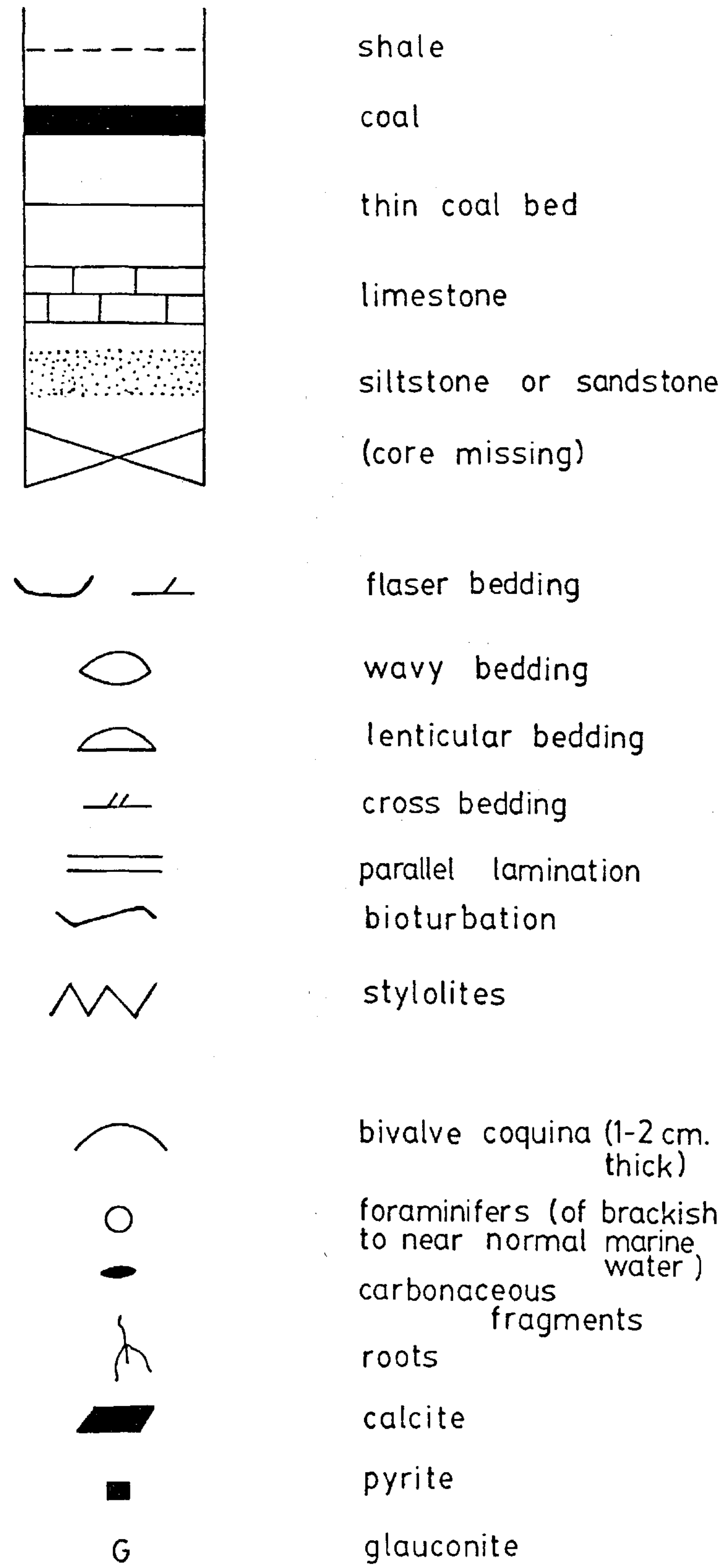
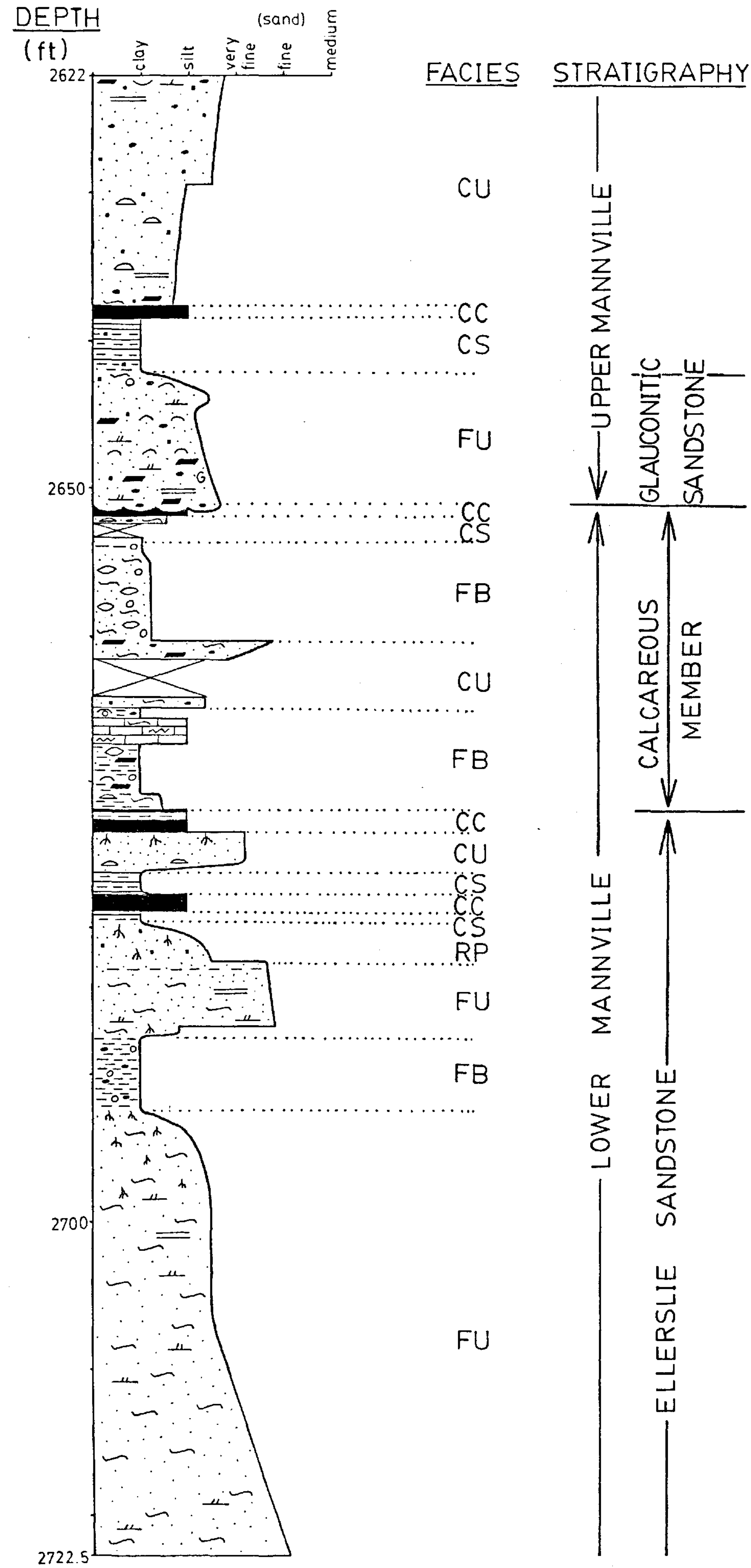


Fig. 5 Legend for the stratigraphic columns.

Fig. 6 Stratigraphic column of the 5-20-40-6W4 core.



DEPTH (ft)
(sand)
clay
silt
very fine
fine
medium
2622
2650
2700
2722.5
FACIES
CU
CC
CS
FU
CC
CS
FB
CU
FB
CC
CU
CS
CC
CS
RP
FU
FB
FU
STRATIGRAPHY
UPPER MANNVILLE
GLAUCONITIC SANDSTONE
LOWER MANNVILLE
CALCAREOUS MEMBER
ELLERSLIE SANDSTONE

Fig. 7 Stratigraphic column of the 5-1-40-7W4 core.

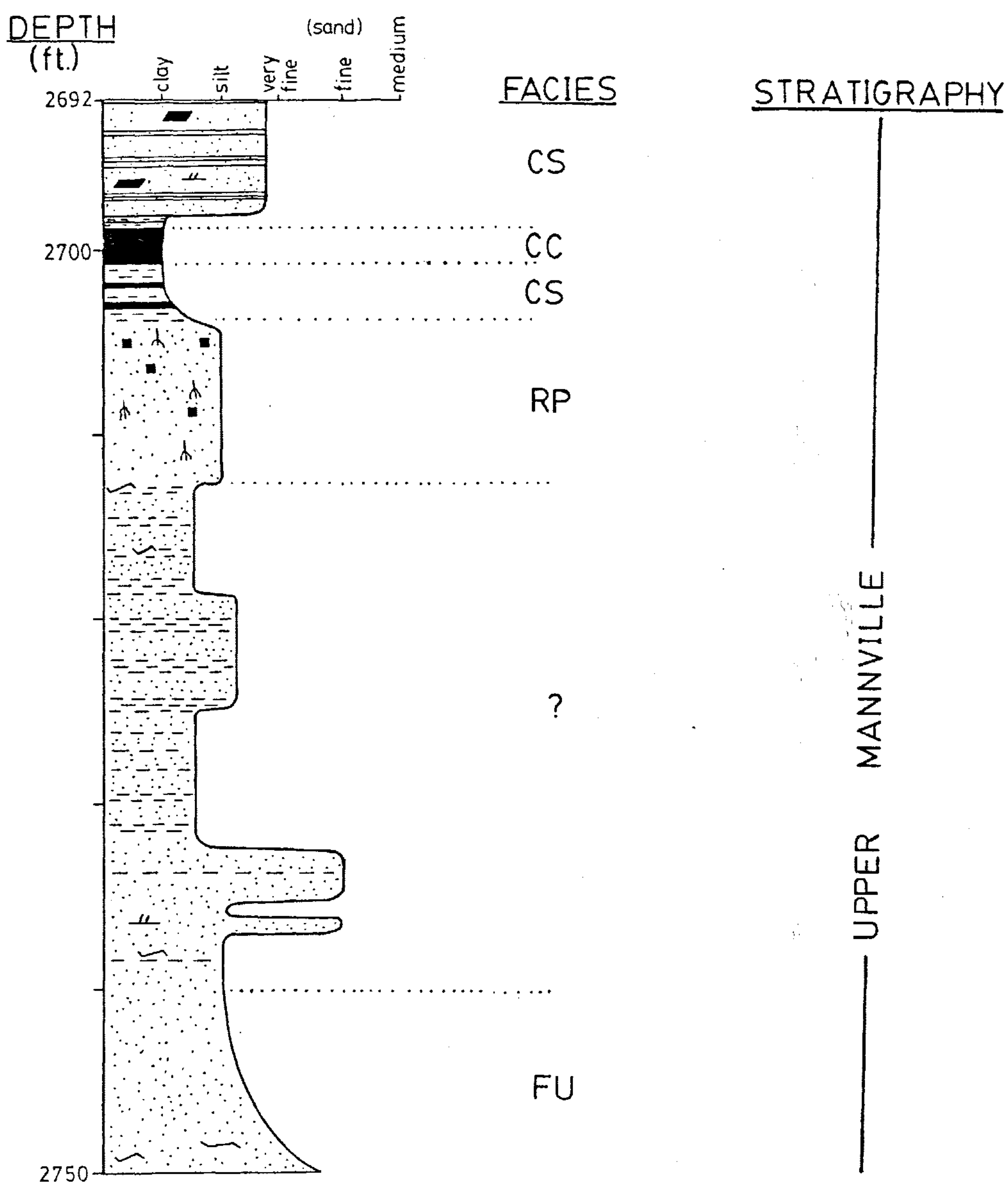
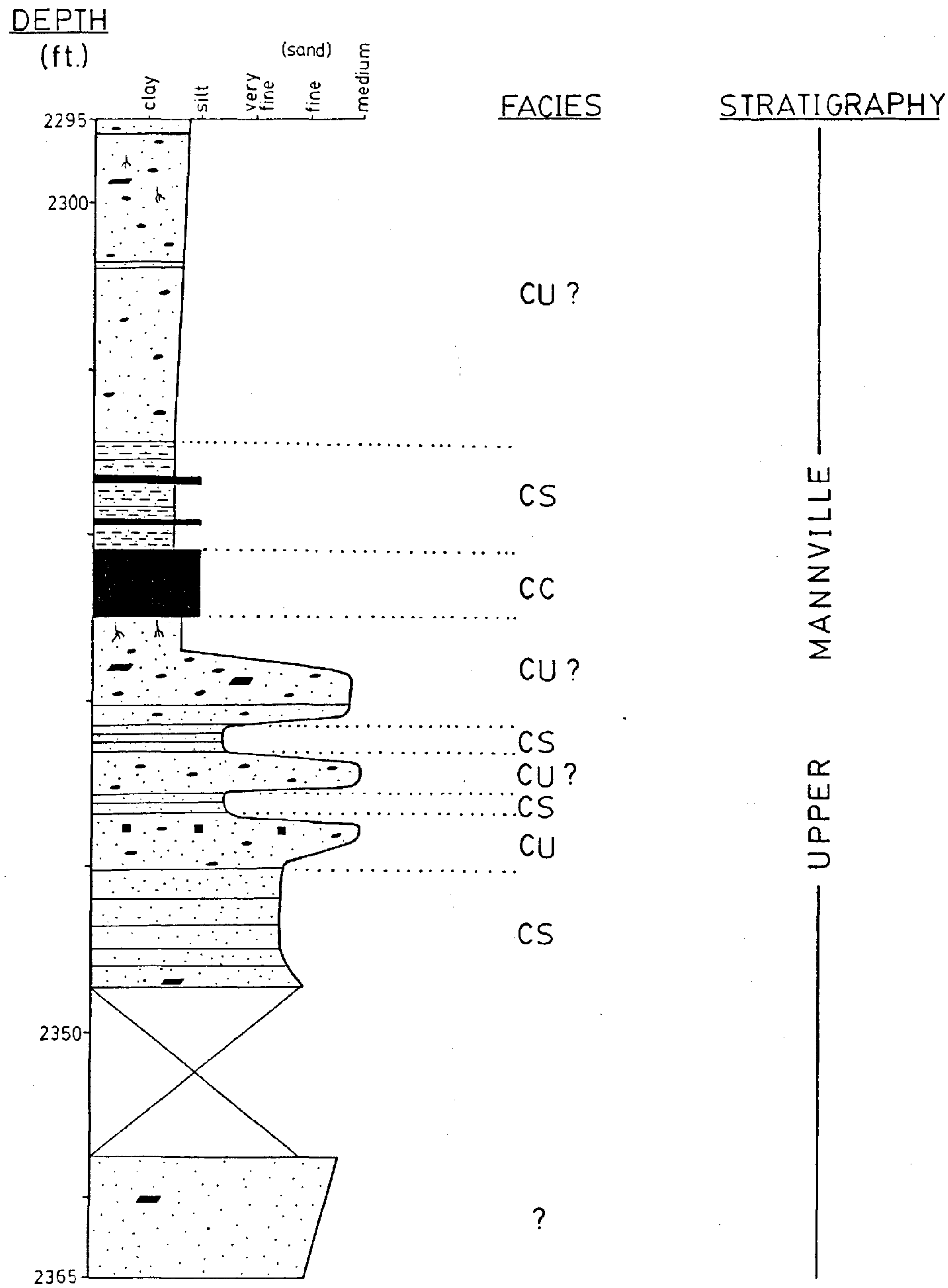

DEPTH
(ft.)
(sand)
clay
silt
very fine
fine
medium
2692
2700
2750
FACIES
CS
CC
CS
RP
?
FU
STRATIGRAPHY
UPPER MANNVILLE

Fig. 8 Stratigraphic column of the 4-32-41-5W4 core.


DEPTH
(ft.)
(sand)
clay
silt
very fine
fine
medium
FACIES
STRATIGRAPHY
2295
2300
2350
2365
CU ?
CS
CC
CU ?
CS
CU ?
CS
CU
CS
?
UPPER MANNVILLE

This facies is composed of fine shaly coal, coaly shale and siltstone, siltstone, and very fine-grained sandstone beds. The siltstone and sandstone units often have carbonaceous fragments.

Facies RP: Rooted, pyritic siltstone.

This facies consists of rooted, pyritic siltstone and may fine upwards as well as increase in root and pyritic content towards the top.

Facies FB: Foraminifera-bearing shale.

Facies FB consist of foraminifera-bearing shale and silty shale and limestone. Foraminifers of brackish to near normal marine water are found in the shales along with occasional ostracods, calcite and carbonaceous fragments. The shales are often bioturbated and interbedded with siltstone showing wavy and lenticular bedding. A small unit of limestone that is bioturbated and shows styolites is found once in the facies.

Facies FU: Fining-upward, cross-bedded sandstone.

This facies is composed of siltstone and fine-grained sandstone that fines upward. It typically shows cross-bedding, Parallel laminations and bioturbation. Roots or foraminiferas of brackish to near normal marine water origin may occur near the top of the facies. Pyrite, calcite, glauconite, carbonaceous fragments and zones of pelecypod shells (1 to 2 cm. thick) may also be present.

Facies CU: Coarsening-upward sandstone.

This facies consists of siltstone to medium-grained sandstone in a coarsening-upward sequence. Carbonaceous fragments normally occur throughout the facies and pyrite is often present. Roots (at the top of the facies) and calcite can also occur in the facies as well as flaser bedding, lenticular bedding, parallel laminations and bioturbations.

Depositional environments

The following depositional environments were interpreted from the preceding facies descriptions.

Facies CC: The massive coal units are interpreted as swamps.

Facies CS: This facies represents a marginal swamp environment. It is always associated with facies CC.

Facies RP: Abundant roots and pyrite and the fine-grained nature of this facies probably indicate a soil environment.

Facies FB: The brackish to near normal marine water foraminifera would indicate an environment of diluted sea water. An estuarine environment seems likely when the fine grain size and the presence of bioturbation is also considered. The wavy and lenticular bedding of the facies (see Appendix I) are likely produced by tidal action (cf. Terwindt, 1975).

Facies FU: This fining-upward, cross-bedded, bioturbated sandstone likely results from the filling in of a channel. The appearance of glauconite in the Glauconitic Sandstone as well as foraminifers at the top of the member indicates a marine origin.

Facies CU: These coarsening-upward units often contain carbonaceous fragments and probably represent splay or delta deposits.

CHAPTER IV

PETROGRAPHY

General

This chapter mainly discusses the petrographic aspects of the detrital portion of the sandstones. Diagenetic constituents and textures will be considered more fully in the following chapter.

Generally the sandstones are very fine to medium grained, moderately to poorly sorted and range from subangular to rounded. Therefore these Mannville sandstones would appear to be texturally submature according to Folk's (1968) classification.

Table 2 and figure 9 present the results of 300 point counts on 12 representative thin sections of the studied sandstones. When classified according to Folk (1968) the sandstones fall into the sublitharenite, litharenite and the feldspathic litharenite fields (Fig. 9). Lower Mannville sandstones are mainly sublitharenites while the Upper Mannville sandstones are mainly litharenites. When the litharenites and the feldspathic litharenite are subdivided according to their rock fragments they plot in the sedarenite field (Fig. 9).

Mineralogy

Detrital constituents

Quartz grains are generally monocrystalline and many are slightly strained. Inclusions of vacuoles are common but heavy mineral inclusions are rare.

Feldspars include orthoclase, plagioclase and microcline generally in that order of decreasing abundance, although plagioclase is most abundant in a few slides. Feldspar grains are commonly altered and/or partially dissolved (Fig. 16a). No compositional zoning of feldspars was observed.

Many rock fragments are squashed together or against more competent grains by compactional forces. This tends to make their grain boundaries indistinct (Fig. 11c) especially where the grains have been partially dissolved. Rock fragments are mainly sedimentary and consist largely of chert with some shale and siltstone. Volcanic rock fragments (Fig. 13c) are mostly mafic and are abundant only in the Upper Mannville above the Glauconite Sandstone. Metamorphic rock fragments are very rare and consist of phyllite and schist.

Muscovite and biotite are found in minor amounts ranging from less than 1% to 3% with muscovite being considerably more abundant than biotite. These mica grains are always oriented parallel to bedding. Many are deformed around other framework grains (Fig. 19a).

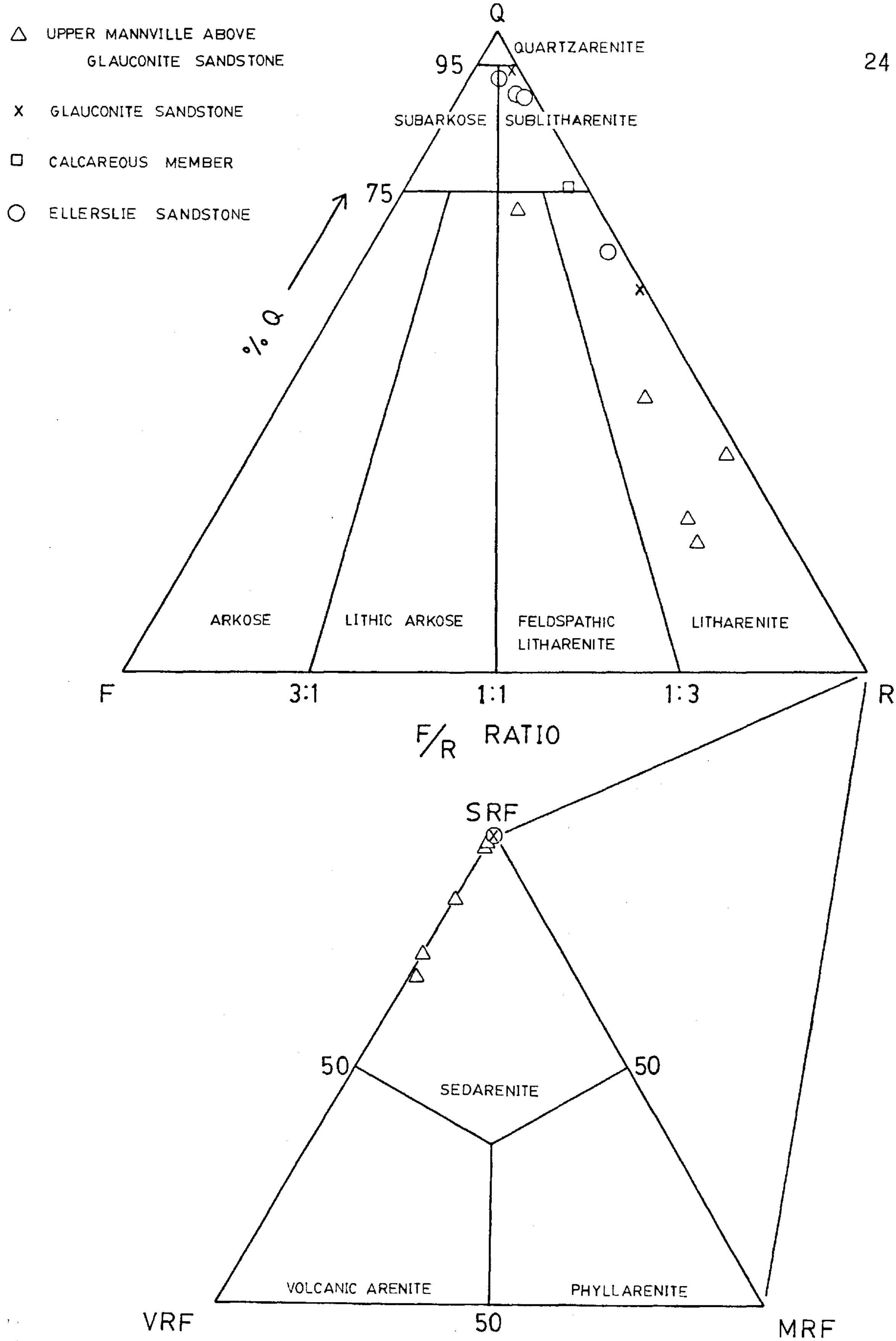


Fig. 9 Ternary plot showing the composition of framework constituents of Mannville Group sandstones. Classification after Folk (1968). Q = quartz, F = feldspar and plutonic rock fragments, R = rock fragments, SRF = sedimentary rock fragments, VRF = volcanic rock fragments, MRF = metamorphic rock fragments.

Note: The following micrographs (Figs. 10 to 19) are presented in a descending stratigraphic order. All SEM micrographs have their original magnification, the well location and the footage of the sample recorded in that order at the base of the photo. Thin section micrograph magnifications are approximate. Porosity and permeability data are given for plugs from the 5-20-40-6W4 core.

Fig. 10 Fine-grained, poorly sorted Upper Mannville sandstone from 2328' in the 4-32-41-5W4 well.

(A) Micrograph of a clayey portion of this very immature sandstone with almost zero porosity consisting of quartz, chert, matrix, cement, mica and rock fragments. Crossed nicols, X 60.

(B) SEM micrograph showing the abundance of detrital clay and minor pore space in this sandstone. 100μ scale divisions.

(C) SEM micrograph of a dissolving feldspar grain (f) beside authigenic quartz overgrowths (q) and kaolinite booklets (k) which are growing into the pore space. 10μ scale divisions.

(D) Detail of the feldspar grain shown in (C). Note authigenic kaolinite booklets along the extreme left of the photo. 10μ scale divisions.

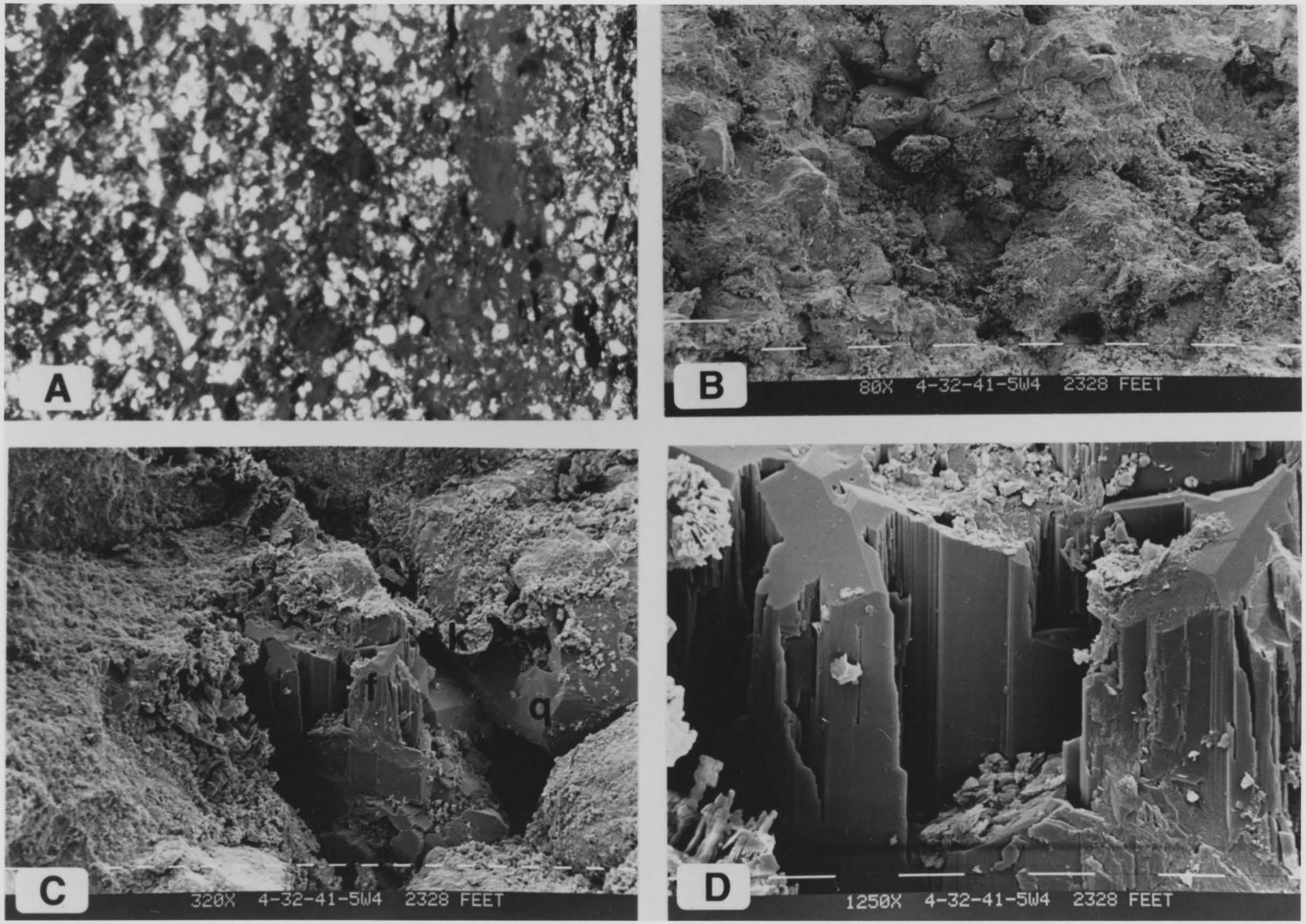

A
B
80X 4-32-41-5W4 2328 FEET
k
f
q
C
320X 4-32-41-5W4 2328 FEET
D
1250X 4-32-41-5W4 2328 FEET

Fig. 11 Upper Mannville sandstones from the 4-32-41-5W4 and the 5-20-40-6W4 wells.

(A) SEM micrograph of a dissolving feldspar grain surrounded by clays (mostly kaolinite) from 2328 feet in the 4-32-41-5W4 well. 10μ scale divisions.

(B) Detail of the feldspar grain in (A). 1μ scale divisions.

(C) Micrograph showing the general texture of Upper Mannville sands at the top of the 5-20-40-6W4 core (2622 feet). Crossed nicols, X 60.

(D) SEM micrograph of the same sample as in (C) showing the fine-grained nature of the rock. Porosity 19.3%. Permeability 0.91 md (millidarcys). 100μ scale divisions.

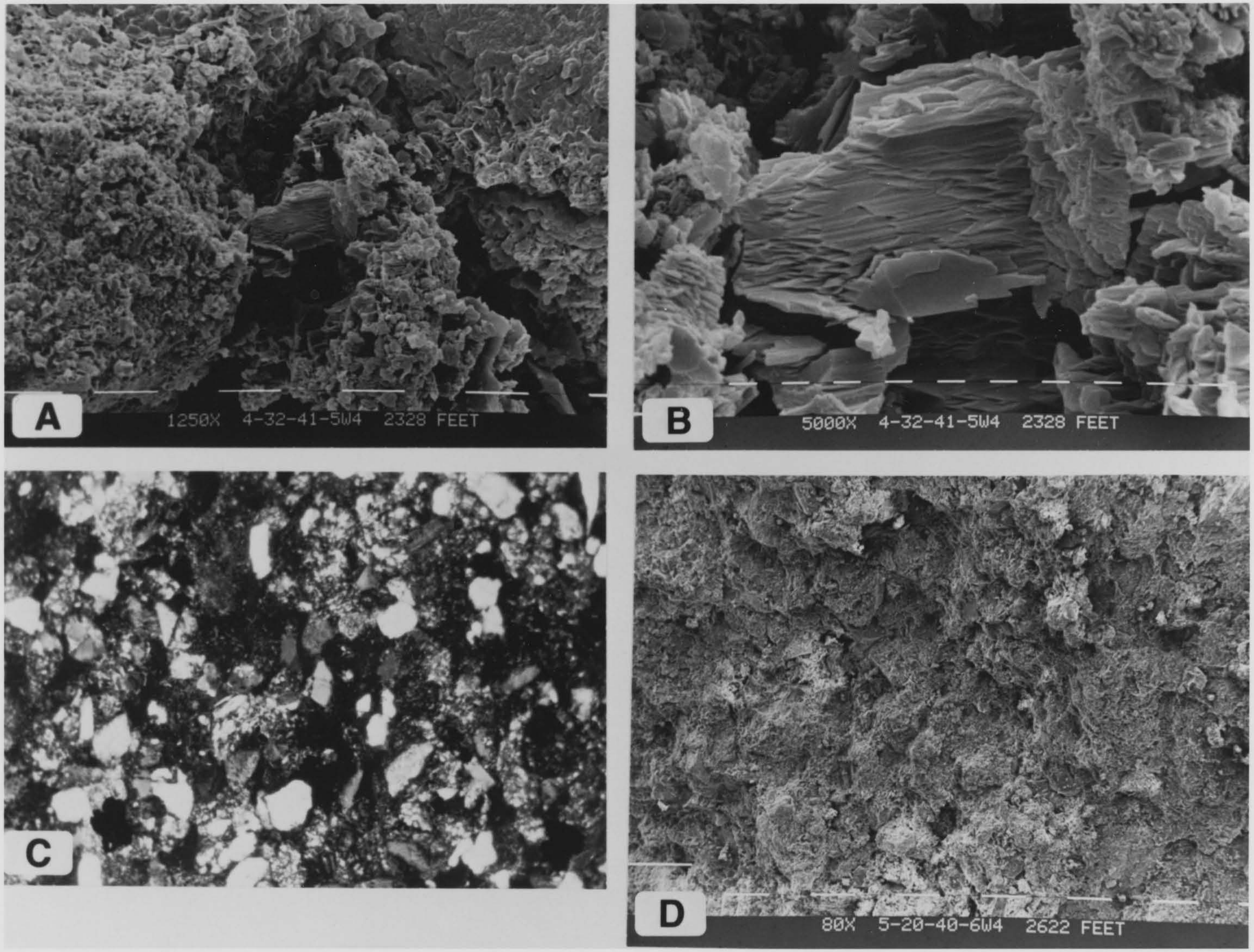

A
1250X 4-32-41-5W4 2328 FEET
B
5000X 4-32-41-5W4 2328 FEET
C
D
80X 5-20-40-6W4 2622 FEET

Fig. 12 Fine-grained, pyritic, carbonaceous, calcareous Upper Mannville sandstone from 2622 feet in the 5-20-40-6W4 well. Porosity 19.3%. Permeability 0.91 md.

(A) SEM micrograph showing authigenic pyrite cubes. 1μ scale divisions.

(B) Micrograph of carbonaceous fragments showing regularly spaced elongated internal pores. Plane light, X 60.

(C) SEM micrograph showing a carbonaceous fragment with pores. 10μ scale divisions.

(D) Detail of the pores shown in (C). 10μ scale divisions.

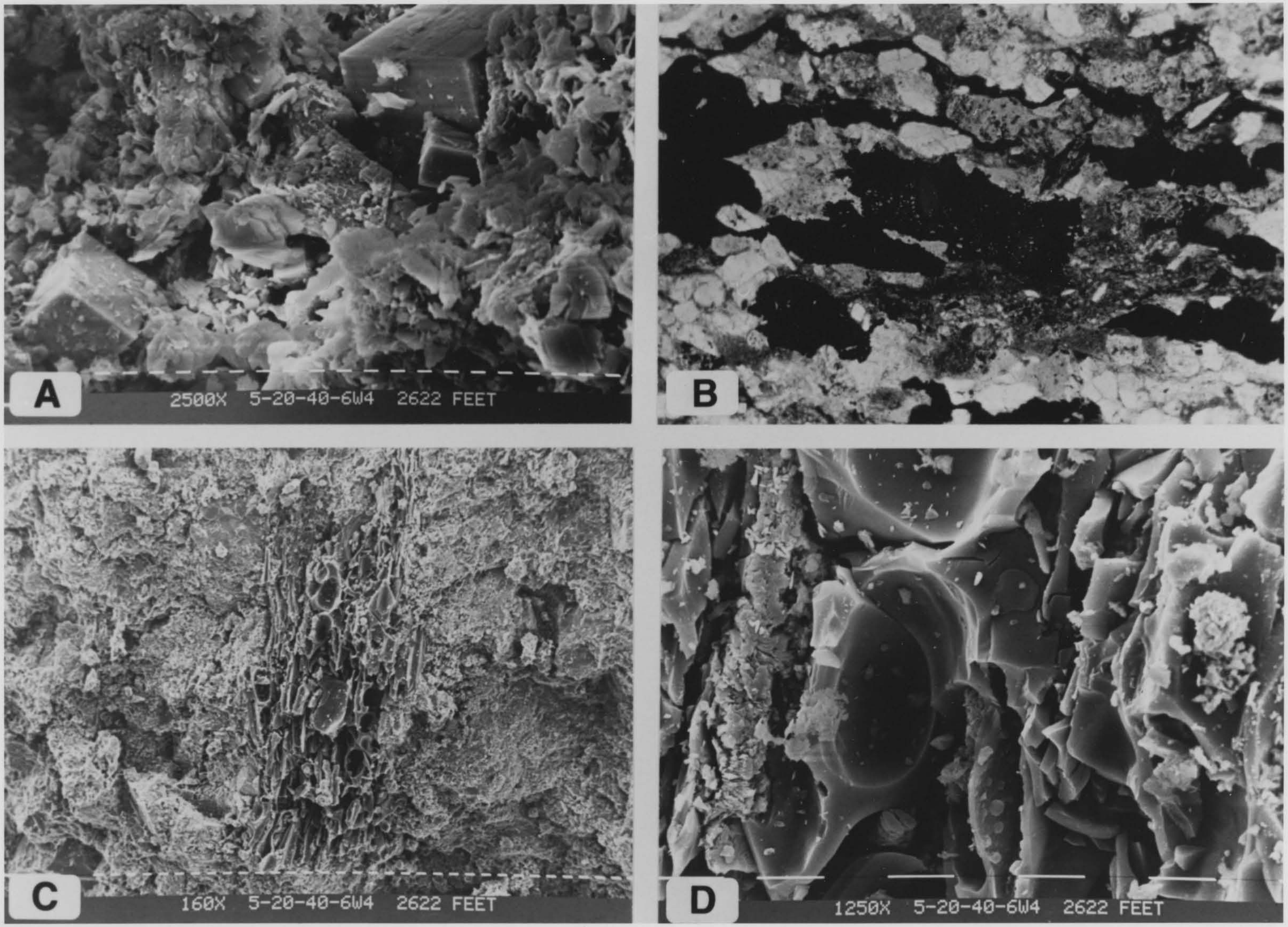

A
2500X 5-20-40-6W4 2622 FEET
B
C
160X 5-20-40-6W4 2622 FEET
D
1250X 5-20-40-6W4 2622 FEET

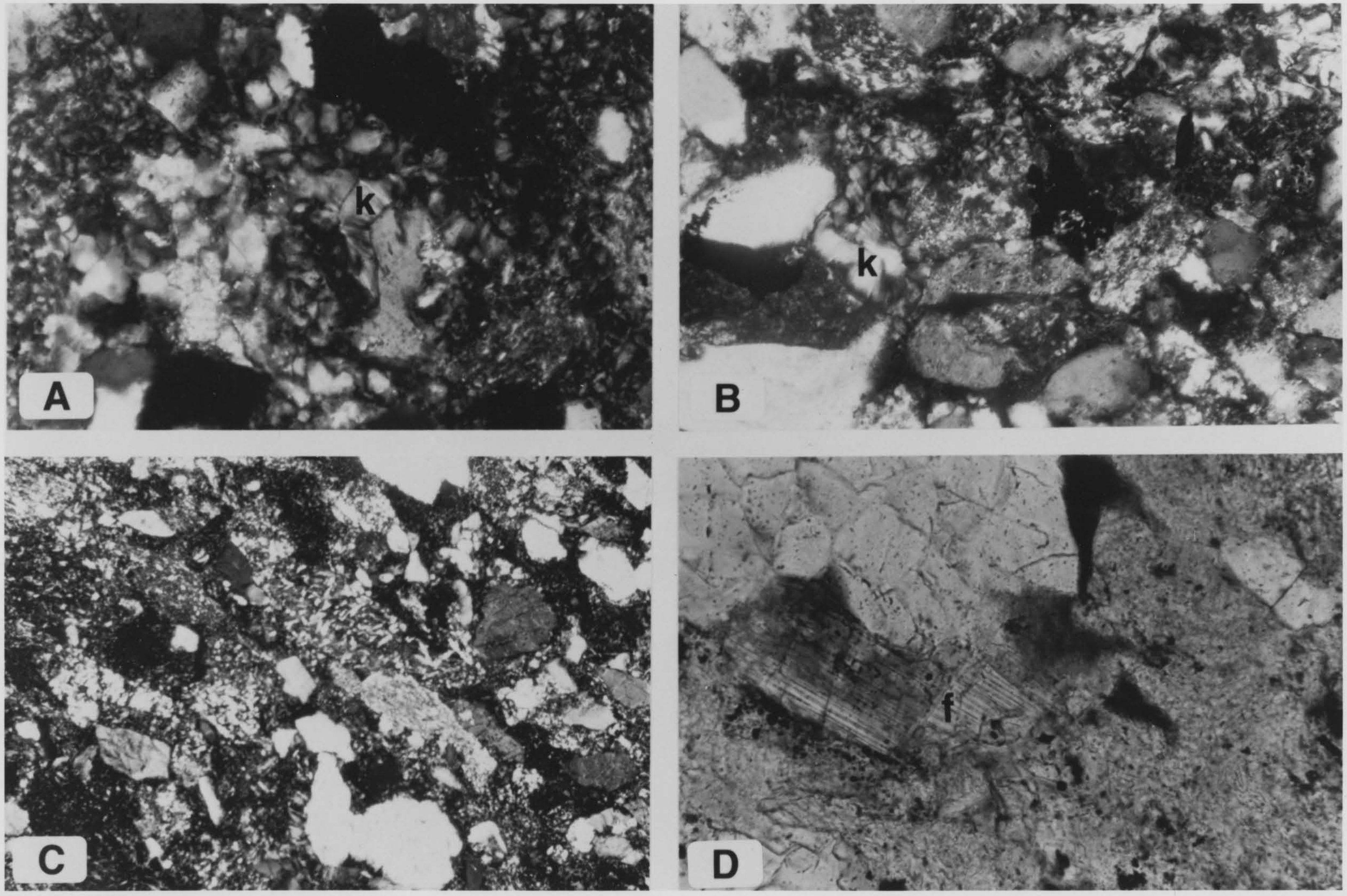
Fig. 13 Micrographs of fine-grained, pyritic, carbonaceous, calcareous Upper Mannville sandstones from 2622 feet (Porosity 19.3%. Permeability 0.91 md) and 2626 feet (Porosity 18.3%. Permeability 0.82 md) in the 5-20-40-6W4 well.

(A) Authigenic kaolinite (k) coating a quartz grain from 2622 feet. Crossed nicols, X250.

(B) Authigenic kaolinite (k) and pyrite (opaque grain near the center of the micrograph) from 2622 feet. Quartz, chert, feldspar and sedimentary rock fragments can also be seen. Crossed nicols, X 160.

(C) General texture of the sample from 2626 feet showing quartz, feldspar and volcanic and sedimentary rock fragments. Crossed nicols, X 60.

(D) A dissolving feldspar grain (f) that has developed a microfault (just above the letter 'f') from compactional forces. Sample from 2626 feet. Plane light, X 250.


k
A
k
B
C
f
D

Detrital clay minerals were rarely seen in thin section and could not be optically identified due to their small size and poor crystallinity. Five shale samples were taken between depths of 2635 and 2654 feet in the 5-20-40-6W4 well to determine the detrital clay mineralogy. These shales would lack the permeability, depth of burial and temperature necessary for a significant change in detrital clay mineralogy. Techniques used in sample preparation and analysis are given in Chapter II. Only kaolinite and illite clay minerals were identified on XRD traces although the machine was not set up for identifying low 2θ angle minerals like montmorillonite. Kaolinite/illite ratios decreased from 1.2 at 2654 feet to 0.82 at 2640 feet and increased to 2.9 at 2635 feet. Kaolinite XRD peaks are generally sharper than illite peaks.

Non-opaque heavy minerals are rare but include tourmaline and apatite (Fig. 16d).

Carbonaceous fragments occur in many of the sandstone units but their abundance is only very locally significant (Fig. 12b). These fragments are normally elongated parallel to bedding and have irregular boundaries that are penetrated by quartz grains.

Chemical constituents

Pyrite constitutes a few percent of most of the observed sandstones. It exceeds 7% in abundance at the top of the 5-20-40-6W4 well where it is associated with minor magnetite and chalcopyrite. It is often found as individual euhedral crystals (Fig. 16c) or as framboidal aggregates which have irregular boundaries due to the small protruding crystals of pyrite.

Calcite is present in a few of the sandstones where it has a patchy distribution (Fig. 17a). It is often found corroding quartz grains.

Quartz overgrowths are very common and are shown by rare "dust rims" (Fig. 19a) or flat grain boundaries on quartz grains (Fig. 16a) but they probably never constitute more than 5% of the rock volume.

Authigenic kaolinite was found as large radiating booklets consuming pore space (Figs. 13a, 13b, 16c, 17a, 17b) or as fine masses replacing feldspar grains. Several grains of glauconite were found in thin sections of the Glauconitic Sandstone.

Provenance

A general change in the proportion of the type of framework grains is seen from the Lower to the Upper Mannville (Fig. 9). The sandstones in the Lower Mannville are very quartzose while Upper Mannville sandstones contain large amounts of rock fragments. The nature of the rock fragments changes upsection also as increasing amounts of volcanic rock fragments accompany the sedimentary rock fragments.

The increasing proportion of lithic constituents in the Upper Mannville was probably produced by orogenic activity to the west which uplifted strata to provide sedimentary, volcanic and metamorphic rock sources for the sediments.

Chert fragments are especially abundant among these Upper Mannville sedimentary rock fragments. Pettijohn et al. (1973) noted the abundance of chert produced by the erosion of a carbonate terrain of moderately low relief in a humid climate. Local highs would have been minor in relief during Mannville time and would have consisted of Mississippian and Devonian carbonates. This along with the warm-temperate to subtropical and humid climate of Alberta during Mannville time as postulated by Singh (1964) could explain the abundance of chert in the sands.

Such a climate would likely produce kaolinitic soils which would account for the detrital kaolinite. The detrital illite is probably from weathered muscovite or from pre-existing sedimentary illite.

Feldspar is consistently deposited in moderate amounts. The Canadian Shield likely provided feldspar from the east while the erosion of uplifted volcanic strata to the west during Upper Mannville time probably contributed to this source.

CHAPTER V

DIAGENESIS

The Formation and Alteration of Clay Minerals

Sedimentary clay minerals are very small (often less than 2μ), layered aluminosilicates which generally consist of the following groups: the kaolinite group, the montmorillonoid or smectite group, the illite group, the chlorite group and the vermiculite group. These minerals can form from the weathering of a silicate rock by the action of soil waters which chemically decompose the parent silicate rock. The nature of the clays formed through this process depends on the mineral composition of the parent rock, the chemical composition of the pore water and the rate of passage of this water through the rock (Berner, 1971). Kaolinite and montmorillonite form by crystal growth from weathering products, illite is generally from pre-existing sedimentary illite or the partial weathering of muscovite, and chlorite is generally from pre-existing chlorite or the weathering of biotite (Keller, 1970).

Kaolinite formation is enhanced in a humid, tropical climate, while montmorillonite formation is enhanced in a semi-arid climate (Table 1). Chlorite formation is aided where chemical weathering effects are minimal (i.e. a cool and dry climate) (Keller, 1970).

Table 1. Comparison of geochemical environments for primary kaolinite and montmorillonite formation (after Keller, 1970).

KAOLINITE	MONTMORILLONITE
(1) Removal of Ca^{++}, Mg^{++}, Fe^{++}, Na^{+}, K^{+} (a) precipitation exceeds evaporation (b) permeable rocks (c) percolating water (d) oxidation of Fe^{++} to Fe_2O_3 or formation of FeS_2	(1) Retention of Ca^{++}, Mg^{++}, Fe^{++}, Na^{+} (a) evaporation exceeds precipitation (b) low effective permeability (c) stagnant water and water logging (d) Fe^{++} not combined with O^{--} or S^{--}
(2) Addition of H^{+} (a) fresh water (b) acids	(2) High HCO_3^{-} (a) alkalinity
(3) High Al:Si ratio (a) removal of silica through ground-water flow and formation of other minerals. (b) high concentration of Al^{+++} in acid solution	(3) Retention of silica (a) ineffective leaching (b) flocculated by Ca^{++}, Mg^{++} and other cations

No significant changes in clay mineralogy have been shown to occur during the processes of erosion, transportation and deposition of detrital clay minerals. After burial, alteration of detrital clays and the formation of authigenic clays can occur in response to changes in temperature, pressure and/or pore fluids. The criteria listed in table 1 for the formation of kaolinite and montmorillonite are as applicable to the process of weathering as they are throughout the entire history of the sediments.

Observed diagenetic features

Compaction features

Observed compaction features include the rotation of grains, the deformation of ductile grains and the fracturing of brittle grains. Concavo-convex and straight grain contacts could not be definitely attributed to pressure solution effects.

Grain slippage and rotation can be the most important mechanism of compaction to depths of 3000 to 4500 feet in quartzose sandstones lacking ductile grains (Füchtbauer, 1974). Evidence of this mechanism can be difficult to distinguish from the original fabric of the sandstone. Slippage and rotation of grains appears to be an important method of compaction in the Ellerslie Sandstone where the average number of contacts per grain is locally high (Fig. 19a).

Figure 19a also illustrates the deformation of a ductile (mica) grain. Rock fragments often become deformed into intergranular pores forming a 'pseudomatrix'. Carbonaceous fragments (Fig. 12b) are often deformed by more competent framework grains. Ductile grain deformation is an important mechanism of porosity reduction that is a function of the type and amount of ductile grains. This mechanism would be especially important in the Upper Mannville sediments.

Brittle grain deformation was observed in a few feldspar grains as microfaulting (Fig. 13d) and fracturing. This mechanism of compaction is of minor importance generally, as well as in the Mannville sandstones.

Authigenic cements and replacements features

Authigenic cements include quartz, kaolinite, pyrite and calcite. Detailed petrographic descriptions of these cements can be found in Chapter IV. Other clay mineral cements appeared to be very minor in abundance and were not identifiable due to their poor crystallinity.

Quartz occurs ubiquitously as overgrowths on quartz grains in the sandstones examined (Figs. 10c, 14a, b, 16a, 19a, c). Some of the silica was precipitated in the form of a meniscus cement between framework grains in the Ellerslie Sandstone (Fig. 19c). The dissolution of quartz overgrowths was observed in one sample from the Upper Mannville

(Fig. 14). Both blades of kaolinite and hexagonal imprints in the surface of the overgrowths were generally observed.

Authigenic kaolinite grains were also found throughout the section. All of the SEM samples showed kaolinite grains of varying sizes (Figs. 10c, d, 11a, b, 12d, 14b, 15c, 16b, 18) but petrographic identification was only possible with large grains of the mineral (Figs. 13a, b, 16c, d, 17a, b).

Cubic pyrite crystals were recognized in only one SEM sample (Fig. 12a) although most thin sections showed some pyrite (Figs. 13b, 16c).

Rhombehedral calcite crystals were seen in only one SEM sample from the top of the 5-20-40-6W4 core. Thin sections and the core itself showed that the cement is sparsely distributed in most sandstones above the Ellerslie Sandstone. Sandstones of the Glauconite Sandstone and the Calcareous Member show calcite cement consuming virtually all the available pore space and replacing margins of quartz and feldspar grains (Fig. 17a).

Secondary porosity

The diagenetic processes considered so far reduce primary (intergranular) porosity. Secondary porosity in sandstones results mainly from the dissolution of carbonate during effective burial (mesodiagenesis) (Schmidt and McDonald, 1979a). Petrographic criteria for the recognition of secondary sandstone porosity are listed in Hayes (1979) and Schmidt and McDonald (1979b). Observed secondary porosity textures

Fig. 14 SEM micrographs of a porous Upper Mannville sandstone from 2749 feet in the 5-1-40-7W4 well.

(A) Low magnification micrograph illustrating the well-sorted nature of the sandstone and the abundance of pore space and quartz overgrowths. 10μ scale divisions.

(B) A close-up of one of the grains in (A) showing the large percentage of the grain covered by quartz overgrowths. 10μ scale divisions.

(C) Dissolution of quartz overgrowths. 1μ scale divisions.

(D) Detail of (B) showing dissolution of the quartz overgrowths. 1μ scale divisions.

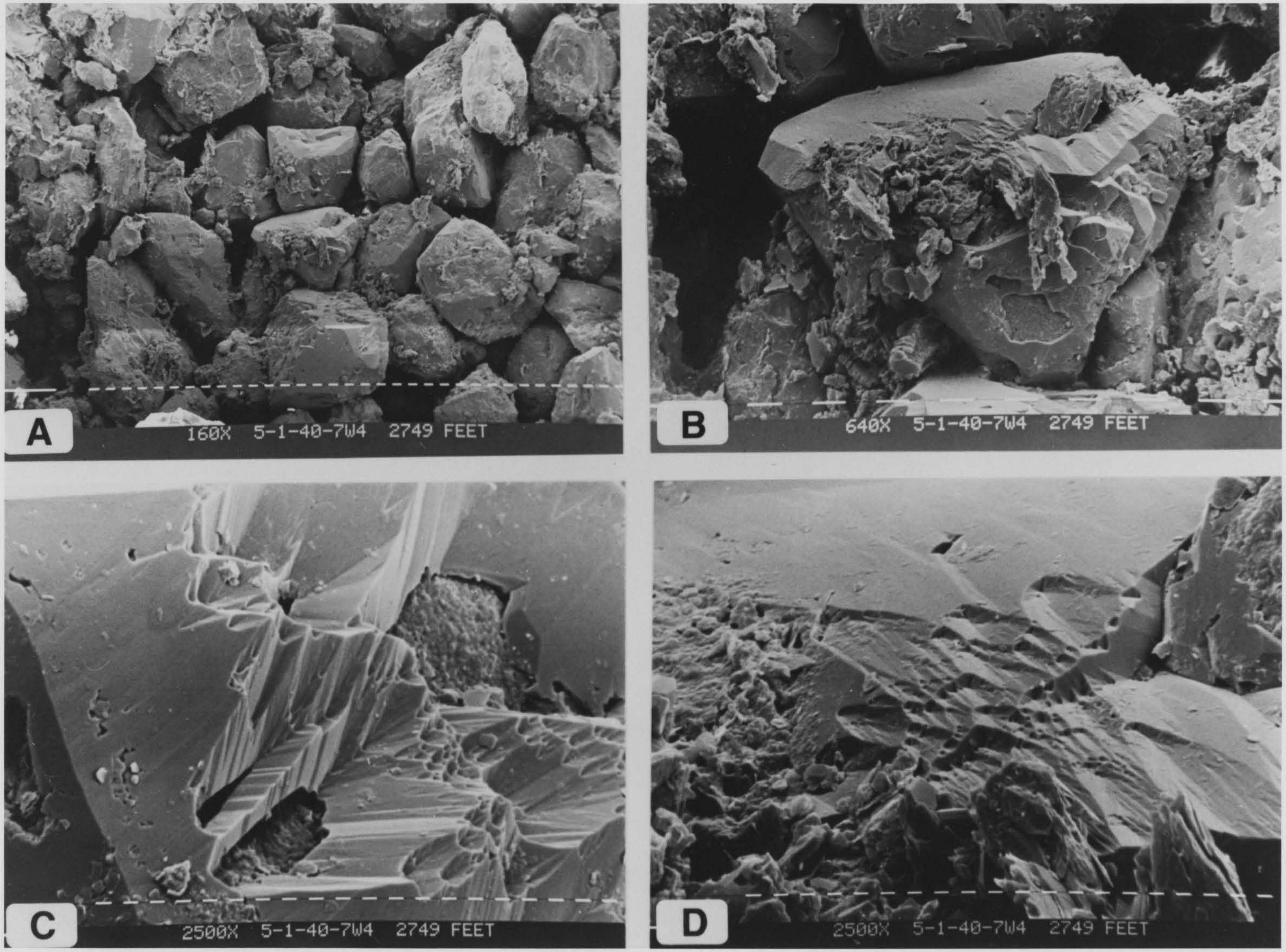

A
160X 5-1-40-7W4 2749 FEET
B
640X 5-1-40-7W4 2749 FEET
C
2500X 5-1-40-7W4 2749 FEET
D
2500X 5-1-40-7W4 2749 FEET

Fig. 15 SEM micrographs showing some peculiar textures of dissolving feldspar grains in the Upper Mannville sandstone at 2749 feet in the 5-1-40-7W4 well. Energy dispersive X-ray analysis of several points on each of these grains indicated a plagioclase composition. The author is still unconvinced that these are feldspar grains.

(A) Indistinct dissolving feldspar grain at the center of the micrograph. 10μ scale divisions.

(B) Detail of the dissolving feldspar grain in (A). 1μ scale divisions.

(C) Platey dissolving feldspar grain. 10μ scale divisions.

(D) Detail of the dissolving grain in (C). 1μ scale divisions.

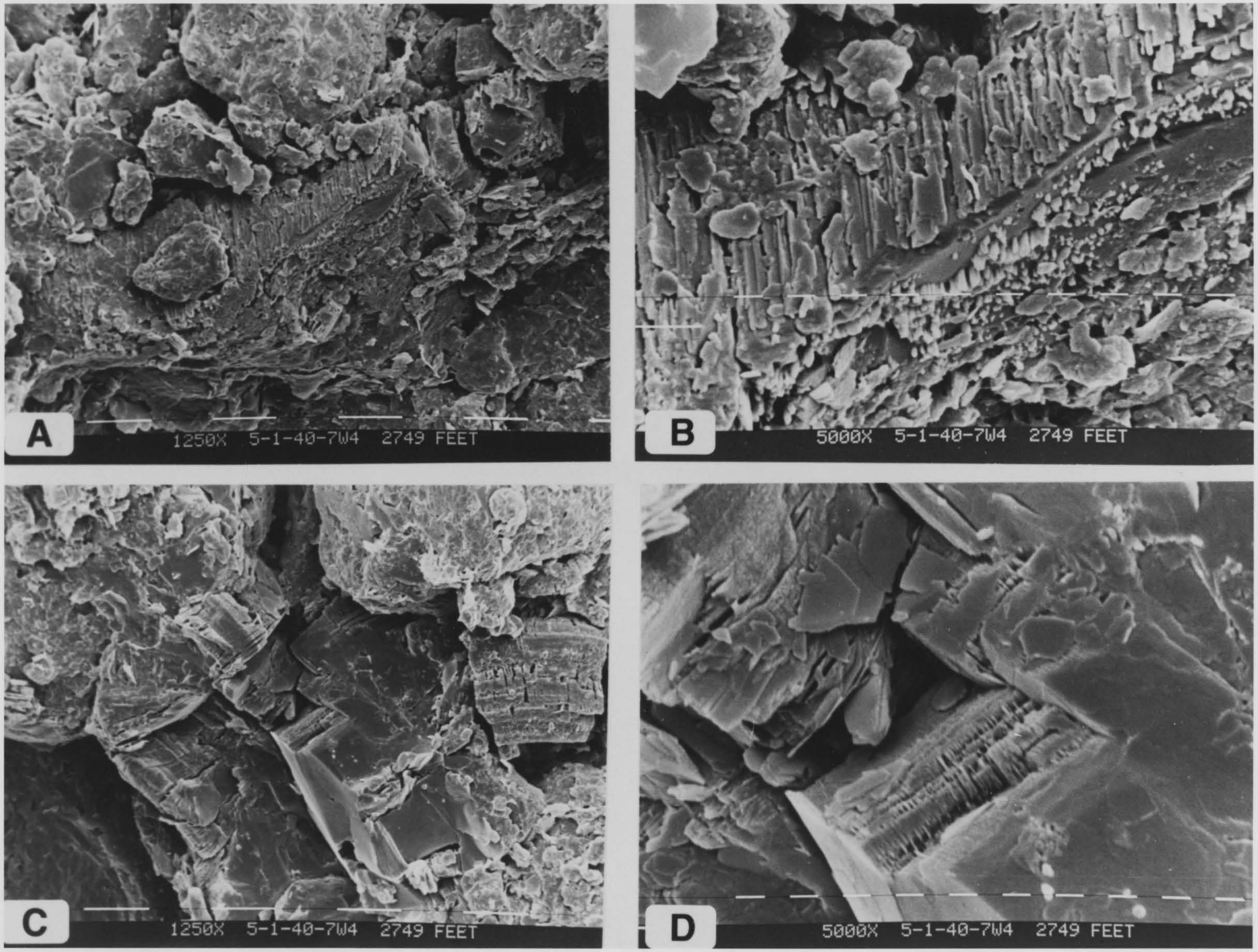

A
1250X 5-1-40-7W4 2749 FEET
B
5000X 5-1-40-7W4 2749 FEET
C
1250X 5-1-40-7W4 2749 FEET
D
5000X 5-1-40-7W4 2749 FEET

Fig. 16 Micrographs from the top of the Glauconitic Sandstone at 2644 feet in the 5-20-40-6W4 well. Porosity 23.9%. Permeability 21.9 md.

(A) Micrograph showing the dissolution of a feldspar grain (right center) resulting in the ragged edge of the grain. The straight edge boundaries of neighboring quartz grains indicate quartz overgrowths. Plane light, X 400.

(B) SEM micrograph showing the cavity probably resulting from the dissolution of a feldspar grain. Authigenic quartz overgrowths and kaolinite grains are also visible. 10μ scale divisions.

(C) Micrograph of authigenic kaolinite (k) and pyrite cubes (near the center). Plane light, X 250.

(D) Micrograph of an apatite (a) crystal (center) beside authigenic kaolinite booklets (k). Crossed nicols, X 250.

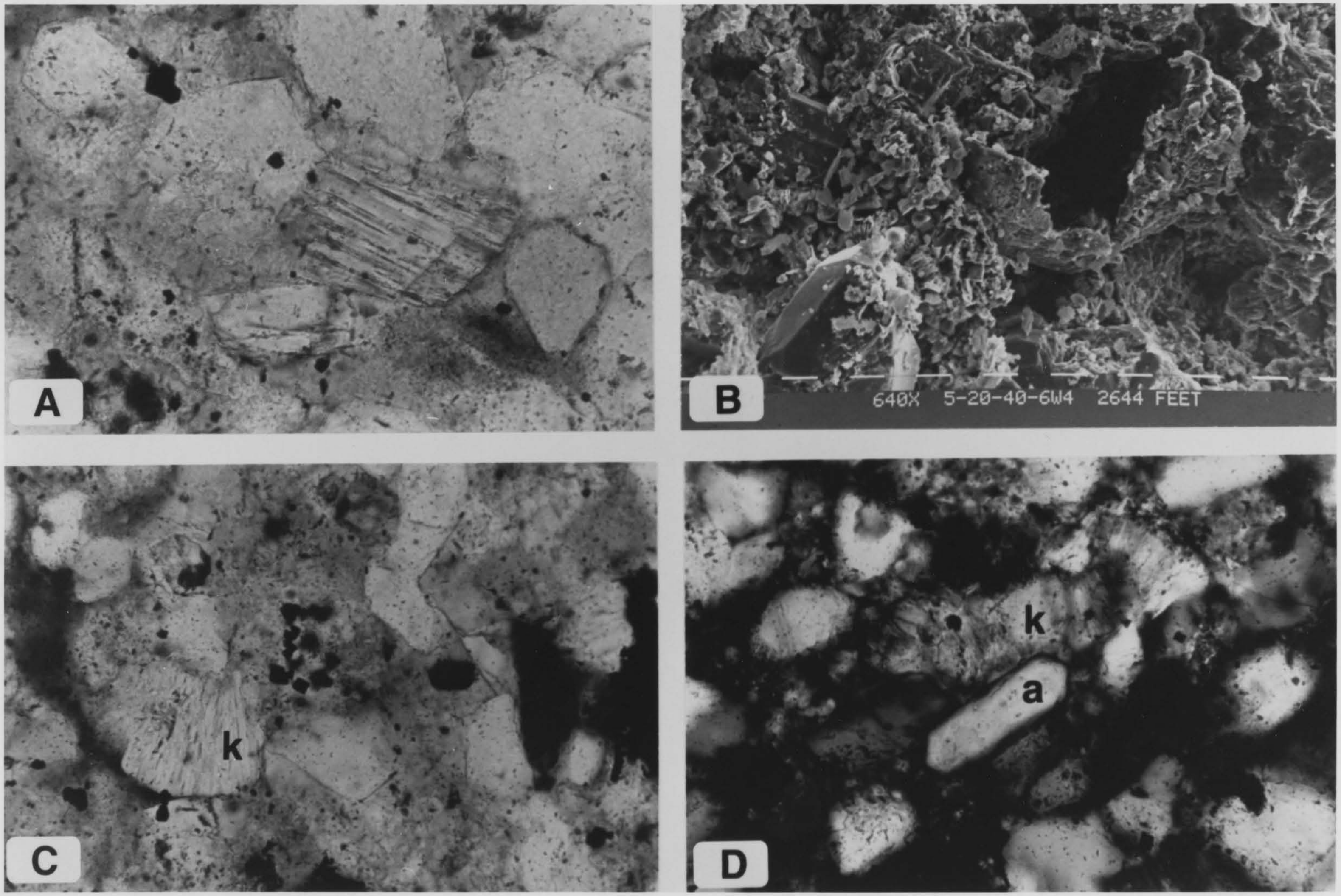

A
B
640X 5-20-40-6W4 2644 FEET
C
k
D
k
a

Fig. 17 Micrographs of features in the Glauconitic Sandstone from 2645 and 2646 feet in the 5-20-40-6W4 well. (A) and (B) are from 2645 feet while (C) and (D) are from 2646 feet. Porosity 15.7%, permeability 0.95 md at 2646 feet.

(A) Authigenic kaolinite (k) and calcite (c) cements in a sandstone with framework grains of quartz and chert. Crossed nicols, X 250.

(B) Radiating, pore-filling kaolinite crystals (k) amongst quartz and chert grains. Crossed nicols, X 160.

(C) Well developed secondary porosity in the Glauconitic Sandstone. Porosity appears grey in the micrograph and includes almost all of the intergrain area. Plane light, X 60.

(D) The center area of (C) showing rounded pores (p) as indicated by by shape of the matrix material (dark areas) and the framework grains. These large pores result from the dissolution of less stable framework grains (e.g. carbonate, feldspar and rock fragment grains). Plane light X 160.

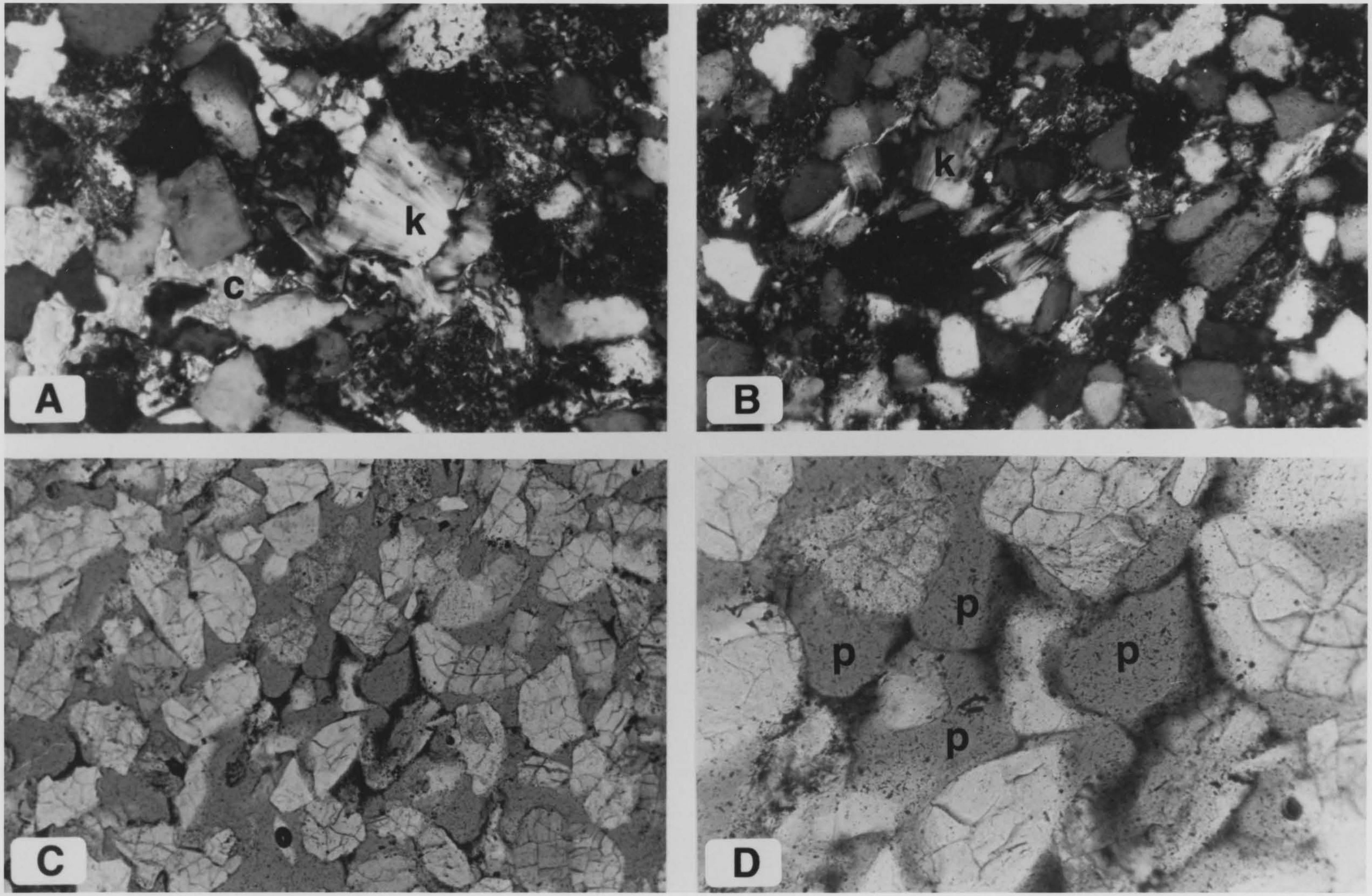

A
k
c
B
k
C
D
p
p
p
p

Fig. 18 SEM micrographs from a sandstone at 2660 feet in the Calcareous Member of the 5-20-40-6W4 well. Porosity 23.1%. Permeability 26.6 md.

(A) A general view of the sandstone showing definite pores. 10μ scale divisions.

(B) Detail of the dissolving feldspar grain in the center of (A). 1μ scale divisions.

(C) A large authigenic kaolinite grain (center) on a larger mica grain. 10μ scale divisions.

(D) Detail of the large kaolinite grain in (C). 1μ scale divisions.

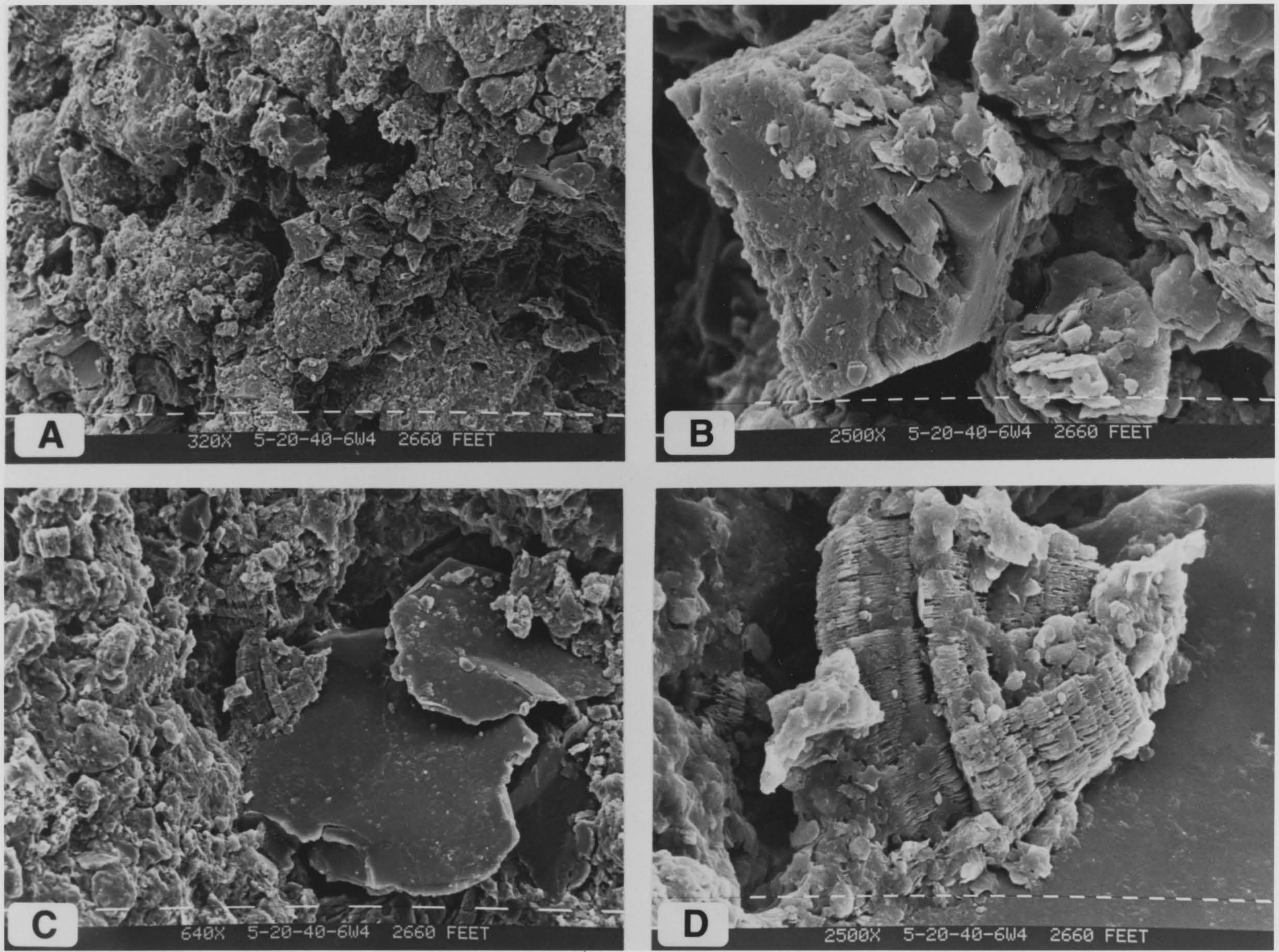

A
320X 5-20-40-6W4 2660 FEET
B
2500X 5-20-40-6W4 2660 FEET
C
640X 5-20-40-6W4 2660 FEET
D
2500X 5-20-40-6W4 2660 FEET

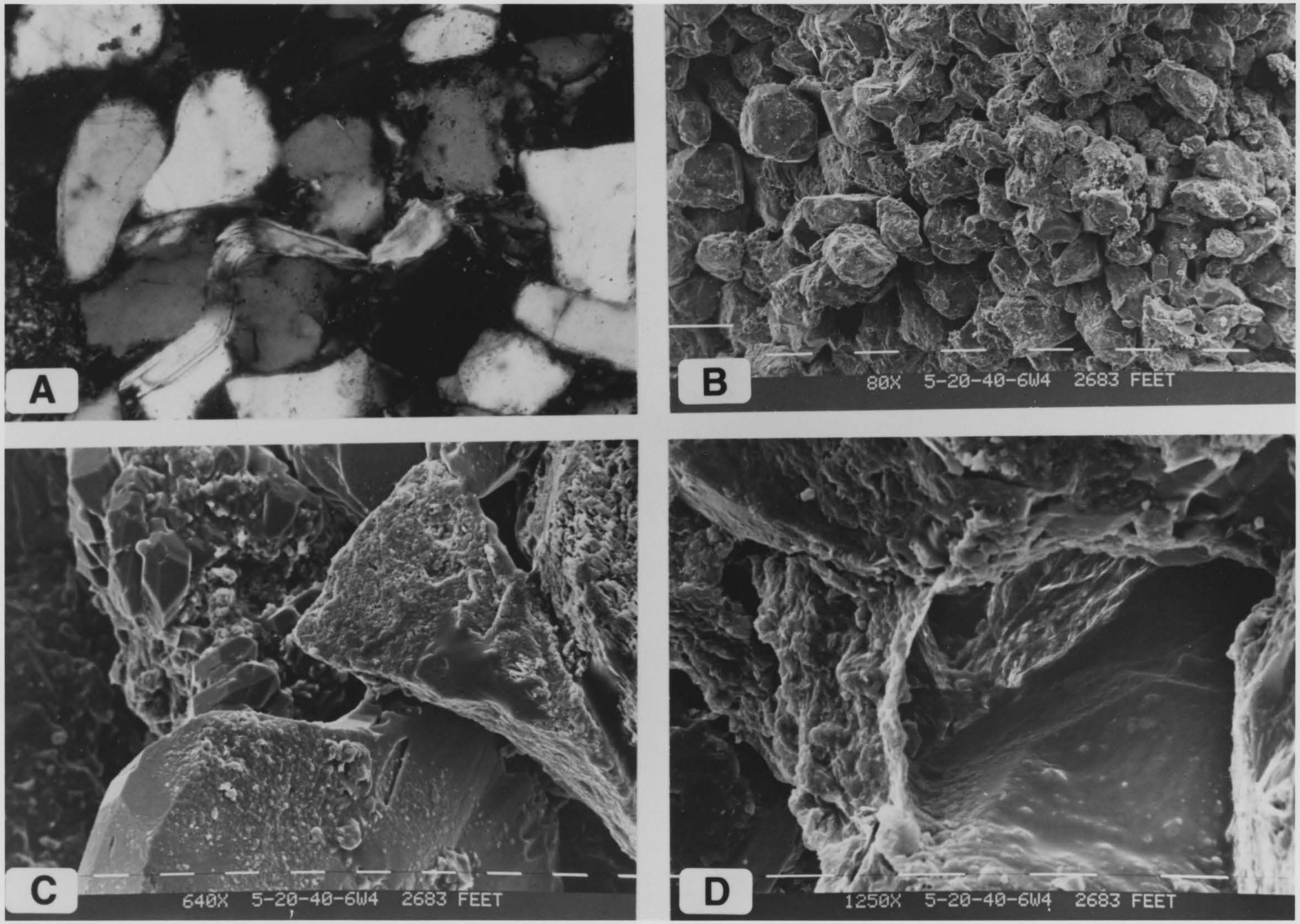
Fig. 19 Micrographs of the Ellerslie Sandstone at 2683 feet in the 5-20-40-6W4 well. Porosity 24.5%. Permeability 231. md.

(A) A muscovite grain deformed around more competent quartz grains. Crossed nicols, X 160.

(B) SEM micrograph showing the general texture of the sandstone and the large amount of pore space. 100μ scale divisions.

(C) Grain contacts with meniscus quartz cement probably formed by diffusion of silica in a water film around the grains while the sandstone was oil saturated. 10μ scale divisions.

(D) A large dissolution pore shown in the center of (B). Compare with Fig. 17d. 10μ scale divisions.


A
B
80X 5-20-40-6W4 2683 FEET
C
640X 5-20-40-6W4 2683 FEET
D
1250X 5-20-40-6W4 2683 FEET

include (1) the partial dissolution of calcite cement, (2) grain molds (Figs. 16b, 17d, 19d), (3) areas of open and close packing of detrital grains in the same sample, (4) oversized pores and (5) corroded grains (Figs. 10c, d, 11a, b, 13d, 14, 15, 16a, 18a, b).

Secondary porosity was best developed in the Ellerslie Sandstone and Glauconite Sandstone where porosity was high and oil was found.

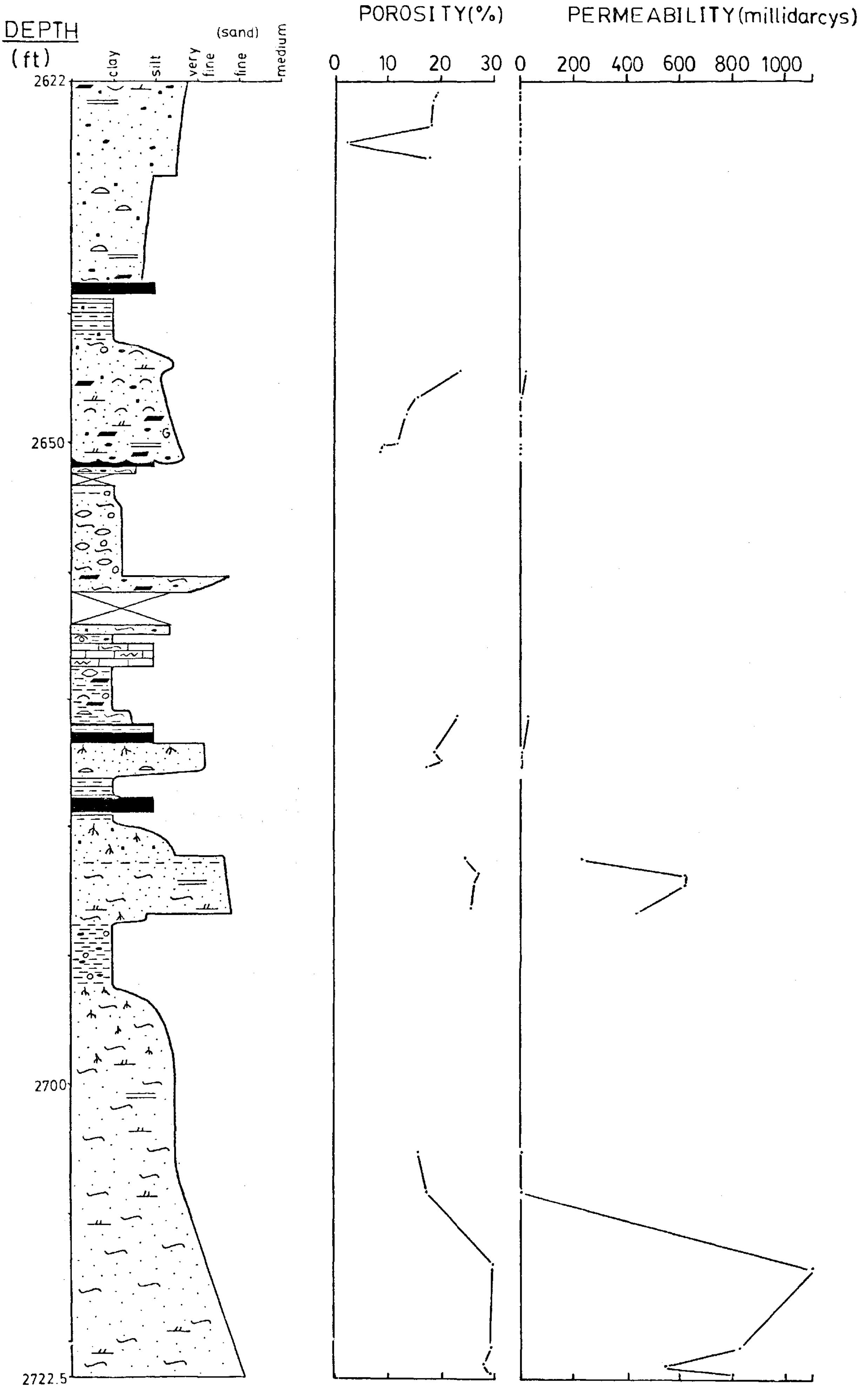
Interpreted Diagenetic Stages

The above diagenetic features are interpreted to have formed in the sequence shown in figure 20. Initially, the sandstones were compacted by the weight of overlying sediment and pyrite was formed from the bacterial decomposition of organic matter. After considerable burial quartz began to precipitate which hindered further compaction. Then calcite cement filled much of the available pore space. Pore waters then became acidic dissolving away feldspar and carbonate as kaolinite and quartz were simultaneously precipitated. This change in pore fluid chemistry was likely brought about by the process of coalification of coal units and carbonaceous matter. This process releases water with dissolved humic acid and carbon dioxide from the coal which creates an acid environment (Füchtbauer, 1967). The secondary porosity created would allow for a minor amount of further compaction. The emplacement of hydrocarbons into the pore space would halt diagenetic processes except where pore water remained (Fig. 19c).

Fig. 20. Schematic representation of interpreted diagenetic stages of the Mannville Group sandstones examined.

Diagenesis of sandstones is controlled by their detrital mineralogy, the pressure and temperature, the chemistry of the pore fluids and the rate with which these pore fluids move through the rock. Variations in diagenesis in the studied sandstones could result from changes in detrital mineralogy, pore fluid chemistry and/or flow rate of the fluid. Pressure and temperature variations would be negligible. The control of detrital mineralogy is simple - pyrite forms where bacterial decomposition takes place, feldspars dissolve only where feldspars are found, etc. The pore fluid chemistry probably did not vary greatly in the sandstones examined since diagenetic textures are so consistent vertically. The rate of passage of pore water through the sediments must have varied stratigraphically with permeability which now changes considerably between the Ellerslie Sandstone and the rest of the section (Fig. 21). In this way permeability is an indirect measure of the degree of diagenesis.

Fig. 21 Porosity and permeability plots for sandstones in the 5-20-40-6W4 core. Based on standard tests by Core Laboratory Canada Inc. on 25 plugs.


DEPTH (ft)
(sand)
clay
silt
very fine
fine
medium
2622
2650
2700
2722.5
G
POROSITY(%)
0 10 20 30
PERMEABILITY (millidarcys)
0 200 400 600 800 1000

CHAPTER VI

SUMMARY AND CONCLUSIONS

Evidence from three cores of the Mannville Group indicate that deposition occurred largely in a coastal environment. During the transgression of the Arctic Sea from the north, river carved valleys in central Alberta were drowned repeatedly. These oscillations of the sea are shown by the gradational and interfingering nature of the Lower Mannville - Upper Mannville contact.

The sandstones change from clean quartz sandstones at the base of the section to very lithic sandstones at the top. The lithic input in the sands of the Upper Mannville is a product of the uplifting of strata in the cordilleran region to the west.

The compaction of rock fragments and ductile grains in the Upper Mannville has greatly reduced the intergranular porosity and permeability there. The degree of diagenesis is largely a function of the permeability in these sandstones. The present permeability of the sandstones (Fig. 21) reflects the severity of diagenesis. Figure 20 summarizes the inferred diagenetic history of the sandstones.

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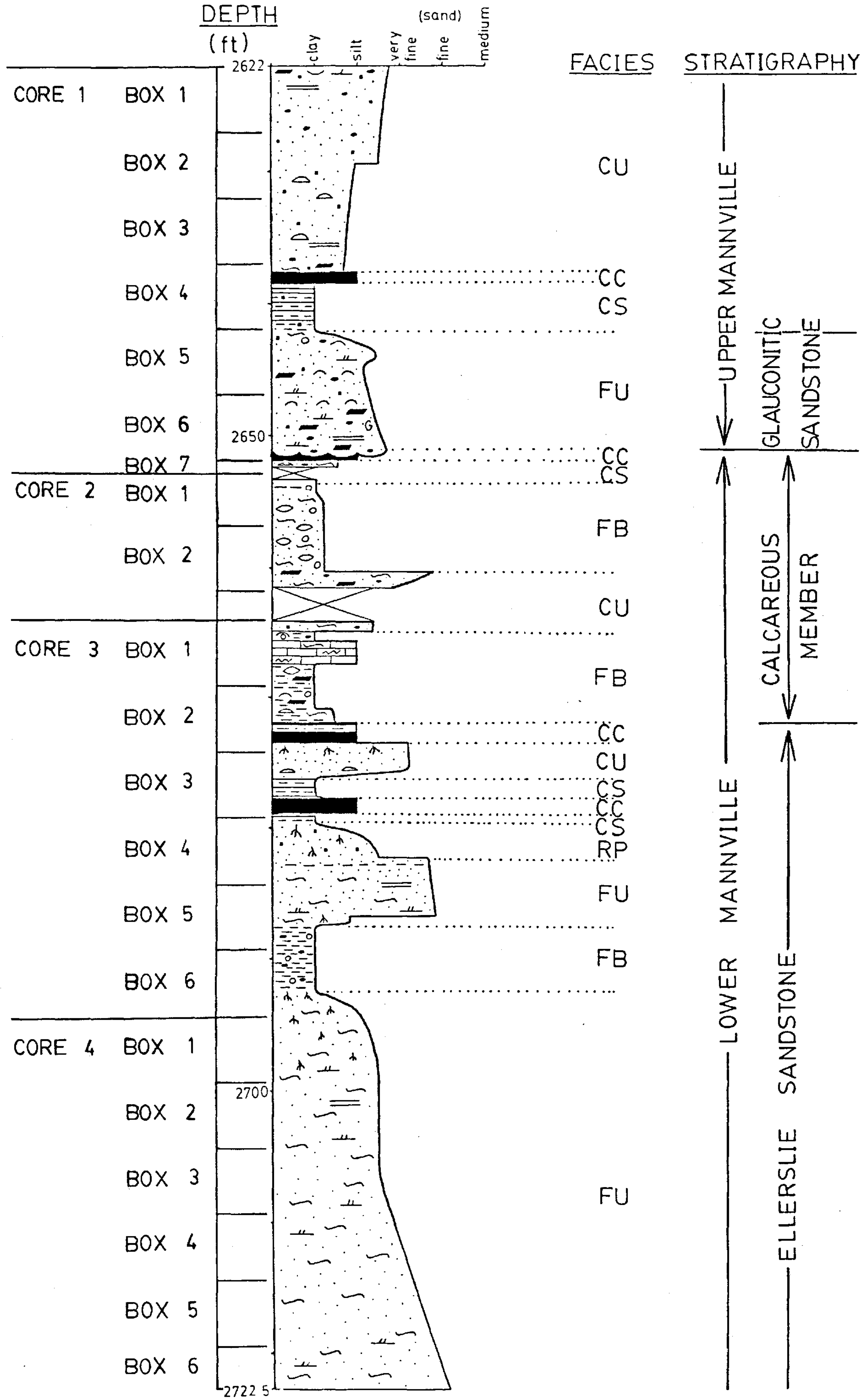
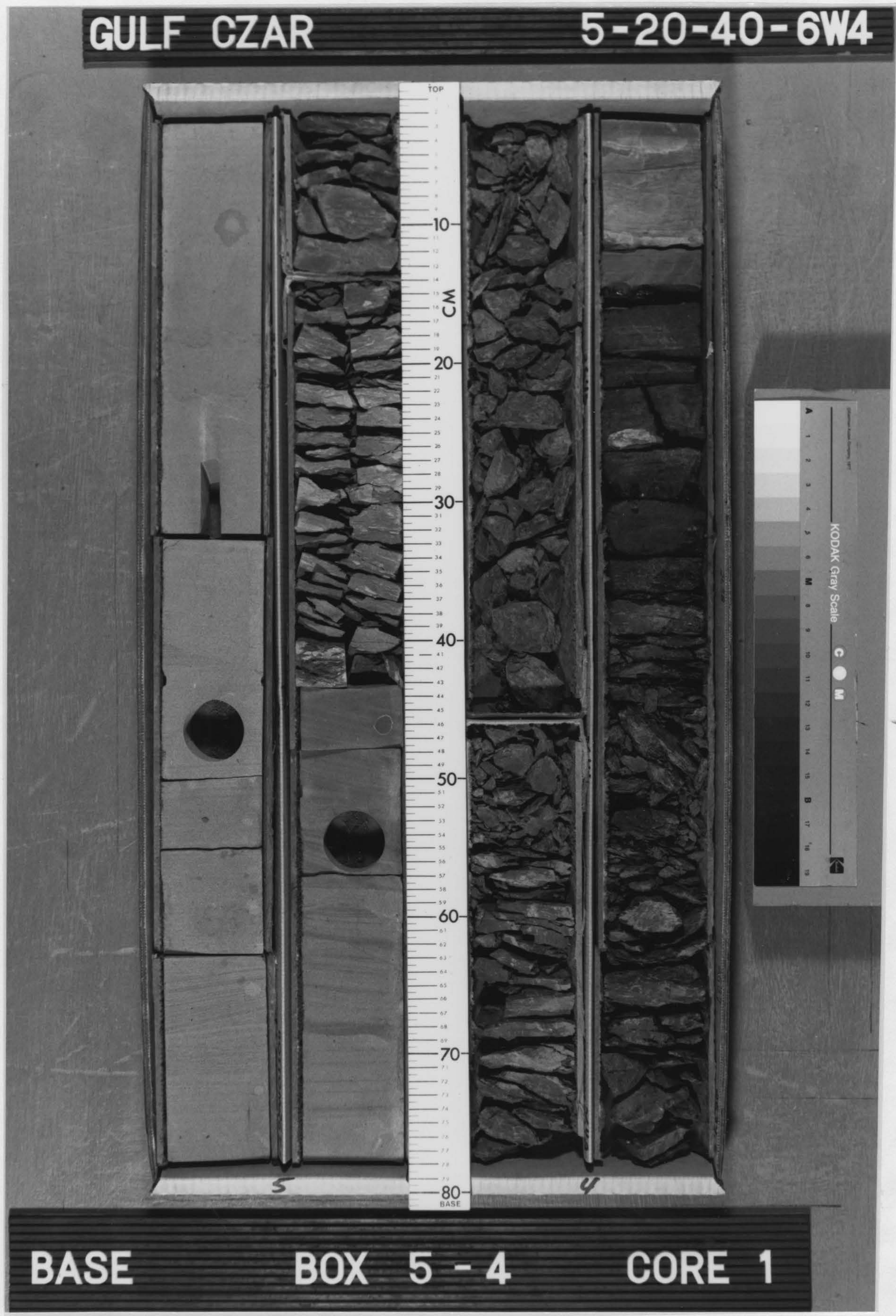
APPENDIX I

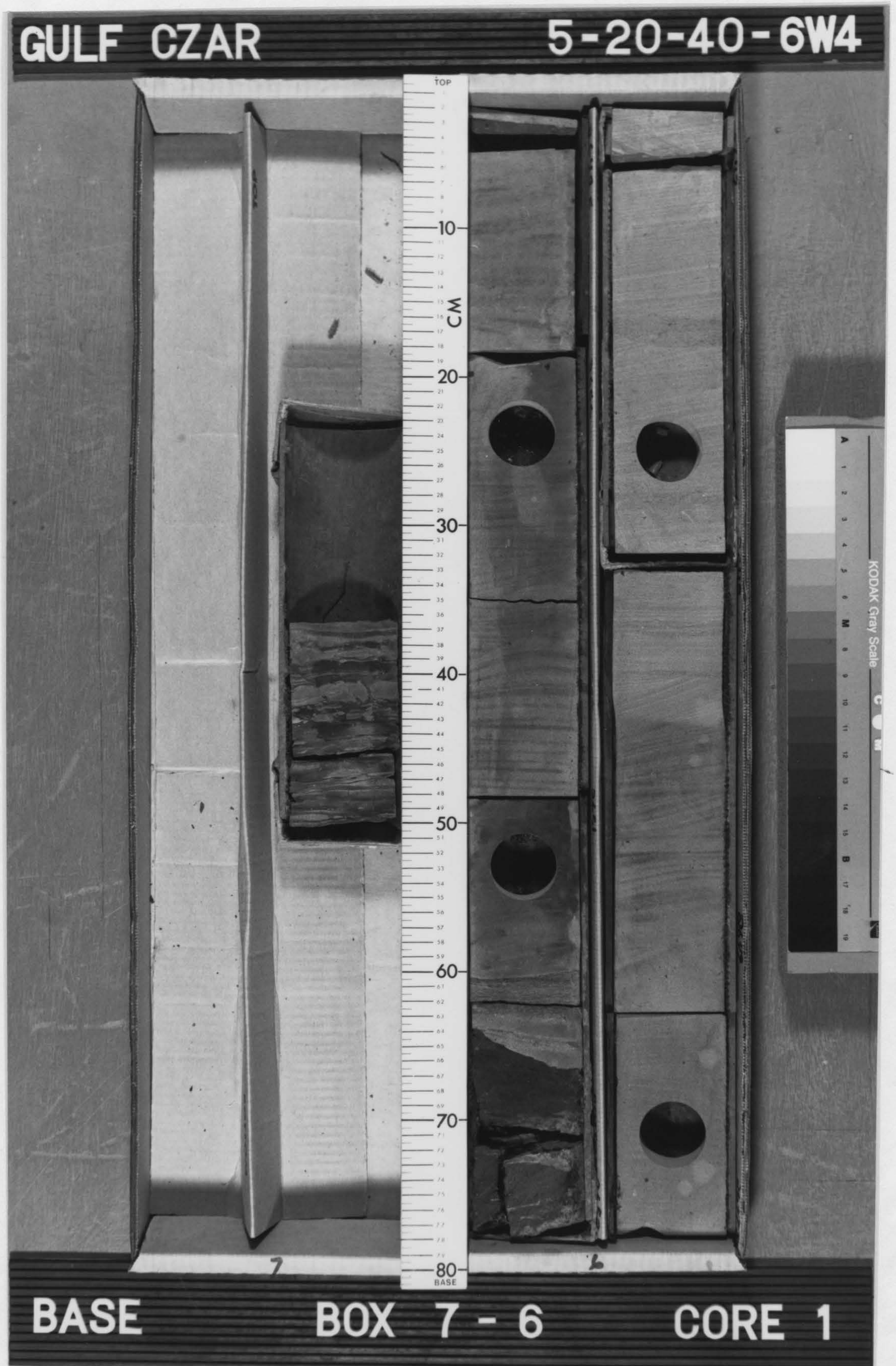
PHOTOGRAPHS OF THE 5-20-40-6W4 CORE

Fig. 22 Key to the core photographs. Core and box numbers refer to those numbers at the base of photos. Figure 5 lists the symbols shown in the stratigraphic column.

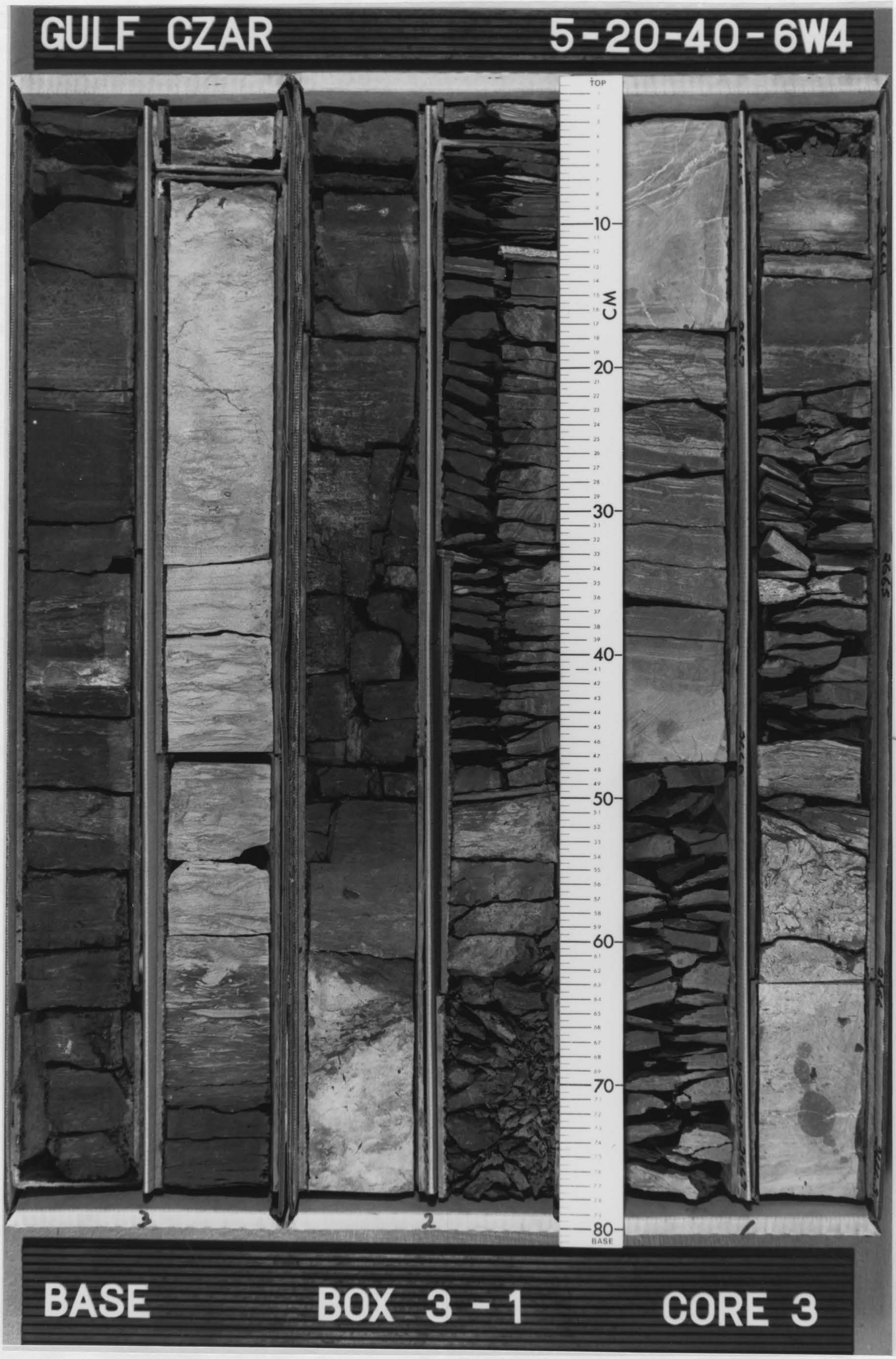

DEPTH
(ft)
(sand)
clay
silt
very fine
fine
medium
FACIES
STRATIGRAPHY
2622
2650
2700
2722.5
CORE 1
BOX 1
BOX 2
BOX 3
BOX 4
BOX 5
BOX 6
BOX 7
CORE 2
BOX 1
BOX 2
CORE 3
BOX 1
BOX 2
BOX 3
BOX 4
BOX 5
BOX 6
CORE 4
BOX 1
BOX 2
BOX 3
BOX 4
BOX 5
BOX 6
CU
CC
CS
FU
CC
CS
FB
CU
FB
CC
CU
CS
CC
CS
RP
FU
FB
FU
UPPER MANNVILLE
GLAUCONITIC SANDSTONE
CALCAREOUS MEMBER
LOWER MANNVILLE
ELLERSLIE SANDSTONE


GULF CZAR
5-20-40-6W4
TOP
CM
10
20
30
40
50
60
70
80
BASE
BOTTOM
BASE
BOX 3 - 1
CORE 1


GULF CZAR
5-20-40-6W4
TOP
CM
BASE
KODAK Gray Scale
5
4
BASE
BOX 5 - 4
CORE 1


GULF CZAR
5-20-40-6W4
BASE
BOX 7 - 6
CORE 1
KODAK Gray Scale


GULF CZAR
5-20-40-6W4
BASE
BOX 2 - 1
CORE 2
KODAK Gray Scale
BOTTOM
TOP
CM
BASE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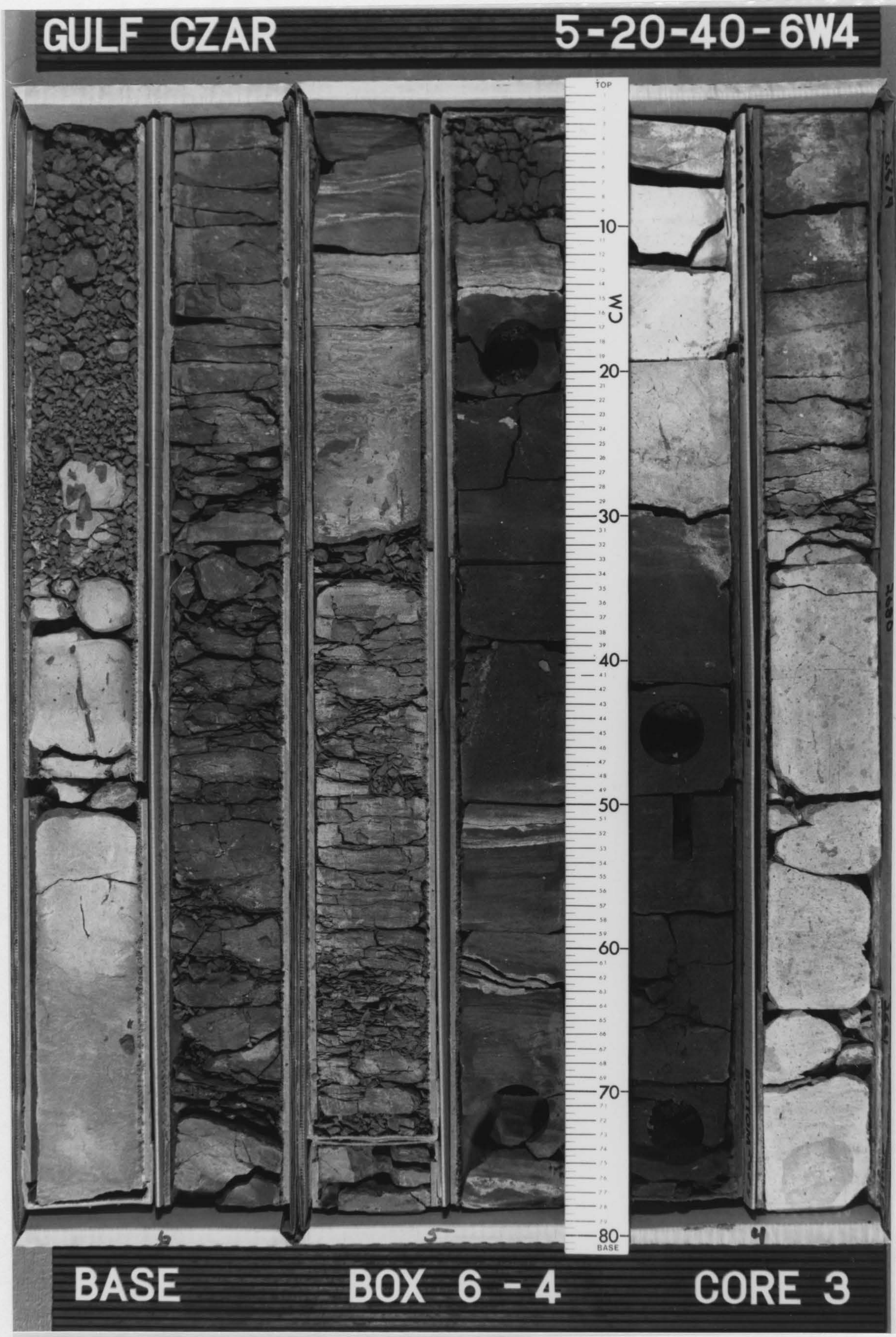
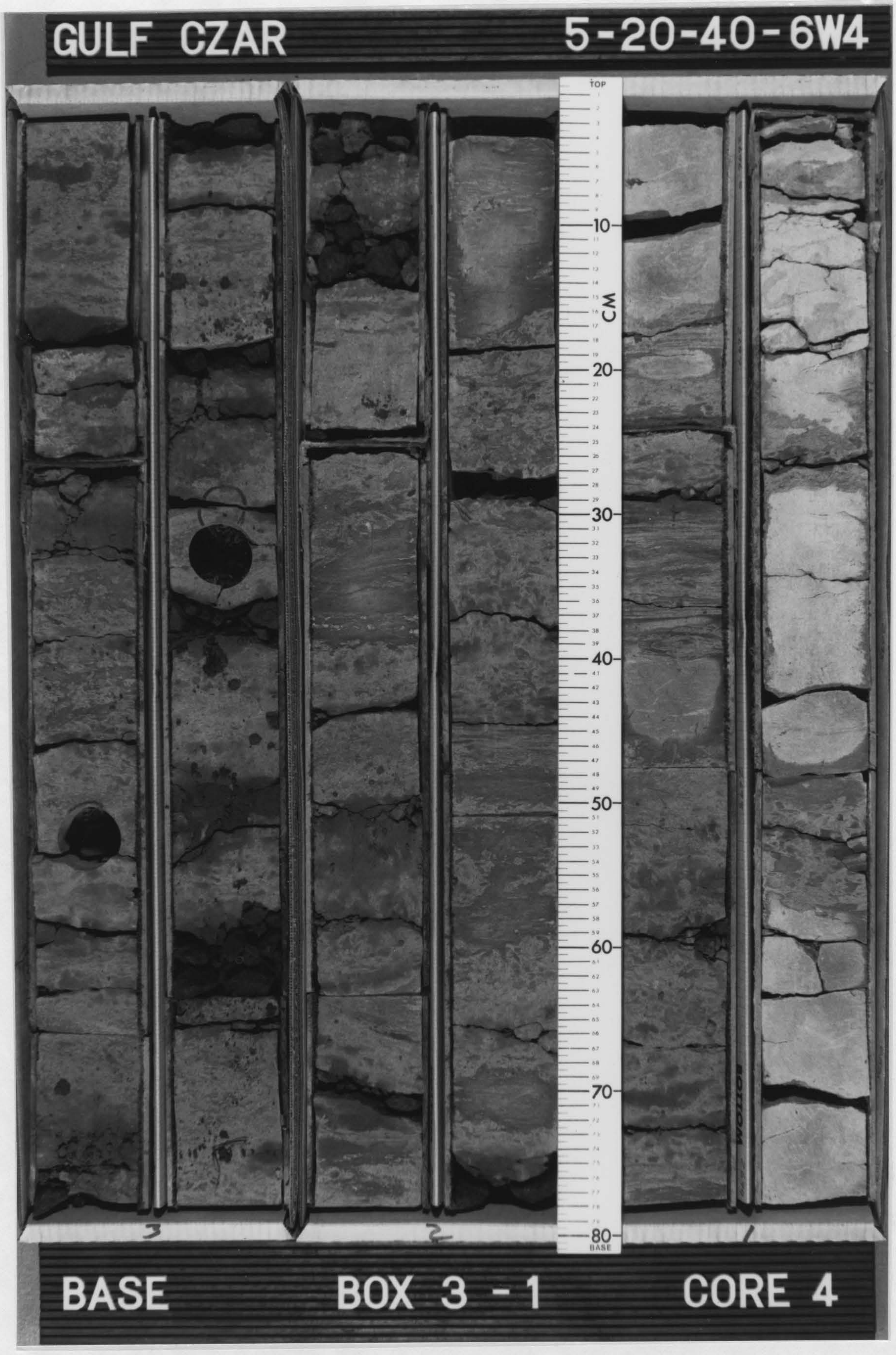
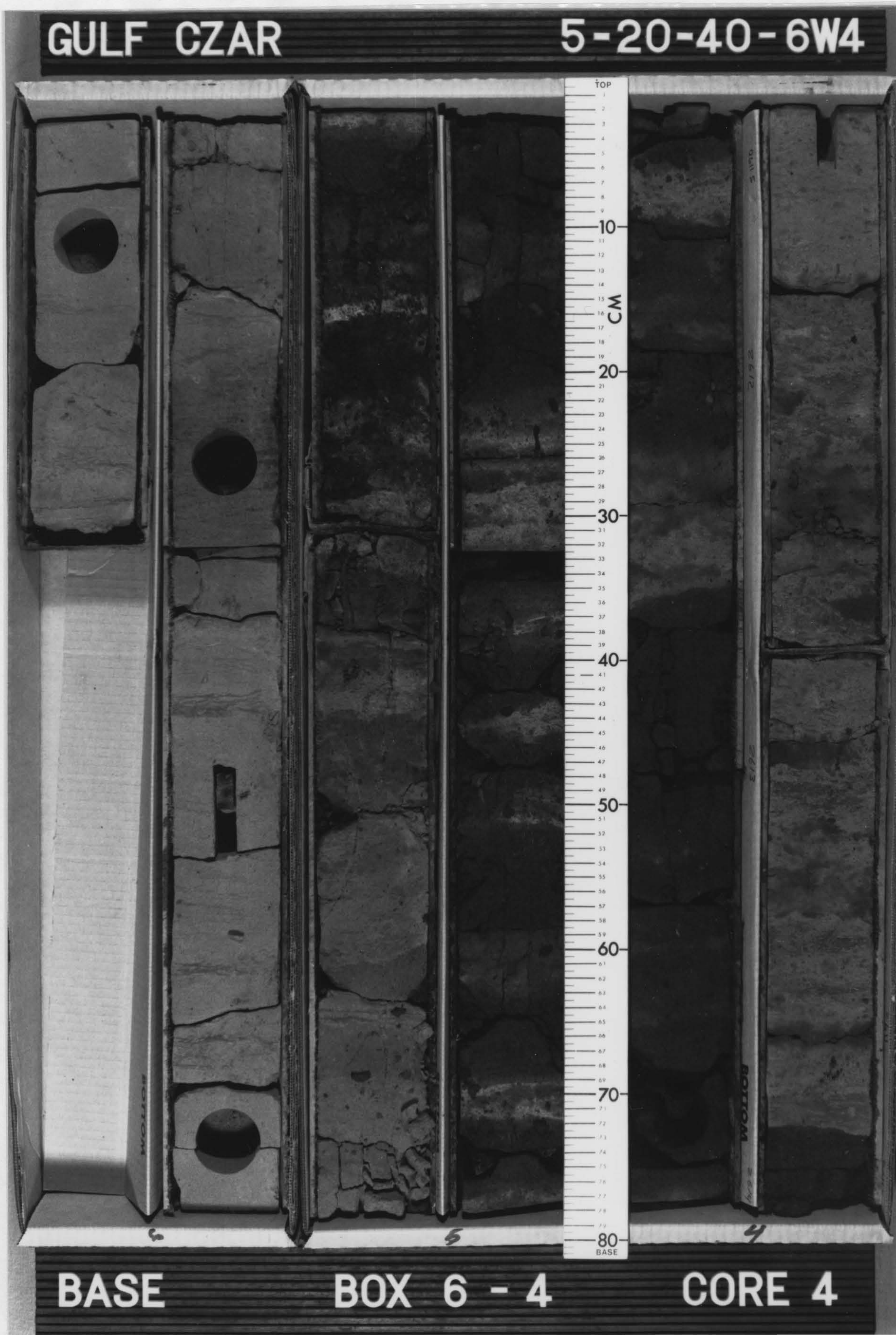
5-20-40-6W4
TOP
CM
BASE
BOX 3 - 1
CORE 3


GULF CZAR
5-20-40-6W4
BASE
BOX 6 - 4
CORE 3


GULF CZAR
5-20-40-6W4
TOP
10
20
30
40
50
60
70
80
CM
BASE
BOX 3 - 1
CORE 4


GULF CZAR
5-20-40-6W4
TOP
CM
BASE
BASE
BOX 6 - 4
CORE 4

APPENDIX II

SUMMARY OF POINT COUNT DATA

Table 2. Means and standard deviations of constituents in representative Mannville sandstones. (See figure 9). Data based on 6 traverses of 50 point counts each made on 12 thin sections. An asterisk (*) indicates porosity data based on Core Laboratory Canada Inc. standard tests. The column 'OTHER' includes matrix, cement, mica and accessory minerals. Q = quartz, Ch = chert, F = feldspar plus plutonic rock fragments, VRF = volcanic rock fragments, MRF = metamorphic rock fragments.

WELL	DEPTH (feet)	STRATIGRAPHY	Q	Ch	F	SRF	VRF	MRF	POROSITY	OTHER
4-32-41-5W4	2328	Upper Mannville	16.0 ±3.4	23.7 ±7.0	8.3 ±3.7	7.3 ±4.8	11.0 ±1.1	0 ±0	0	33.7
4-32-41-5W4	2362	Upper Mannville	16.0 ±6.1	34.0 ±9.0	9.7 ±3.7	2.7 ±1.6	15.7 ±4.8	0.7 ±1.6	5.3	16.0
5-1-40-7W4	2692	Upper Mannville	59.7 ±7.0	9.3 ±2.1	9.0 ±5.9	2.7 ±1.6	2.0 ±1.8	0 ±0	5.7	11.7
5-20-40-6W4	2623	Upper Mannville	22.0 ±6.2	8.7 ±1.0	4.3 ±2.9	15.7 ±2.7	0.3 ±0.5	0 ±0	19.3*	29.7
5-20-40-6W4	2628	Upper Mannville	25.3 ±5.0	21.7 ±4.6	1.5 ±1.7	25.7 ±6.9	0.3 ±0.8	0 ±0	18.1*	7.4
5-20-40-6W4	2646	Glauconitic Sandstone	66.0 ±6.1	2.3 ±1.5	0.7 ±1.0	1.3 ±1.6	0 ±0	0 ±0	15.7*	14.4
5-20-40-6W4	2650	Glauconitic Sandstone	28.3 ±8.2	0.3 ±0.8	0 ±0	18.7 ±3.5	0 ±0	0 ±0	8.9*	43.8
5-20-40-6W4	2660	Calcareous Member	52.3 ±5.4	2.3 ±1.5	2.0 ±2.5	13.0 ±7.2	0 ±0	0 ±0	23.1*	7.2
5-20-40-6W4	2674	Ellerslie Sandstone	52.3 ±4.5	21.3 ±8.7	1.3 ±1.0	4.7 ±1.0	0 ±0	0 ±0	20.3*	0
5-20-40-6W4	2682	Ellerslie Sandstone	80.7 ±7.6	2.7 ±2.1	2.3 ±1.5	1 ±1.7	0 ±0	0 ±0	13.3*	0
5-20-40-6W4	2709	Ellerslie Sandstone	57.7 ±5.1	3 ±2.1	0.7 ±1.0	2.7 ±1.6	0 ±0	0.3 ±0.8	17.1*	18.6
5-20-40-6W4	2721	Ellerslie Sandstone	63.7 ±7.5	2.7 ±2.1	1.3 ±1.0	2.3 ±1.5	0.3 ±0.8	0 ±0	28.4*	1.3