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Differences in Reservoir Characteristics of Marine and Nonmarine Sandstones of the Mesaverde Group, Northwestern Colorado

John C. Lorenz, Allan R. Sattler, Carol L. Stein

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ABSTRACT

Reservoir and rock properties change with the different diagenetic and depositional environments present in strata of the Cretaceous Mesaverde Group. These changes can be seen in the 4200 ft (1280 m) of core taken from the Mesaverde Group at the U.S. Department of Energy's Multiwell Experiment site, located in the Rulison field in the east-central part of the Piceance basin, northwestern Colorado. Comparative measurements of porosity, permeability, water saturation, Young's modulus, Poisson's ratio, compressive and tensile strengths, and fracture toughness suggest that variations in these petrophysical properties are controlled by petrologic changes, that are in turn a function of depositional and diagenetic environments. For example, sandstones deposited in high-energy marine environments are "cleaner" and therefore have uniform permeability distributions and high Young's Moduli. Sandstones formed in coal-bearing strata have irregularly distributed but generally higher porosity and permeability due to irregular nonmarine environments and the presence of organic acids during diagenesis.

ACKNOWLEDGMENTS

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DIFFERENCES IN RESERVOIR CHARACTERISTICS OF MARINE AND NONMARINE SANDSTONES OF THE MESAVERDE GROUP, NORTHWESTERN COLORADO

INTRODUCTION

Despite gross petrologic similarity, reservoir and rock properties in sandstones of the Mesaverde Group, northwestern Colorado, change significantly with changes in the environment in which the sandstones were deposited. The purpose of this report is to list and summarize the numerous petrophysical and reservoir properties that were made during the course of the US Department of Energy's Multiwell Experiment (MWX). These parameters were measured for input into specific tests and modeling efforts that were part of the experiment, but have not yet been compiled into one report for the record and for future use. This report also explores the basic petrological characteristics that underlie the differences in the petrophysical and reservoir properties, and discusses the sedimentological causes for the variability in petrology. Varying depositional and diagenetic conditions modified the initial sand composition in different ways in different zones. These effects can be seen in detailed analyses of 4200 ft (1280 m) of core from the Mesaverde Group, obtained from three Multiwell Experiment wells located in Sec. 34, T6S, R94W, in the Rulison gas field (Figure 1, Table 1).

This experiment is a field laboratory consisting of three wells arranged in a triangle with leg lengths of between 110-215 ft (34-66 m) at depth. The objective of the experiment was to characterize low-permeability, natural gas reservoirs, and to use this characterization for both the design of optimal stimulations and the assessment of existing and new stimulation technologies (Northrop et al., 1984; Northrop, 1988).

Preliminary reports on some of the reservoir properties in the MWX wells have been published or are in press. The principal references include Pitman and Spencer (1984), who reported on the petrological characteristics of these rocks, based on unpublished data from the MWX contractor's reports (Bendix Field Engineering Corporation, 1982-1984), and Sattler (1988), who discusses many of the MWX reservoir and rock properties.

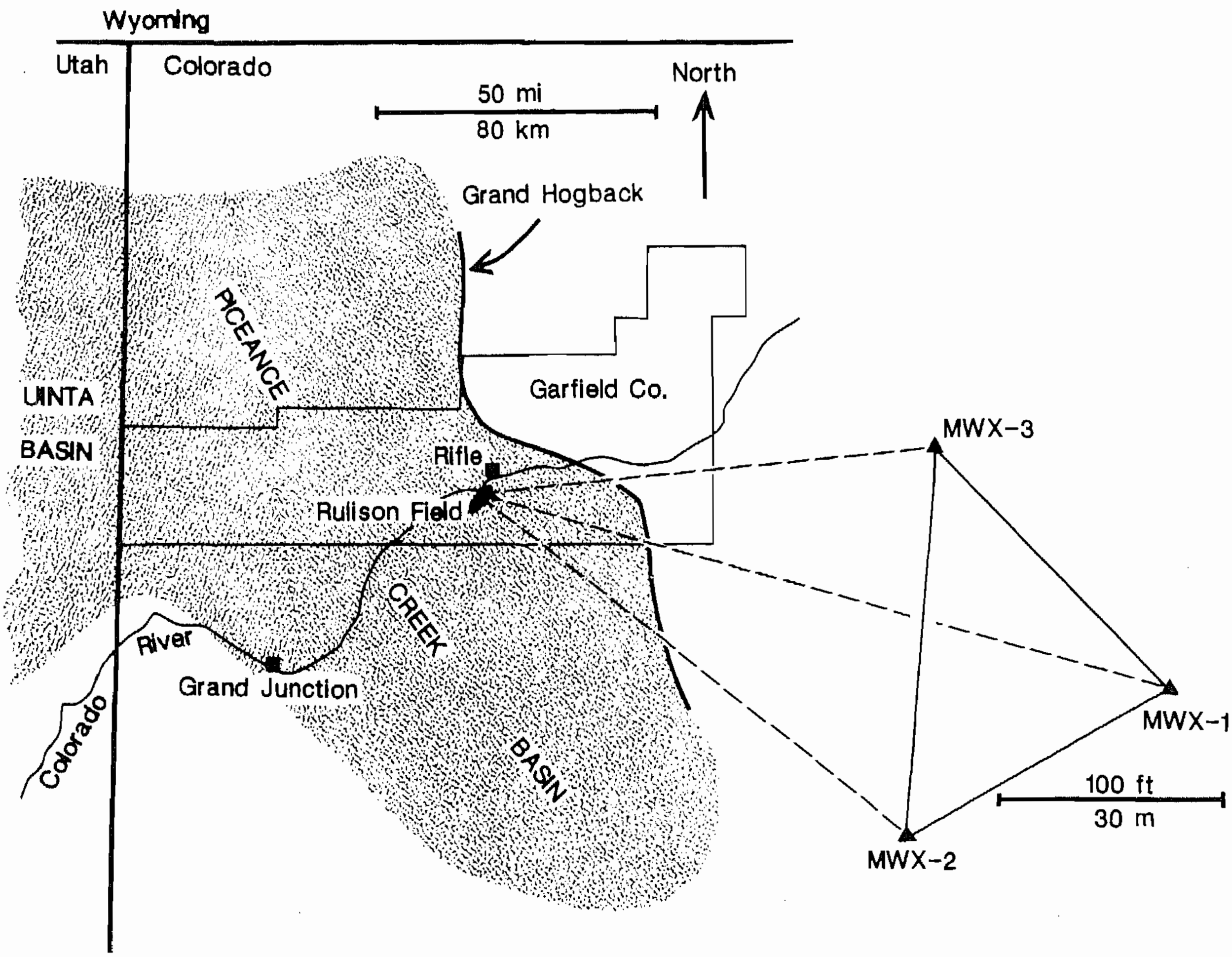


Figure 1. Location Map of the MWX Wells in the Piceance Basin, Northwestern Colorado

Table 1. Basic Field Data, Rulison Field

GENERAL:

Field Name: Rulison Field (Gas)
Location: T6S, R94W, Garfield County, Colorado
Basin: Piceance Creek Basin
Regional Paleogeographic Setting: Progradational; marine through fluvial
Nature of Reservoirs: Shallow-marine, distributory channel, and meander-belt
Trapping Style: Stratigraphic pinchouts
Source Rocks: Marine shales and nonmarine carbonaceous rocks

RESERVOIRS:

Geologic Age: Late Cretaceous (Campanian)
Depositional Environments: Shallow marine, delta-plain distributory channel, and fluvial meander-belt
Productive Facies: All sandstone facies
Diagenesis: Complex; includes silicate dissolution and cementation by calcite, quartz, and authigenic clay: varies by facies
Entrapping Facies: Marine shales to nonmarine mudstones
Porosity Types: Grain dissolution, intergranular, fracture

FIELD DATA:

Trap Type: Stratigraphic
Reservoir Dimensions:
- Range of Depth of Pay: 4500-8300 ft (1370-2530 m)
- Range of Reservoir Thicknesses: 20-50 ft (6-15 m)
- Reservoir Widths: 200 ft - 2 mi (60 m-3.5 km)
- Gas Recoverable: (inadequate production test data)
- Cumulative Production: (not tested)

Drive Type: Overpressured gas
Average IP: between 25 - 600 MCFD per sandstone at MWX
Porosity in Pay (Max/Ave): 7.6/7.3[1]; 12.1/10.5[2]; 8.7/7.0[3]; 8.1/6.7[4]
Permeability in Pay (Ave): 0.5 - 1.0[1]; 1.0 - 2.0[2]; 0.1 - 0.5[3]; 0.1 - 2.0[4] (microdarcies)
S_w in Pay (Min/Ave): 28/36[1]; 19/27[2]; 27/38[3]; 45/60[4]
Average Temperature (°C): 110[1]; 96[2]; 82[3]; 70[4]

Source Rock: Associated coals and marine shales
- Age: Late Cretaceous
- Timing: Laramide

[1]marine
[2]paludal
[3]coastal
[4]fluvial

The reservoir strata of the MWX site have a relatively simple history of subsidence and uplift, and display little, if any, local flexure (Figure 2; see also Johnson, 1983, and the seismic lines in Waechter and Johnson, 1985). However, they are intensely fractured (Lorenz and Finley, 1987; Lorenz et al., 1988; Finley and Lorenz, 1988). Natural fractures dominate the reservoir system permeability (Lorenz et al., 1986). The submicrodarcy to microdarcy range matrix permeabilities, and the other properties characterized here, however, (Table 2) are important to gas drainage from matrix blocks into the fracture system, to reservoir volume considerations, and to questions of reservoir damage during drilling and simulation.

STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENT

The types of reservoirs encountered in the 4000-ft (1220-m) thick Mesaverde Group at the MWX site include--from the bottom up (Figures 3A and 3B)--(1) shallow-marine to shoreline blanket sandstones; (2) lenticular distributary-channel sandstones and overbank splays of the lower delta plain ("paludal") environment; (3) reservoirs similar to those of the paludal (but without interbedded coals) of the upper delta plain ("coastal") environment; and (4) complex meander-belt sandstones deposited in a fluvial environment (Lorenz, 1984; 1987). These strata lie between the depths of 8350 ft (2545 m) and 4300 ft (1310 m) in the MWX wells. They are underlain by the Mancos Shale, and overlain by the Ohio Creek Member (the "paralic" interval, Figs. 3A and 3B) of the Mesaverde Group. The Ohio Creek Member may be a gas reservoir in other parts of the basin (Lorenz and Rutledge, 1985) but it is water-saturated in the MWX wells. The Ohio Creek Member is unconformably overlain by the Wasatch Formation (Johnson and Nuccio, 1984). These strata are exposed and have been studied at nearby outcrops in Rifle Gap and elsewhere along the Grand Hogback (Lorenz and Rutledge, 1987).

The shallow-marine to shoreline reservoirs (the Corcoran, Cozzette, and Rollins Sandstone Members of the Iles Formation, Mesaverde Group) are

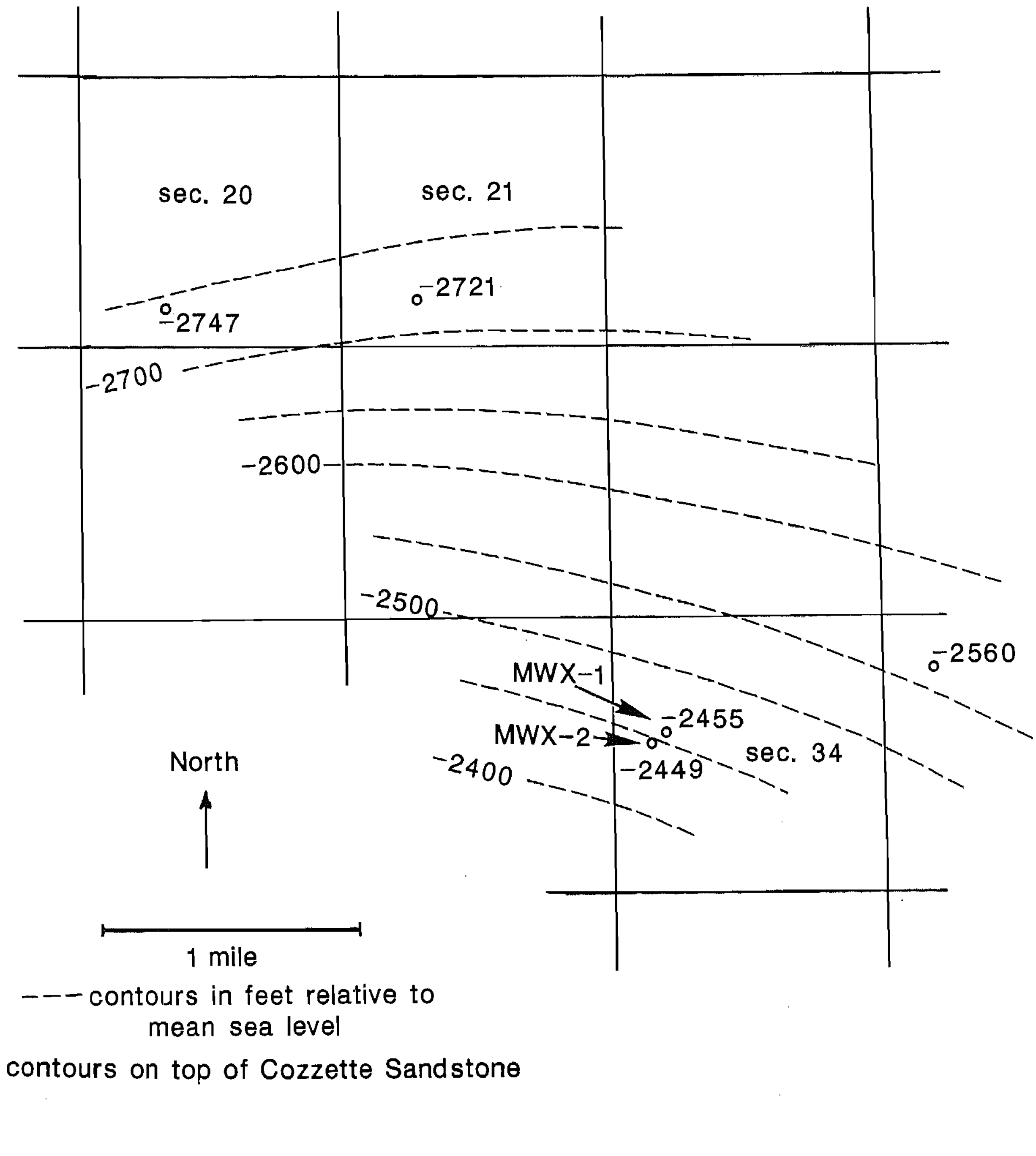


Figure 2. Structure-Contour Map on Top of the Cozzette Sandstone Member, Including All Wells in the Vicinity of the MWX Site Drilled to This Reliable Horizon

Table 2. Reservoir Properties by Depositional Environment

Environment	Average Porosity (percent)	Average Permeability (μd)*	Average Water Saturation (%)	Average Cation Capacities (meg/110 g) Sandstone	Shale	Average Capillary Pressures (psi) at Water Saturation (%)
Fluvial	6-8	0.1-2.0	30-40, (increases uphole)	2.2	10	~200/~46 to ~900/~46
Coastal	6-7	0.1-0.5	30-40	2.7	12	>1300/~38
Paludal	8-10	1.0-2.0	20-30	1.7	6	>1000/~27
Marine	6-8	0.5-1.0	30-40	0.5 to 1.1	17 to 5	~800/~30

* Restored-state (pressure and water saturation) conditions.

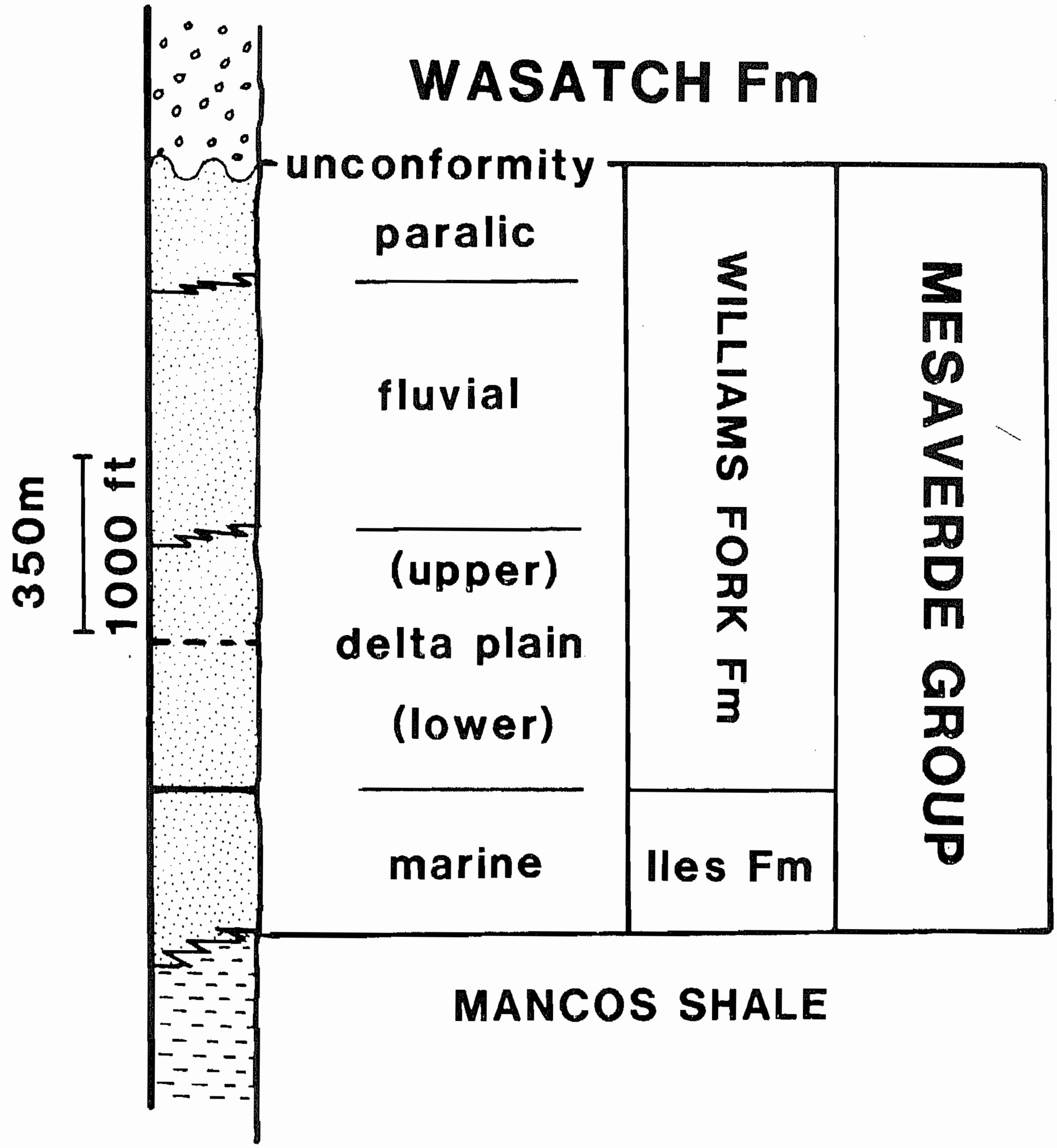


Figure 3A. Stratigraphic Column of the Mesaverde and Its Subdivisions at the MWX Site

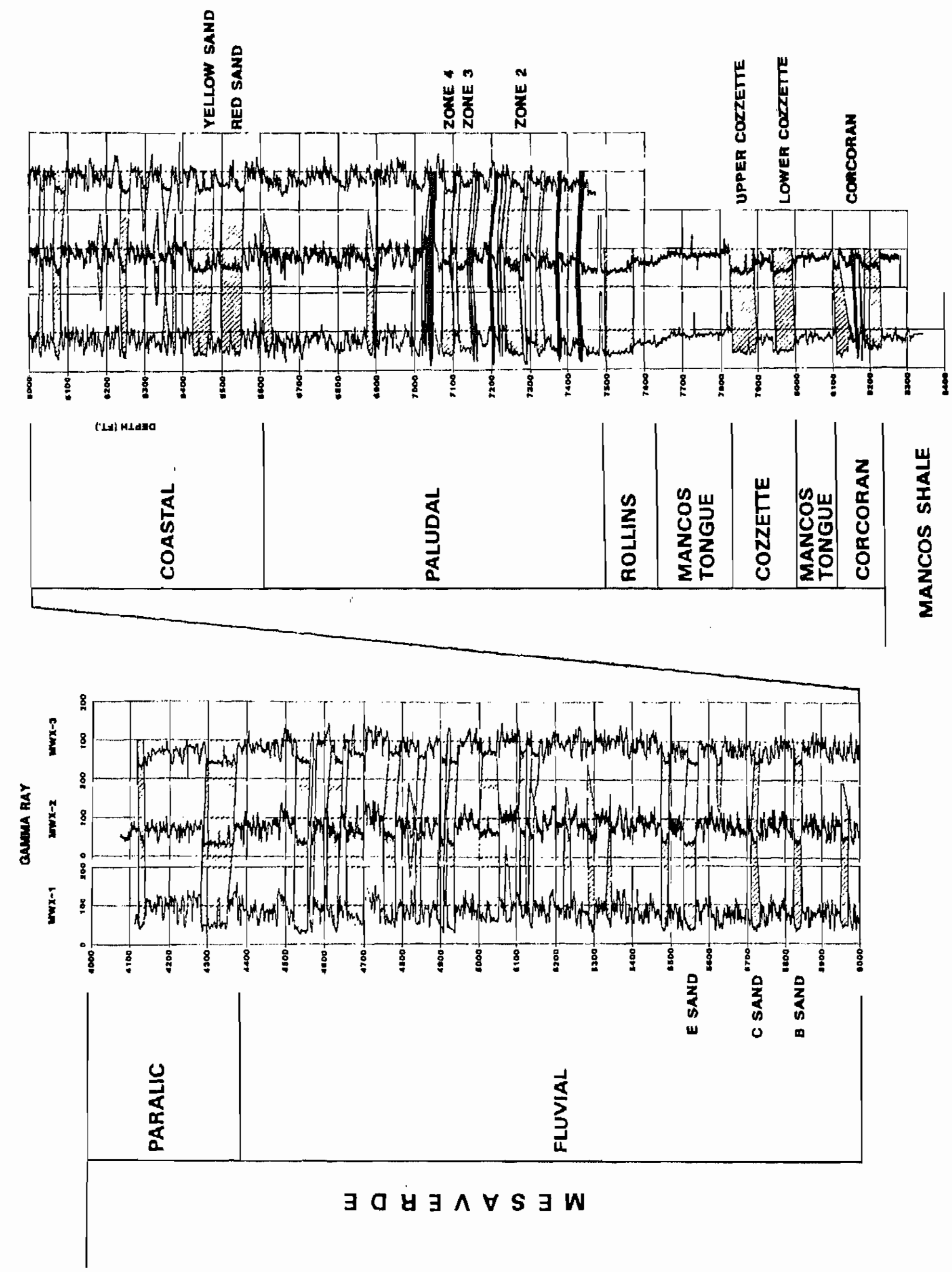


Figure 3B. Correlation of Gamma Ray Logs of the 3MWX Wells Through the Mesaverde relatively homogeneous (Figure 4), and laterally extensive on a scale of several miles. The lower zones of these reservoirs typically grade down into bioturbated offshore marine siltstones and shales, but the bulk of the reservoirs consist of sandstones that are parallel-bedded and cross-bedded, and often burrowed (Plate 1A). Many of these sedimentary structures are probably hummocky cross-bedding. The sandstones are separated by tongues of the Mancos Shale. The upper sandstone bed of the Corcoran interval at the MWX site is a distributary channel, but most of the deposits represent shoreface environments.

In the paludal zone, the MWX wells penetrated five sandstones of reservoir quality and seven coal beds greater than 10 ft thick. Interbedded strata include thin coals, carbonaceous mudstones, mudstones, and thin beds of siltstone and sandstone (Figure 5). The reservoir sandstones were deposited as narrow (80-550 ft/25-165 m; Lorenz, 1985), low-sinuosity distributory channels, and more amorphous splays (Plate 1B), in a lower delta plain environment.

The gross reservoir morphologies and sizes of the overlying coastal interval are comparable to those of the paludal zone (Figure 6), since the depositional environment--an upper delta plain--was similar (Plate 1C). However, as will be shown, the absence of interbedded coals in this depositional environment resulted in somewhat different internal reservoir properties.

Reservoirs in the fluvial zone are composite meander-belt sandstones (Plate ID), ranging from 1000-2500 ft (300-760 m) wide, with abundant lithologic heterogeneities (Lorenz et al., 1985). The section is about 40% sandstone and the wide reservoirs correlate well between the closely spaced MWX wellbores (Figure 7). The interbedded mudstones, siltstones, and thin sandstones represent overbank sedimentation.

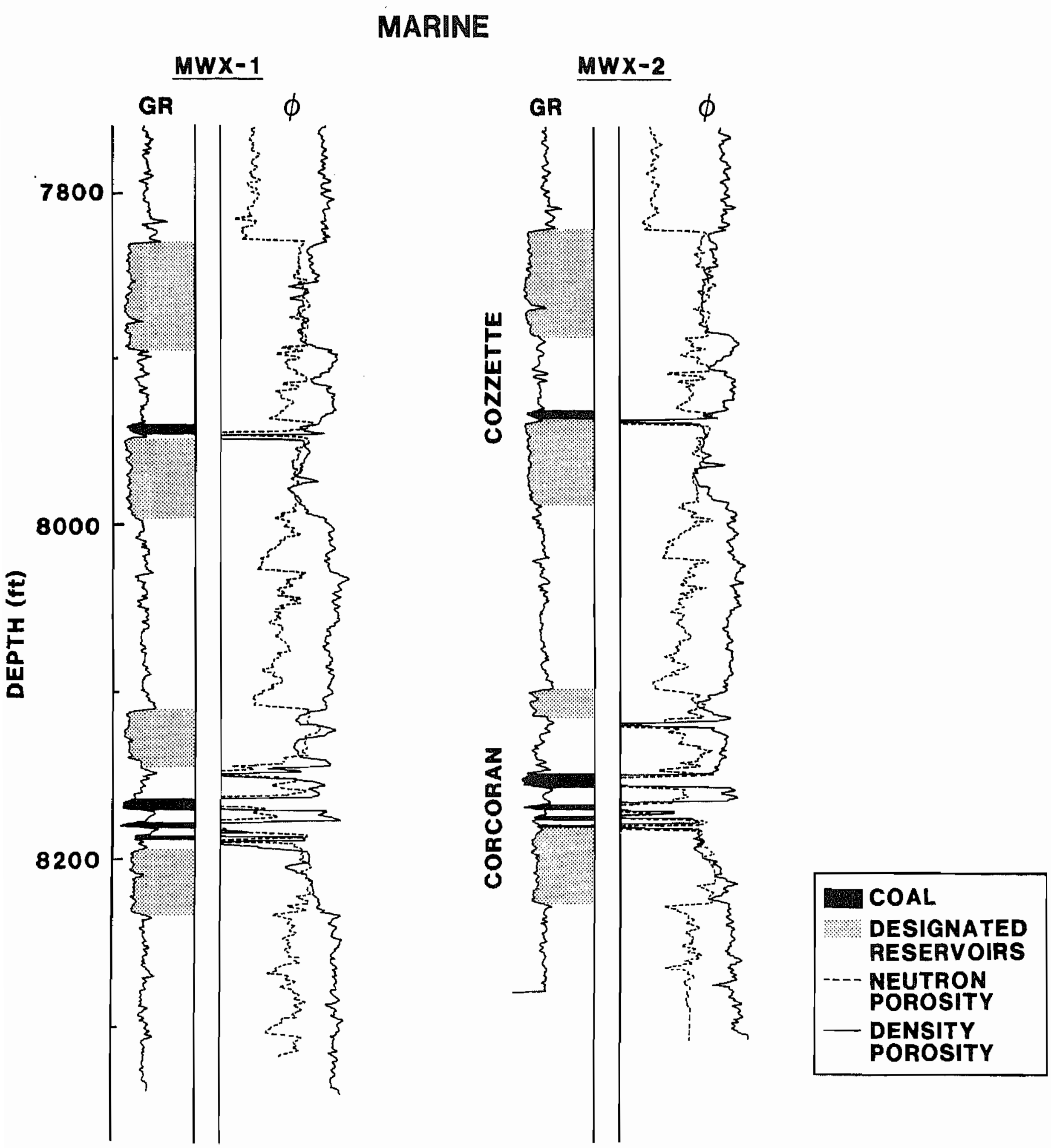


Figure 4. MWX Gamma-Ray and Porosity Logs Through the Marine Zone

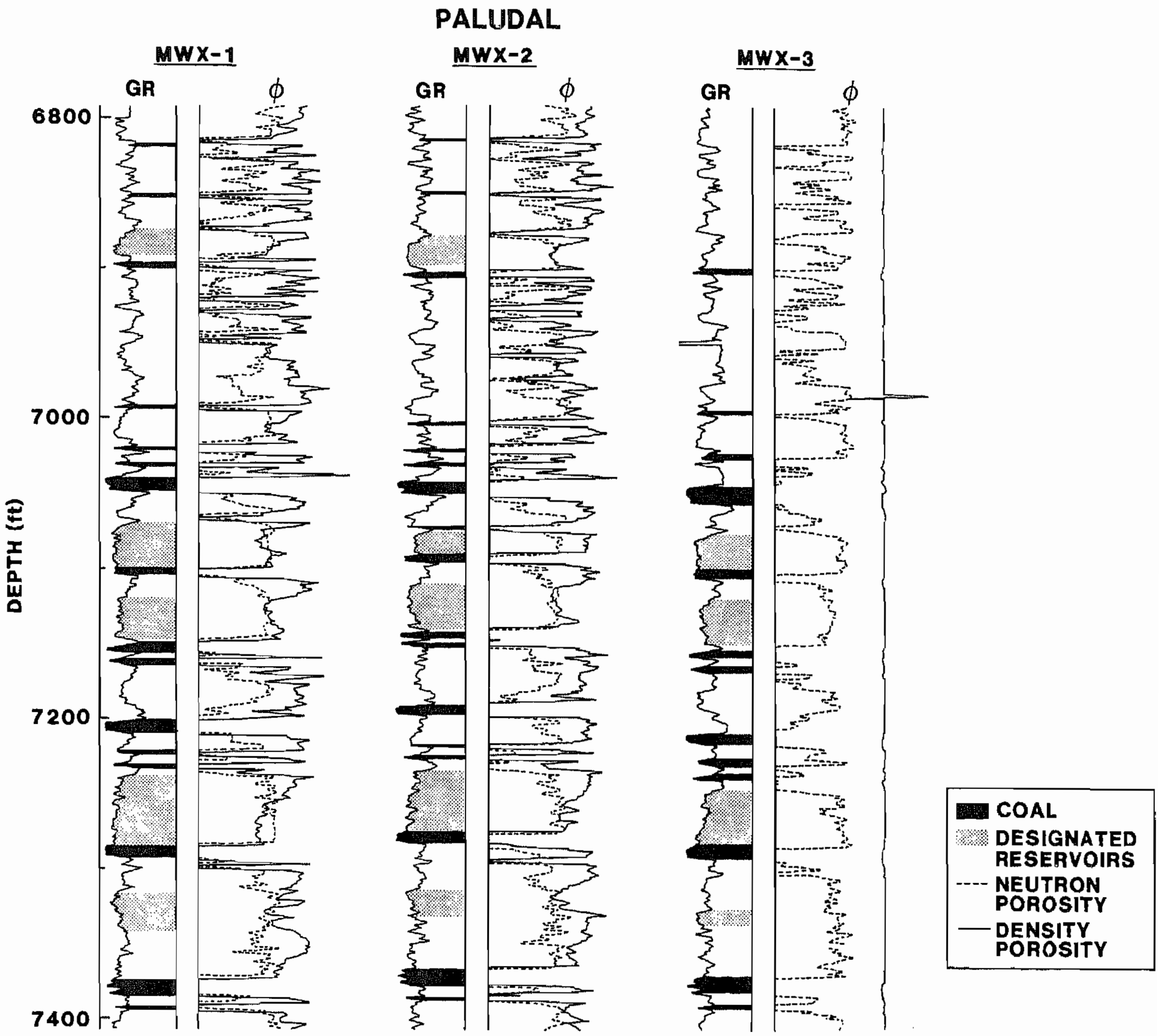


Figure 5. MWX Gamma-Ray and Porosity Logs Through the Paludal Zone

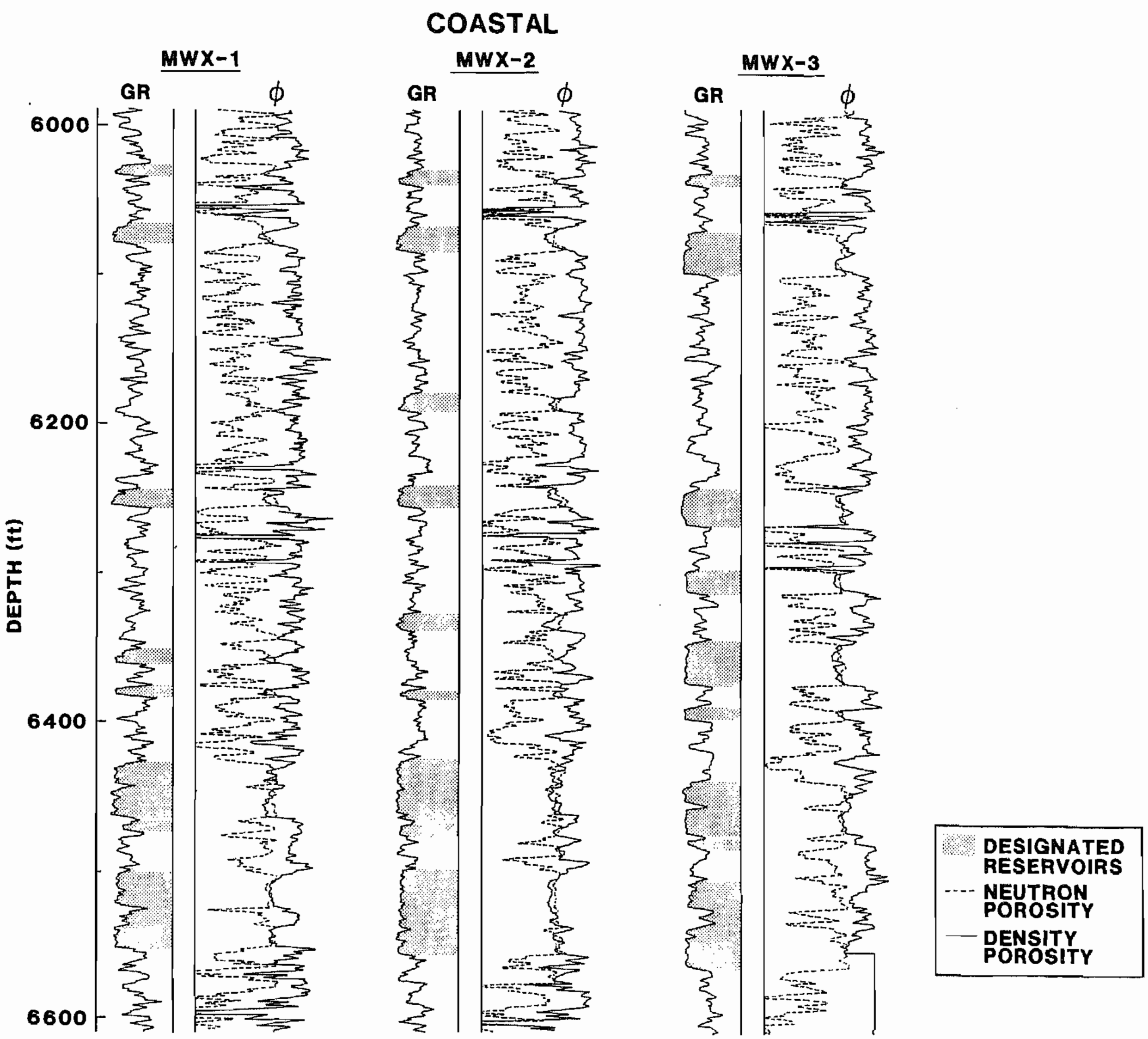


Figure 6. MWX Gamma-Ray and Porosity Logs Through the Coastal Zone

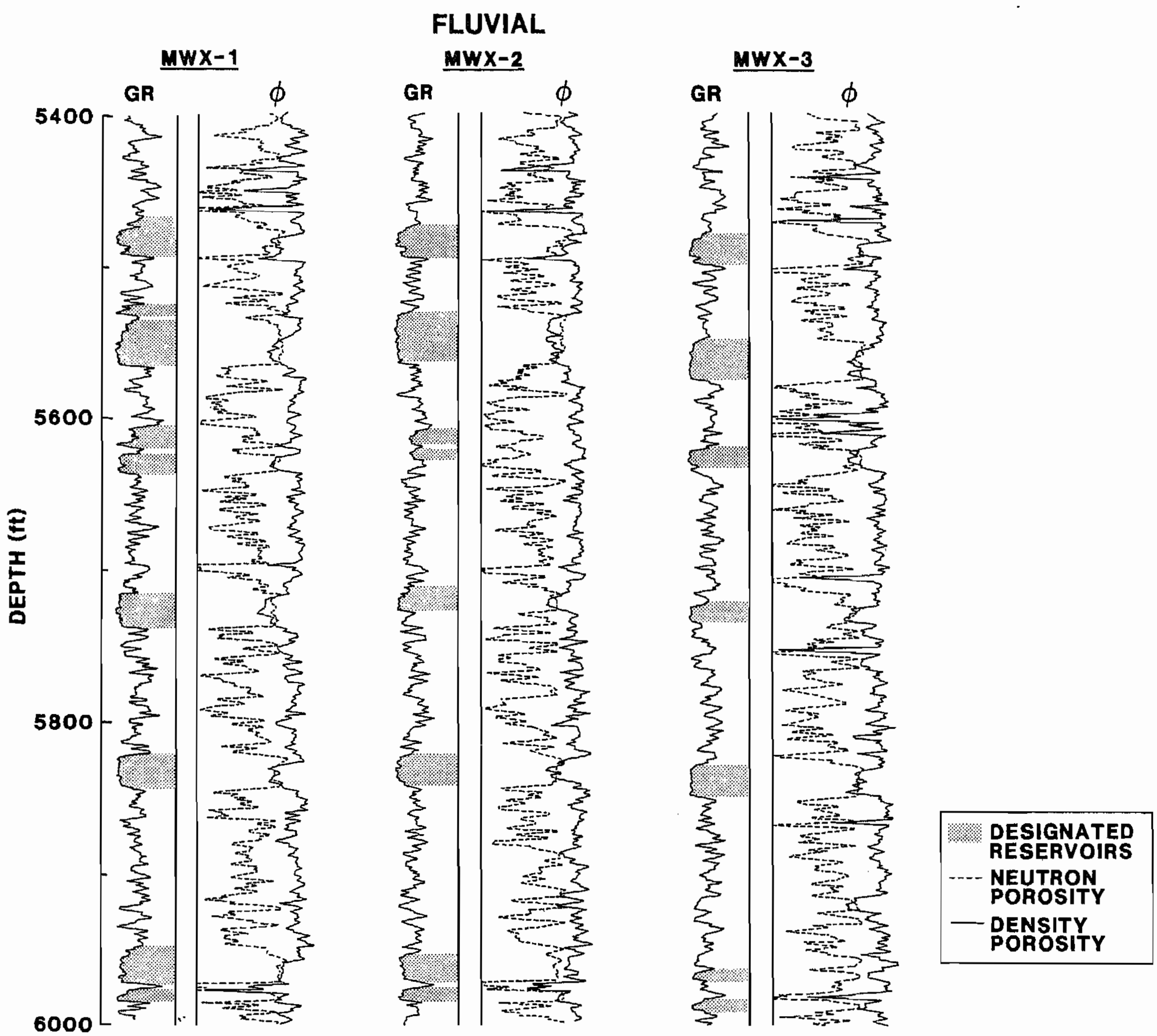


Figure 7. MWX Gamma-Ray and Porosity Logs Through the Fluvial Zone

PETROLOGY

Marine Facies

Although the source of the marine sands was essentially the same as that for other zones, sorting and roundness parameters are higher in the marine reservoirs, and these sandstones are "cleaner" in composition (Plate 2A, Figure 8A). High-energy marine depositional conditions segregated the sand by size, and selectively destroyed many of the less stable grains. The Corcoran and Cozzette Sandstone Members are classified as subarkoses (Pitman and Spencer, 1984). Both of these members contain abundant quartz, with little feldspar or lithic-fragment content.

Table 3. Summary of Thin-Section Petrology Data for Selected Sandstones of the Marine Zone

	Corcoran		Cozzette	
	average	(range)	average	(range)
Grain Size (mm):	0.11	(0.09-0.12)	0.08	(0.06-0.13)
Pore Space (%):	14.5	(9-18)	10.6	(2-18)
Mineral Composition of Sandstones* (%)				
Calcite:	0.2	(tr-1)	0.9	(0-21)
Dolomite:	5.2	(1-7)	7.7	(0-23)
Quartz:	49.5	(27-62)	59.5	(43-69)
K-Feldspar	0.2	(tr-1)	0.9	(tr-3)
Plagioclase:	5.4	(3-8)	6.1	(2-11)
Lithic Fragments:	5.4	(4-7)	3.4	(1-8)
Chert:	1.7	(tr-3)	1.5	(tr-3)
Silica Overgrowths:	4.0	(2-7)	4.4	(1-10)
Clays (not in pores):**	3.0	(tr-18)	3.0	(tr-10)

* Trace minerals, not listed, include biotite, muscovite, siderite, zircon, tourmaline, anatase, pyrite, glaucophane/celadonite, rutile, garnet, epidote, detrital chalcedony, and carbonaceous material

** Clays identified by X-ray diffraction include illite/montmorillonite and chlorite.

The marine sandstones are fairly uniformly fine-grained (Table 3). The Corcoran and Cozzette contain some feldspar (primarily plagioclase) and

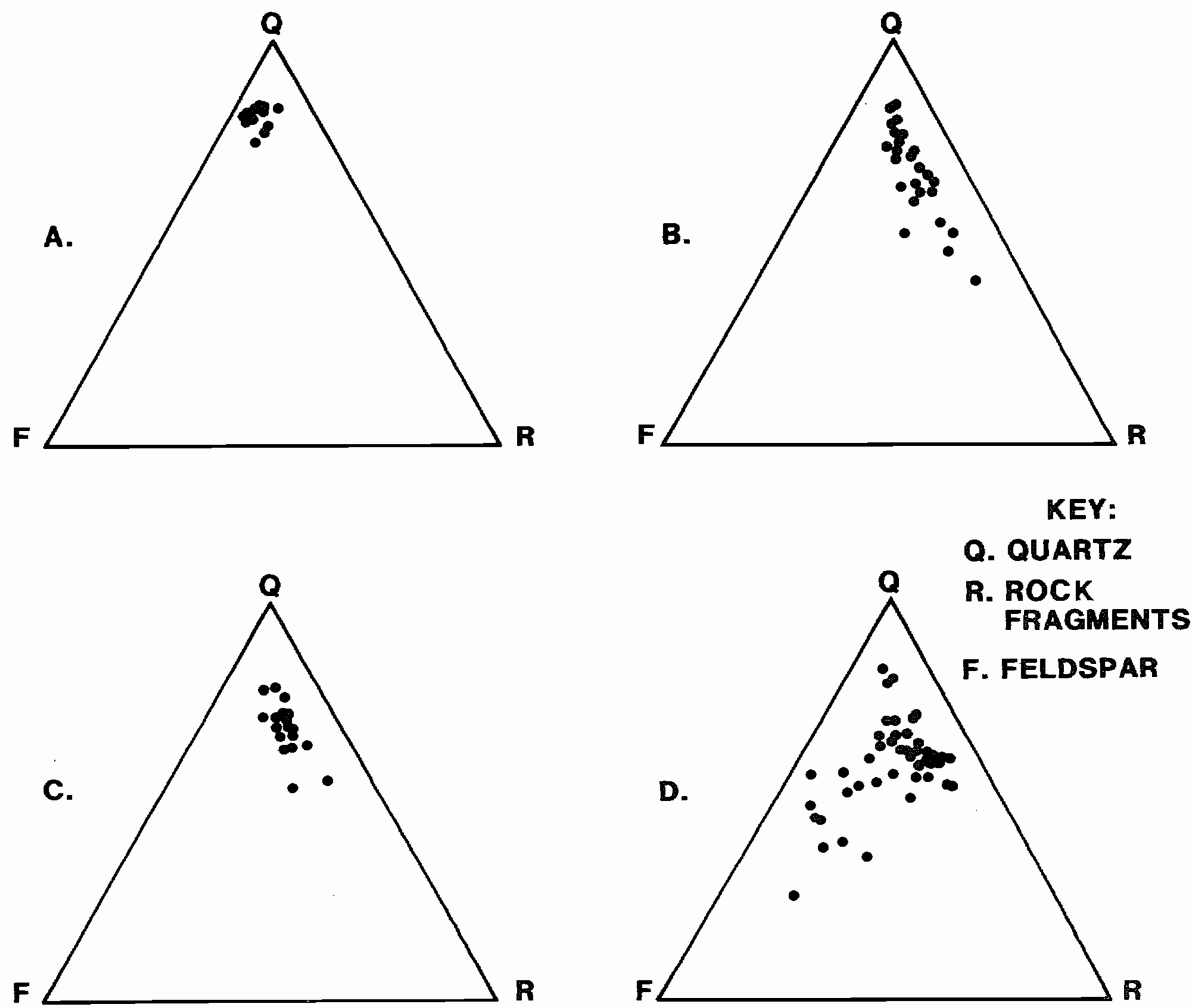


Figure 8. Ternary Diagrams Showing Petrologic Composition of the Mesaverde Sandstones in the MWX Wells (after Pitman and Spencer, 1984, reproduced with permission of the U.S. Geological Survey). A - marine zone; B - paludal zone; C - coastal zone; D - fluvial zone.

lithic fragments, and abundant quartz (50%-60%). Calcite cementation is relatively minor in the Corcoran and Cozzette. While this mineral phase appears throughout much of the rest of the cored section, its absence here suggests its subsequent removal by later dissolution, and the enhancement of porosity. Alteration of chert and lithic fragments provided a source of silica for quartz overgrowths (up to 10%) as well as for void-filling clays. Clays in the marine zone consist of mixed-layer illite/montmorillonite, with minor amounts of iron-bearing chlorite.

The petrologic studies by Bendix (1982-1984) suggest the following diagenetic sequence in the marine zone:

1. Early calcite cementation;
2. Feldspar alteration/authigenic clay formation (except in the Corcoran, perhaps due to the lack of abundant detrital feldspar);
3. Quartz overgrowths/second episode of calcite cement, in the Corcoran and Cozzette;
4. Development of secondary porosity in the Rollins and upper Cozzette;
5. Formation of authigenic clays;
6. Dolomitization of calcite cement.

Lower Delta Plain Facies

Results of mineralogical analyses of the paludal zone (Bendix, 1982-1984) are summarized in Table 4. The paludal sediments contain relatively high percentages of lithic fragments and detrital feldspars (predominantly plagioclase). Sand-sized, rounded grains of iron-stained dolomite are locally abundant (Plate 2B, Figure 8B). Grain size is also more heterogeneous than that of the underlying marine sands (e.g., varying from 0.03-0.34 mm in one of the zones examined). Percentage of rock fragments, which may be interpreted as an indicator of energy conditions during sedimentation as well as extent of post-depositional diagenesis, varies widely between the three MWX cores. The abundance of organic matter as coals and

Table 4. Summary of Thin-Section Petrology Data for Selected Sandstones of the Paludal Zone

	Zone 3		Zone 4	
	average	(range)	average	(range)
Grain Size (mm):	0.9	(0.02-0.41)	0.11	(0.03-0.34)
Pore Space (%):	11.0	(tr-24)	13.0	(2-18)
Mineral Composition of Sandstones* (%)				
Calcite:	1.8	(tr-8)	2.5	(tr-5)
Dolomite:	12.5	(1-34)	14.4	(5-41)
Quartz:	40.7	(24-53)	48.3	(24-62)
K-Feldspar:	0.4	(tr-1)	0.6	(tr-1)
Plagioclase:	6.3	(3-9)	5.7	(3-9)
Lithic Fragments:	8.8	(1-19)	7.4	(4-14)
Chert:	2.8	(tr-6)	2.3	(tr-6)
Silica Overgrowths:	3.4	(2-5)	not measured	
Clays (not in pores):**	9.9	(tr-42)	3.4	(1-15)

* Trace minerals, not listed, include pyrite, siderite, anatase, muscovite, biotite, tourmaline, zircon, apatite, epidote, and carbonaceous material

** Clays identified by X-ray diffraction include illite/montmorillonite, illite, and traces of chlorite

carbonaceous stringers, as well as finely disseminated throughout the matrix, suggests that organic acids were also important in this section as a mechanism of feldspar/rock fragment dissolution, and for the formation of pore-filling authigenic clays during diagenesis. The presence of pyrite is also consistent with the presence of carbonaceous material, and implies, at least locally, a reducing environment.

The potassium feldspars in the paludal sands have been almost entirely replaced by carbonate, and the plagioclase feldspars have been sericitized. In addition to the presence of organic acids from the associated carbonaceous strata, carbonic acid may have been contributed by the process of qualification (Fuchtbauer, 1967). The clay fraction in the interval consists of mixed-layer illite/montmorillonite and illite.

The diagenetic sequences listed in the different Bendix reports for the paludal zone vary slightly. This variation is probably the result of both real variation between the paludal rocks of the different wells, and the different approach and interpretations of different sets of petrologists. Many of the processes listed may have been concurrent.

	MWX-2	MWX-3
1.	Early carbonate	Early carbonate
2.	Feldspar alteration and compaction	Feldspar alteration and compaction
3.	Formation of chlorite	Early quartz overgrowths
4.	Secondary porosity	Secondary porosity
5.	Later carbonate	Authigenic clay
6.	Authigenic clay	Late carbonates
7.	Dolomitization of calcite	Late silicification, dolomitization

Upper Delta Plain Facies

Reservoirs in the coastal facies (upper delta plain) are similar to those of the marine sandstones in porosity and mean grain size. The percentages of feldspars and rock fragments are higher than in the marine sandstones (Table 5) and are approximately inversely correlated with the presence of quartz overgrowths and pore-filling clays. The clays include illite and mixed-layer illite/montmorillonite.

Table 5. Summary of Thin-Section Petrology Data for Selected Sandstones of the Coastal Zone

	Red Zone		Yellow Zone	
	average	(range)	average	(range)
Grain Size (mm):	0.12	(0.08-0.18)	0.13	(0.07-0.18)
Pore Space (%):	7.6	(tr-21)	7.8	(2-14)
Mineral Composition of Sandstones* (%)				
Calcite:	7.0	(2-16)	8.0	(3-25)
Dolomite:	7.0	(3-11)	4.6	(1-10)
Quartz;	65.6	(52-78)	66.7	(35-81)
K-Feldspar:	1.2	(tr-4)	0.7	(tr-4)
Plagioclase:	7.7	(4-12)	9.6	(4-15)
Lithic Fragments:	18.8	(6-34)	12.8	(4-29)
Chert:	7.4	(1-12)	9.5	(2-21)
Silica Overgrowths:	3.4	(1-9)	5.1	(tr-12)
Clays (not in pores):**	7.6	(1-14)	9.2	(2-21)

* Trace minerals, not listed, include siderite, muscovite, biotite, pyrite, zircon, tourmaline, apatite, epidote, and hornblend

** Clays identified by X-ray diffraction include illite/montmorillonite, illite, and chlorite

The sandstones in this interval are fine-to very fine-grained, moderately to well-sorted, feldspathic litharenites (Plate 2C; Figure 8C). Calcite is the dominant cementing agent. Some dolomite is present but may be in part detrital (Spencer and Pitman, 1984).

The general diagenetic sequence for the samples analyzed is interpreted as follows (Bendix, 1982-1984):

1. Early carbonate
2. Feldspar alteration

3. Authigenic feldspar
4. Quartz overgrowths
5. Later carbonate
6. Authigenic clay
7. Dolomitization of calcite

Fluvial Facies

Maximum petrologic heterogeneity is found in the fluvial reservoirs (Table 6, Plate 2D, Figure 8D). Early phases of authigenic clay formation and compaction are more prevalent in this zone than in others, whereas calcite precipitation appears to have occurred later than in the other facies. The dominant rock type of the samples is feldspathic litharenite. The sandstones are very fine-to medium-grained and moderately sorted. Calcite is the dominant carbonate mineral. Clay minerals include illite, mixed layer illite/montmorillonite, and chlorite.

Table 6. Summary of Thin-Section Petrology Data for Selected Sandstones of the Fluvial Zone

	Zone B		Zone C		Zone E	
	average	(range)	average	(range)	average	(range)
Grain Size (mm):	0.18	(0.08-0.27)	0.20	(0.14-0.27)	0.24	(0.10-0.35)
Pore Space (%):	8.0	(1-14)	10.0	(tr-19)	5.0	(0-12)
Mineral Composition of Sandstones* (%)						
Calcite	9.3	(tr-48)	4.0	(tr-22)	9.0	(2-39)
Dolomite:	2.0	(tr-8)	0.5	(tr-4)	2.0	(tr-5)
Quartz:	44.0	(28-58)	49.0	(36-64	50.0	(36-57)
K-Feldspar:	1.0	(tr-7)	1.5	(tr-5)	3.5	(2-7)
Plagioclase:	6.3	(3-12)	7.3	(1-15)	9.0	(5-12)
Lithic Fragments:	15.3	(6-34)	10.2	(4-35)	11.0	(7-13)
Chert:	7.3	(1-16)	6.3	(3-11)	7.0	(4-12)
Silica Overgrowths:	3.6	(tr-8)	3.0	(tr-9)	1.0	(tr-5)
Clays:** (not in pores)	2.0	(tr-9)	4.3	(tr-39)	3.0	(1-8)

* Trace minerals, not listed, include zircon, tourmaline, garnet, rutile, pyrite, anatase, apatite, epidote, monazite, and muscovite

** Clays identified by X-ray diffraction include illite/montmorillonite, illite, and chlorite

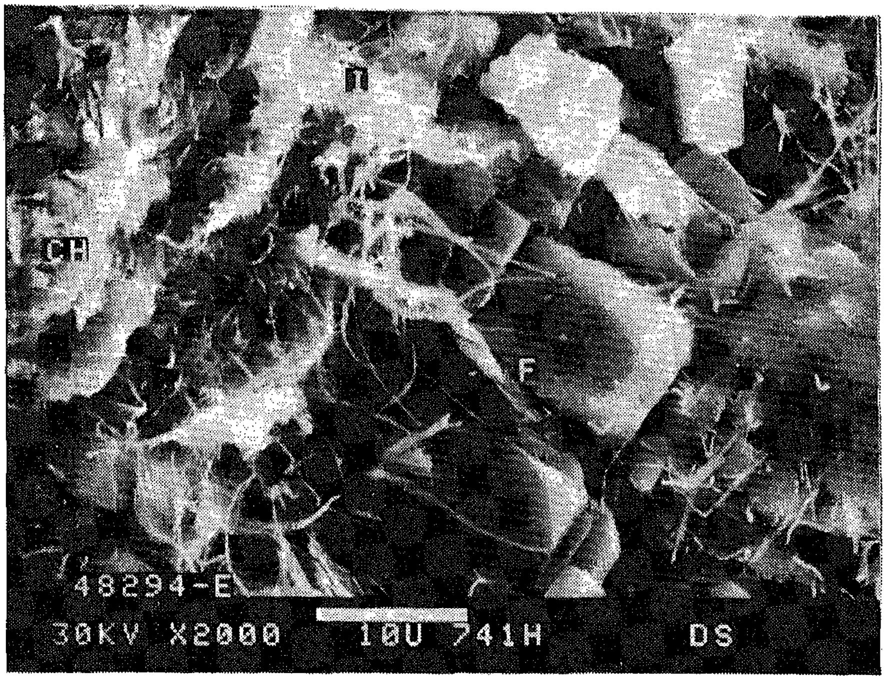
The generalized diagenetic sequence is listed below:

1. Early authigenic clay
2. Compaction and feldspar alteration
3. Formation of chlorite
4. Quartz overgrowths
5. Calcite cement
6. Secondary porosity
7. Authigenic clay

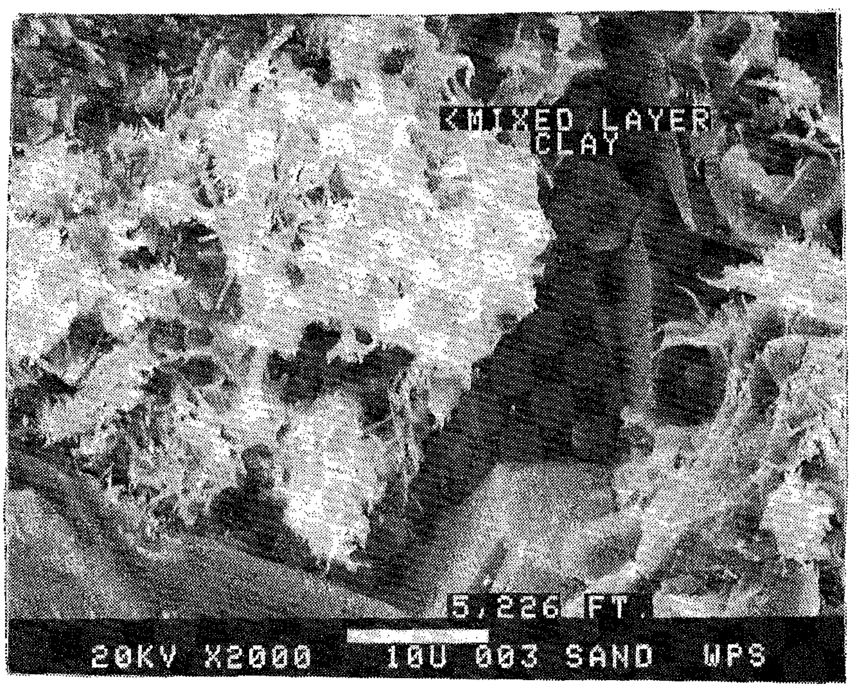
Clay Composition

The composition of the Mesaverde clays in both the sandstones and other strata varies somewhat with depositional environment. Much of the clay that was originally indentified (by X-ray analysis) as kaolinite was subsequently found to be a variety of iron-bearing chlorite that gives a similar diffraction pattern. True kaolinite--in the subsurface--exists only in a few samples of the fluvial and coastal zones (Pollastro, 1984; Pitman and Sprunt, 1984).

The dominant clays are authigenic illite and mixed-layer illite/ montmorillonite. These are common as pore lining and bridging material (Figure 9), and the delicate fibrous nature of the illite is a potential mechanical obstruction to fluid flow in the rocks (Pollastro, 1984). The clays in pore spaces were most likely derived from components produced during the alteration of the detrital components. The presence of iron-rich chlorite, locally abundant, and the formation of authigenic kaolinite suggest that these two phases perhaps formed quite early in the diagenetic sequence (Fuchtbauer, 1967). According to the observations of Fuchtbauer, the formation of kaolinite is inhibited by the presence of other clays (notably illite) and the early cementation by dolomite.



(A)



(B)

Figure 9. SEM Photomicrographs of (A) Illite and (B) Mixed-Layer Illite/Smectite, in Pores in Sandstone (Photos courtesy of Dowell-Schlumberger and the Western Company) I = illite, F = feldspar, CH = chlorite

ROCK AND RESERVOIR PROPERTIES

Porosity and Permeability

Marine: Homogeneous vertical and lateral distribution of grain size and sandstone composition in the marine reservoirs is reflected in a relatively uniform distribution of laboratory-measured porosities and permeabilities (Figure 10), which average 6-8% and 0.5-1.0 microdarcys at restored-state conditions,* respectively (Table 2). Porosity is dominated by microporosity in clay-filled intergranular pores. Open pores are rare, and pore throats are frequently bridged with clay. The porosity of the Cozzette Sandstone measured in thin section ranges from 2-18% with an average porosity of 10%. The thin-section porosity in the Corcoran Sandstone samples ranges from 0 to 18%, with an average porosity of about 10%. The porosity of the Rollins is somewhat lower, probably because the percentage of rock fragments and intergranular clays is higher than the Corcoran or Cozzette sandstones.

A 25-ft thick zone of pyrobitumen, or "cooked-out oil" has been recognized at the top of the Cozzette Sandstone (Pitman and Spencer, 1984), and this additional, immobile material significantly reduces the porosity/permeability characteristics of that zone (Figure 10), as it occupies two-thirds of the available pore volume.

Paludal: The laboratory porosity and permeability values of the paludal zone average 8-10% and 1.0-2.0 microdarcys (restored-state) respectively (see Table 2), and are generally the highest encountered in the Mesaverde reservoirs at the MWX site. In thin section, the sandstone porosity is seen to be dominated by microporosity in intergranular authigenic clays, and ranges from trace to 24% with an average of 12%.

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* Note that the average permeabilities listed in Table 2 are corrected for water saturation, and are therefore lower than the dry permeabilities measured and plotted on Figures 10, 11, 13 and 14. The dry permeabilities are plotted principally in order to show vertical and lateral variations rather than absolute reservoir values.

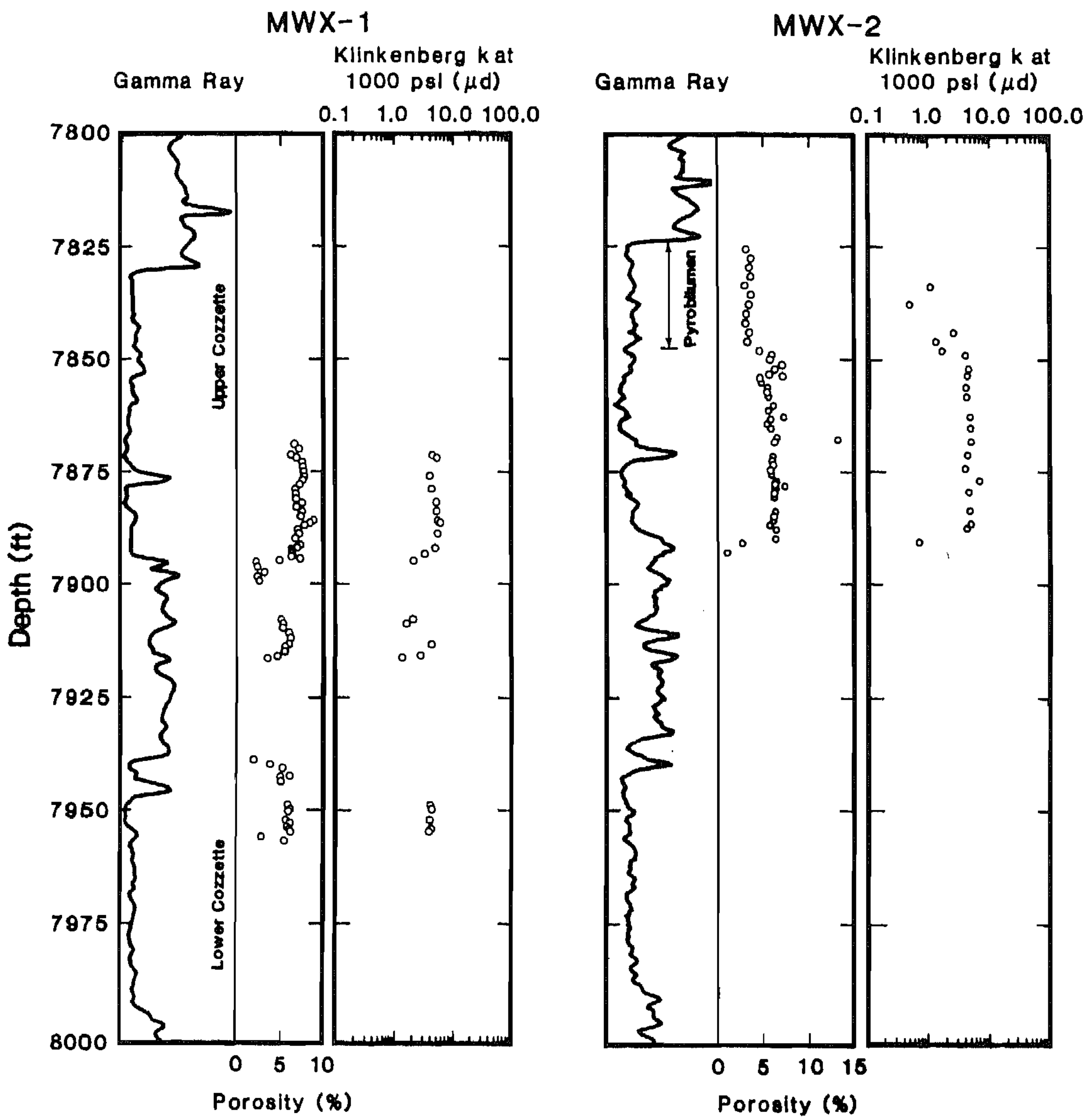

Figure 10. Vertical Porosity and Dry Klinkenberg Permeability Distributions Measured in Core Plugs From Sandstones in the Marine Zone (from Lorenz, 1987)

Pore space is very poorly developed in sandstones with extensive carbonate cement, and open pore space is rare. Although relatively high, porosity and permeability in the paludal sandstones are irregularly distributed (Figure 11). They change rapidly over lateral distances of a few hundred feet, especially in splay deposits. As in the other zones, porosity and permeability maintain a roughly proportional relationship to each other, but for a given permeability, paludal samples tend to have higher porosities than fluvial samples (Soeder and Randolph, 1984) (Figure 12).

The depositional and diagenetic environments controlled these parameters. More unstable rock fragments were preserved in this lower-energy environment than in the marine environments, tending to reduce porosity and permeability in the deposits. However, organic acids produced by the associated carbonaceous beds created secondary porosity by the dissolution carbonate cements and some of the feldspars, (probably by the processes described by Surdam and Crossey, 1985), resulting in relatively good reservoir properties.

Coastal: Porosity and permeability in the coastal zone were probably not enhanced by organic acids, due to the diminished quantity of carbonaceous source material. At restored-state conditions, porosity and permeability are of the same magnitude as porosity and permeability in the marine and fluvial intervals (Table 2). As with the paludal reservoirs, the coastal sandstones have a more irregular distribution of porosity and permeability values laterally and vertically (Figure 13) than do the marine reservoirs. Porosity is mostly secondary. Pores and pore throats are clay filled and porosity exists between clay platelets. Thin-section porosity ranges from trace to 21%.

Fluvial: Petrologic heterogeneity and a wide variability in grain sizes resulted from the irregular temporal and spatial distribution of sedimentary events in the fluvial environment, producing the highest degree of variability in permeability observed in the MWX reservoirs (Figure 14). Average restored-state permeabilities also show considerable variation,

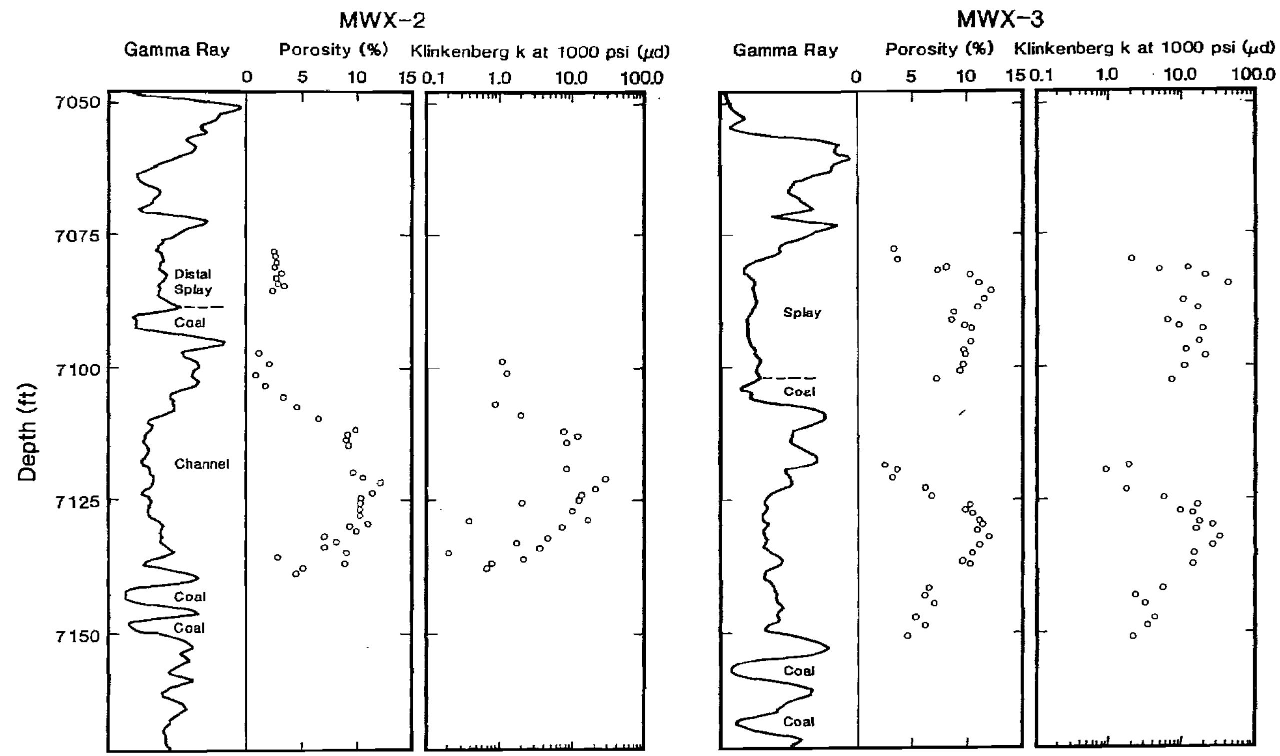

Figure 11. Vertical Porosity and Dry Klinkenberg Permeability Distributions Measured from Core Plugs from Sandstones in the Paludal Zone (from Lorenz, 1987). [Note the abrupt lateral changes as well: Permeability in the distal splay deposit (MWX-1) was too low to be measurable.]

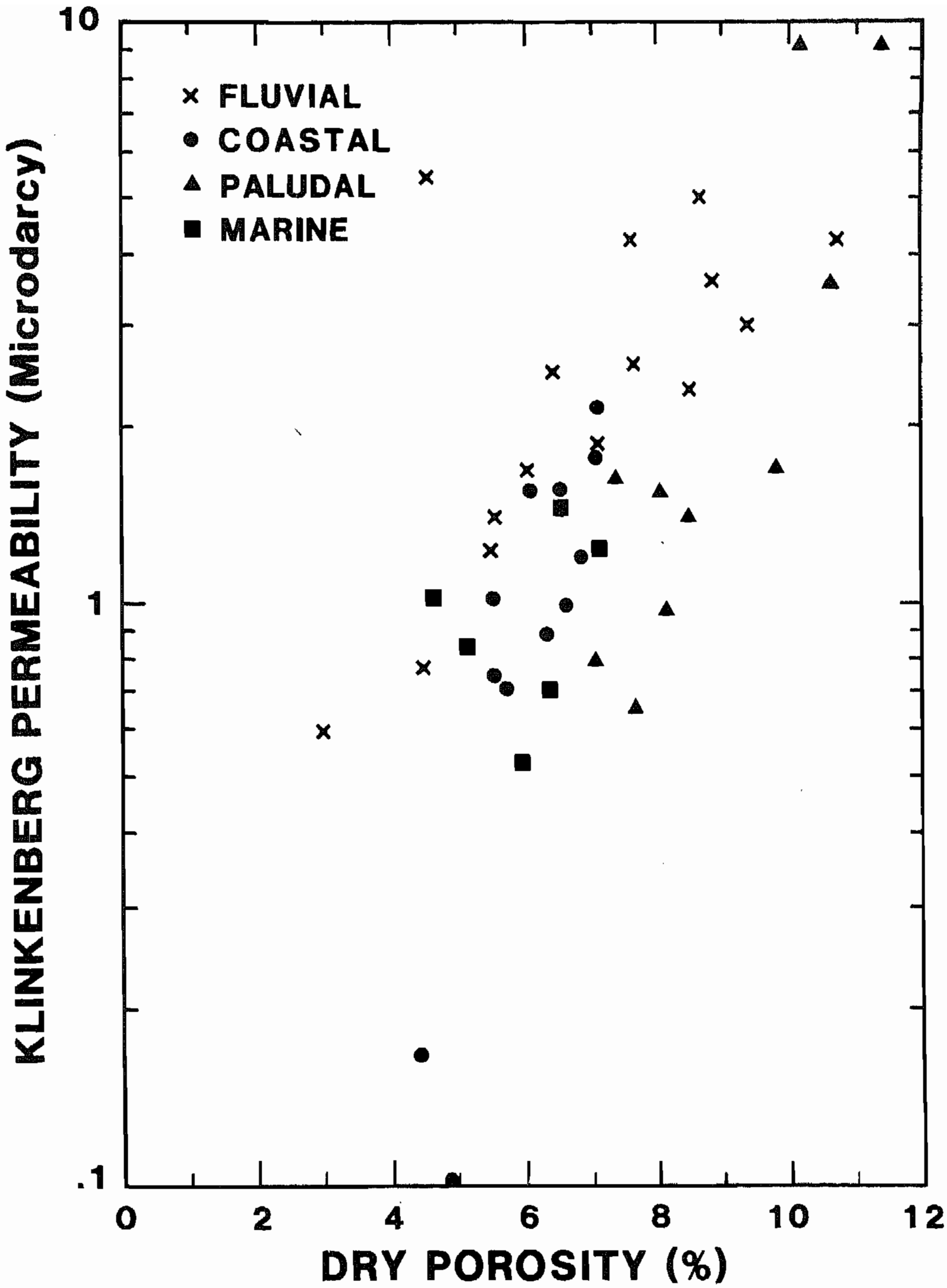

Figure 12. Porosity vs Dry Permeability Plot for Selected Samples, Differentiating Measurements by Depositional Environment. Measurements Made at Reservoir Net Confining Stress. [Modified from Soeder and Randolph, 1984, Figure 8, reproduced with permission of the Society of Petroleum Engineers.]

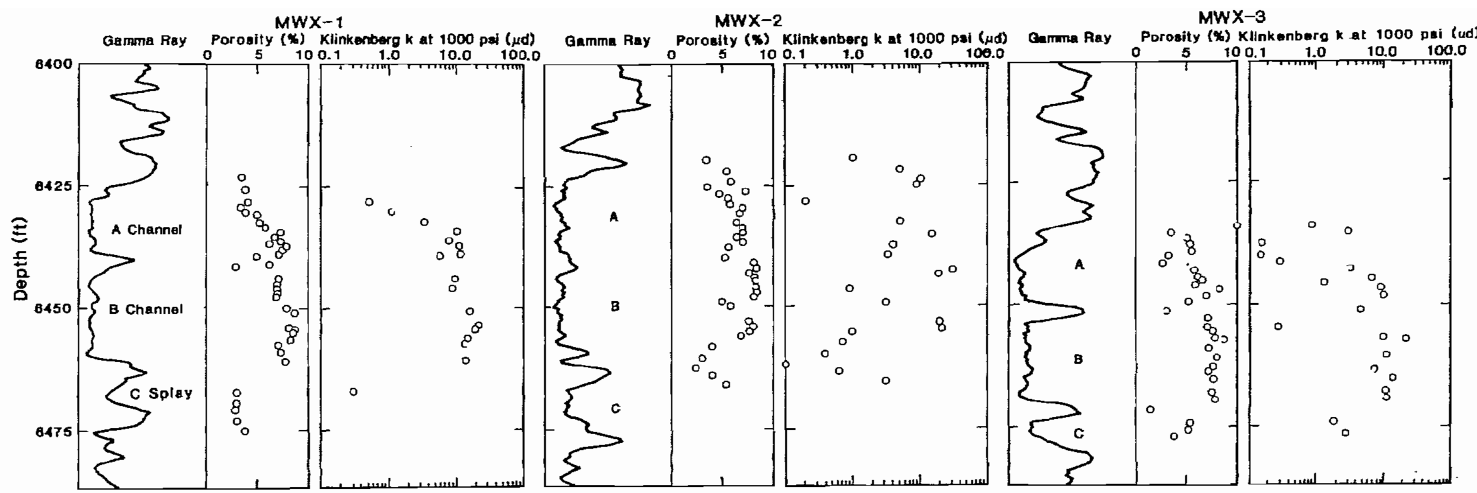

Figure 13. Vertical Porosity and Dry Klinkenberg Permeability Distributions Measured from Core Plugs from Channel and Splay Sandstones in the Coastal Zone (from Lorenz, 1987)

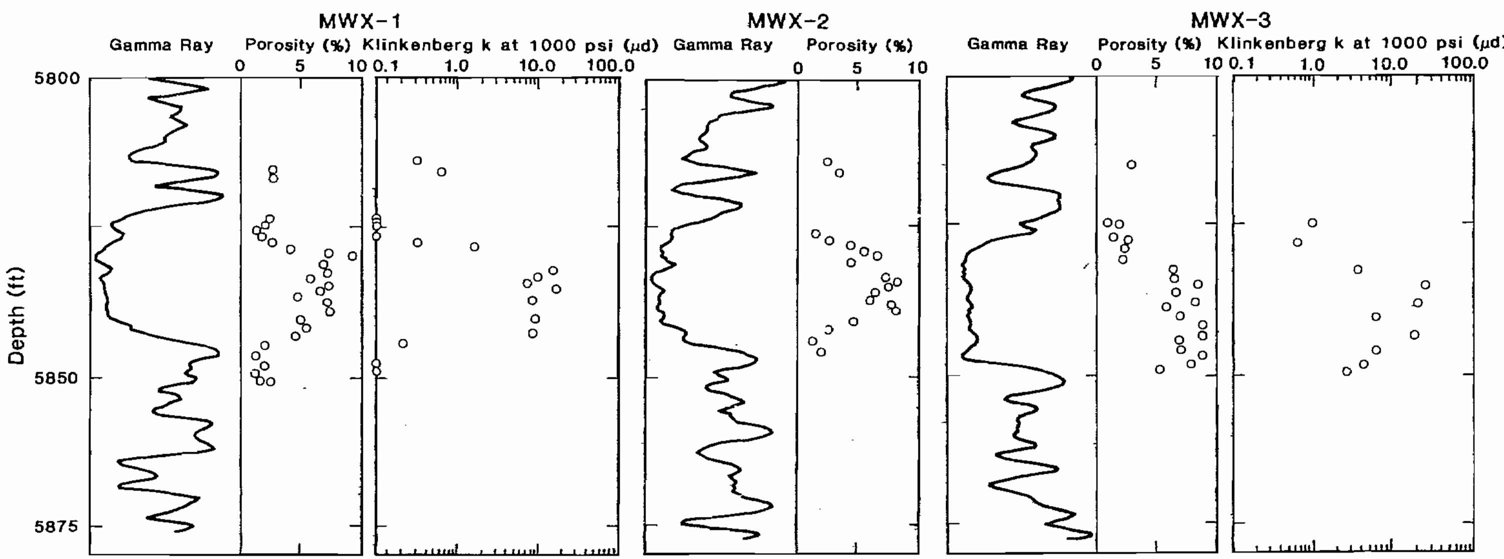

Figure 14. Vertical Porosity and Dry Klinkenberg Permeability Distributions Measured from Core Plugs from Composite, Meander-Belt Sandstones in the Fluvial Zone (from Lorenz, 1987)

ranging from 0.1 to 2.0 microdarcys (Table 2). However, the permeability tends to be slightly higher for a given porosity in this zone than in others (Figure 12). Most of the porosity is secondary; both reduced intergranular and intragranular porosity are present. Most of the pore space is clay-filled and open pores are rare. Thin-section porosity ranges from 0% to 19%.

Permeability of fluvial reservoirs is more sensitive to changes in stress than the permeability of other zones. Figure 15 shows a comparison of stress sensitivity of the fluvial zone (generally the most sensitive) to that of the paludal zone (generally the least sensitive). The higher volume of authigenic dolomite in the paludal reservoirs is suggested to account for a low sensitivity, as well as for a generally lower and narrower range of pore volume compressibility (Figure 16) (Soeder and Randolph, 1984). Kilmer et al. (1987) also report that the permeability of the paludal sandstones has generally low stress sensitivity. Their measurements also show that the lower the permeability of a sandstone, the more sensitive it is to changes in confining pressure.

The mudstones and shales that confine the sandstone reservoirs throughout the formation have permeabilities to brine in the subnanodarcy range. The water-displacement threshold pressures for these strata are well in excess of 1000 psi as measured in the laboratory.

Water Saturation

Water saturations of pore space in the marine sandstones range from 30-40% (Table 2), and are significantly less (20-30%) in the overlying paludal reservoirs. The measured water saturations in the coastal interval are 30-40%, comparable to the marine zones. Water saturation of the fluvial reservoirs increases up-section from 30-40% to a measured high of 62% (Sattler, in preparation). Because of the extremely narrow permeability paths in the matrix rock, increases in water saturation rapidly degrade matrix permeability (Figure 17). The less permeable the rock, the

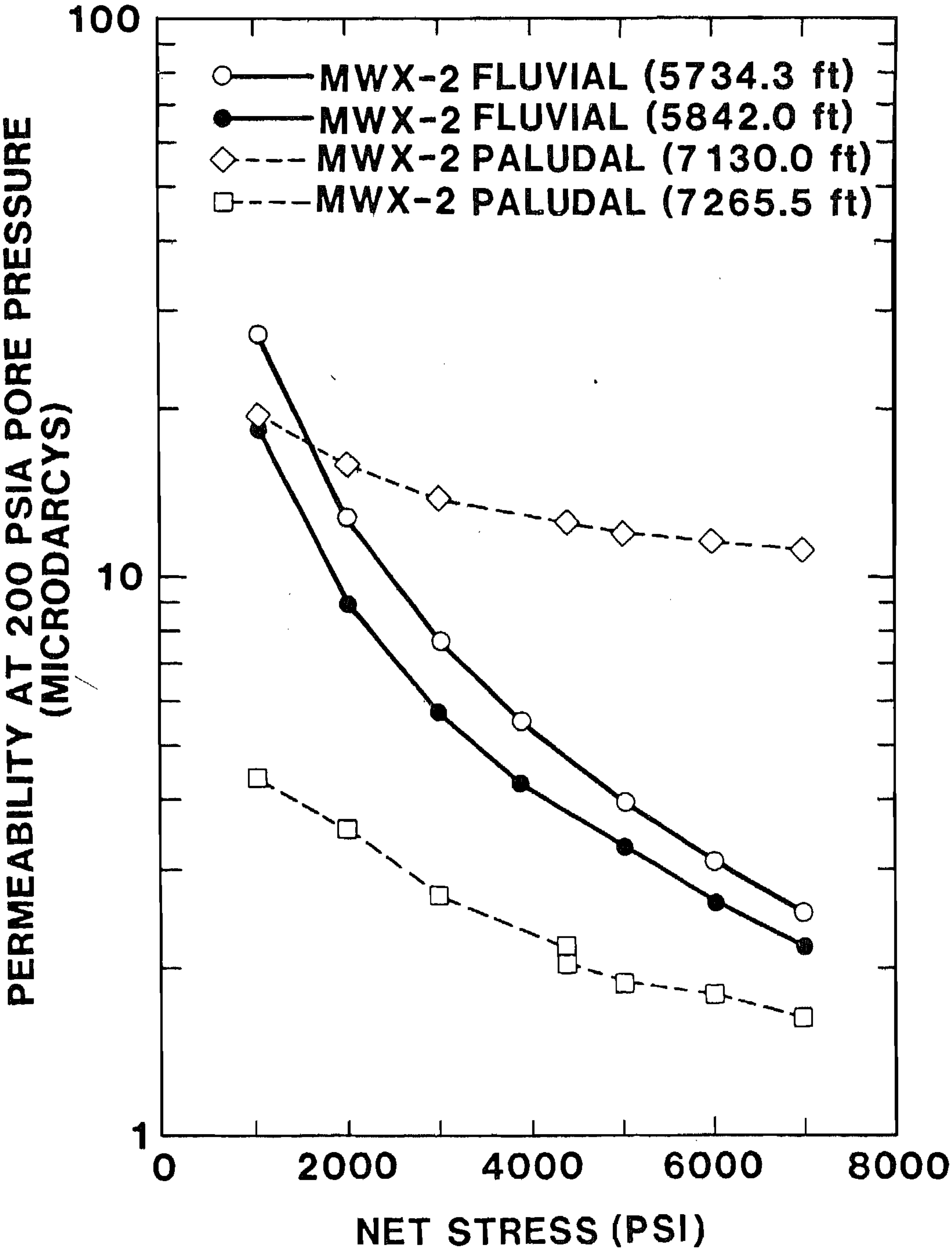

Figure 15. Differences in Stress Dependence of Permeability in Sandstones of Different Depositional Environments (from Sattler, in preparation)

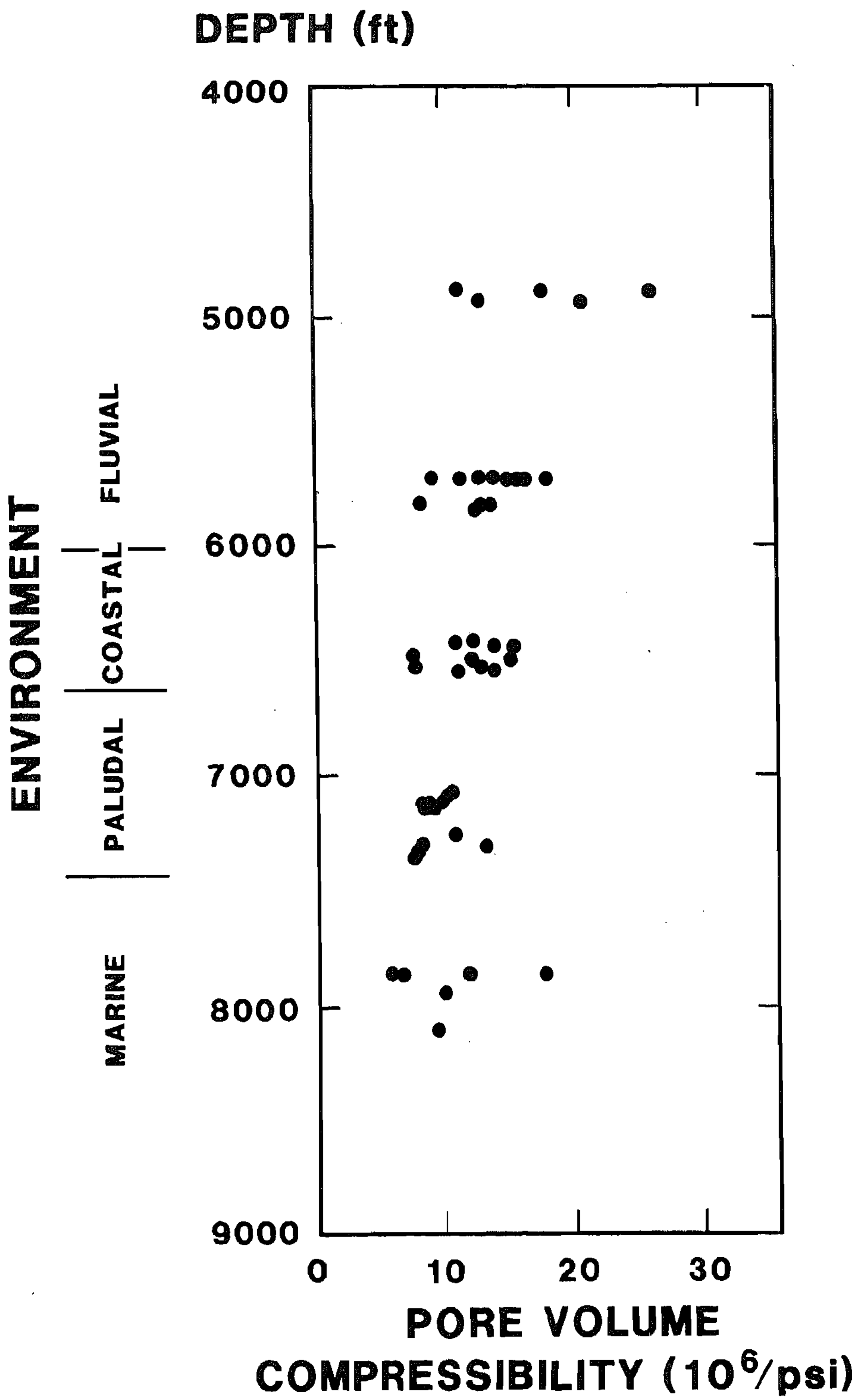

Figure 16. Pore Volume Compressibility Measurements From Sandstones of Different Depositional Environments. (Modified from Soeder and Randolph, 1984, Figure 2, reproduced with permission of the Society of Petroleum Engineers.)

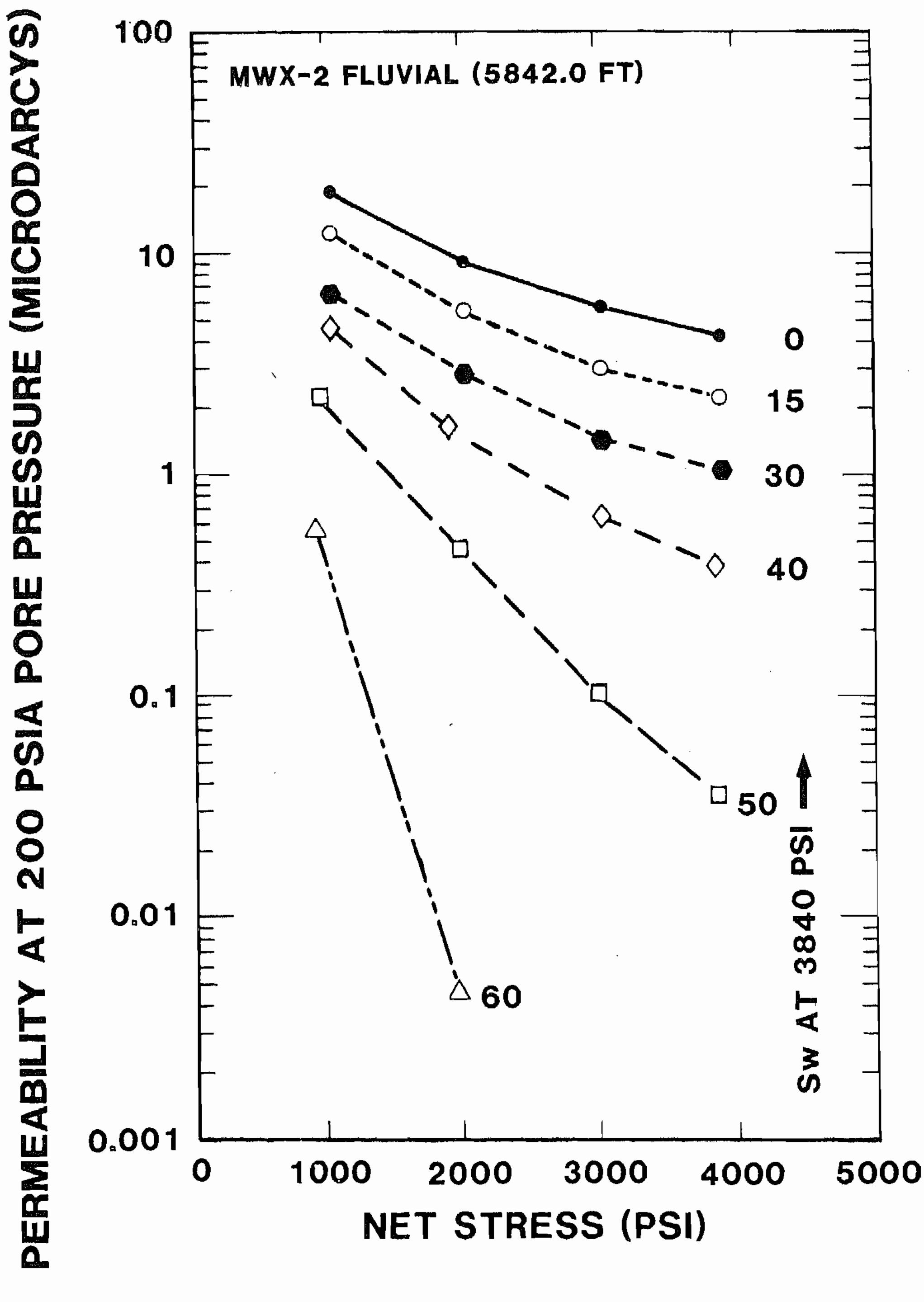

Figure 17. Permeability Dependence of Low-Permeability Sandstones on Water Saturation of the Rock (from Sattler, in preparation)

more pronounced this relationship becomes. Moreover, the higher the water saturation, the greater the dependence of the permeability on changes in confining pressure (Sattler, in preparation). The natural fractures that occur in the same rock are more open, however, and laboratory tests show that with an increase in water saturation, the degradation of the permeability of the fracture system is much less than that of the matrix rock (New Mexico PRRC, 1987; Core Laboratories, 1987).

Water Resistivity

Log analysis suggests that the formation waters of the paludal zone are significantly fresher than other zones of the Mesaverde (Figure 18). This is probably the result of fresh water that was produced during the maturation of the associated coals (Law et al., 1983).

Capillary Pressure

Capillary pressures measured in samples of the reservoirs range from 200-1300 psi at realistic saturations (Table 2), and the variation does not seem to be a direct function of the depositional environment of the rock. The capillary pressures are extremely high--commonly on the order of 1000 psi--in these low-permeability sandstones. This is a result of the higher ratio of surface area to unit pore volume, which (because of surface adsorption and capillary forces) contributes to the retention of significant amounts of water (Ward and Morrow, 1985).

Cation Exchange Capacity

The cation exchange capacity of a rock is primarily a function of its clay content. Thus, the sandstones with the least detrital and anthigenic clay (those in the marine zone) have the lowest cation exchange capacities (Table 2). The marine shales have higher clay contents than the nonmarine mudstones, and therefore can have higher capacities. The cation exchange capacities of the coastal and fluvial sandstones are somewhat higher than

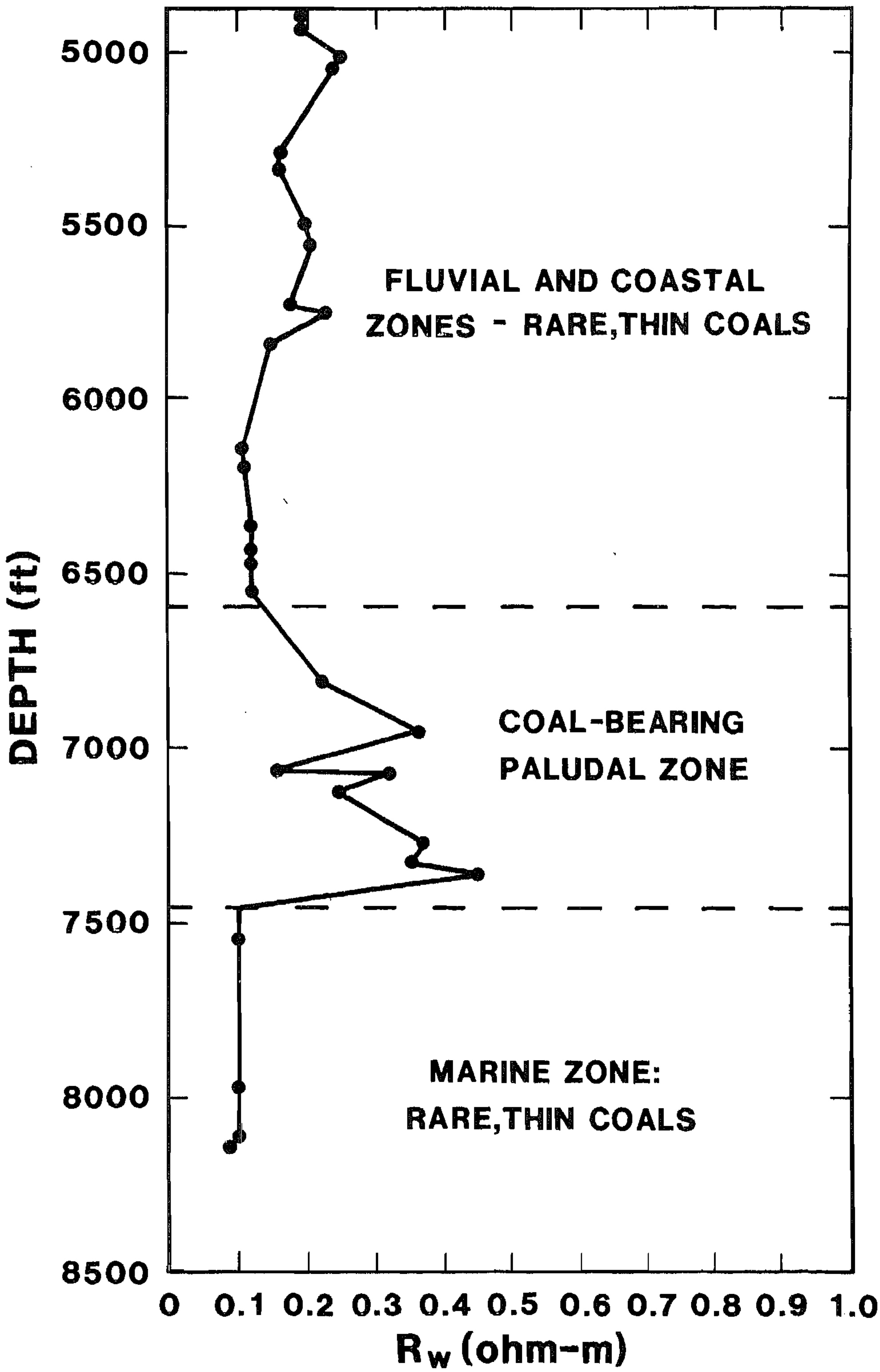

Figure 18. Formation Water Resistivity Profile Through Part of the Mesaverde Group in the MWX Wells, Showing an Anomalous Zone of Freshwater Associated With the Coal-Bearing Interval. (From Law et al., 1983, Fig 5, reproduced with permission of AAPG.)

those of the marine sandstones. In part, this may be correlatable to the overall increasing content of clay and rock fragments upsection. The correlation between clay content and cation exchange capacity is illustrated by Figure 19, showing a parallelism between cation exchange capacity and gamma ray count in two sandstones. Cation exchange capacities of individual sandstones also increase significantly near mudstone contacts.

Young's Modulus

In most zones, Young's Moduli (Figure 20) tend to be highest in siltstones followed by those of sandstones, and then that of mudstones.* The mudstones are composed predominantly of ductile clay platelets with low moduli, but the siltstones and sandstones are composed of quartz, feldspar and rock fragments, and the smaller grain size of the siltstones eliminates many of the ductile rock fragments that lower the Young's Modulus in the sandstones. This effect is also present as a general trend in the sandstones (coarser-grained sandstones tend to have lower Young's Moduli), but grain size is not the only factor, and considerable variability exists. In the marine sandstones, where rock fragments and clays were removed during deposition, the moduli of the sandstones and siltstones are equivalent.

The moduli of the sandstone reservoirs increase with confining pressure, whereas the moduli of the nonreservoir lithologies do not (RE/SPEC. 1982, 1984). In the coastal zone, Young's modulus measured (unconfined) parallel to bedding is significantly higher than the modulus of the same rock when measured perpendicular to bedding (Figure 21). This effect is most pronounced for mudstones, but is also apparent in the sandstones. The difference decreases with increasing confining pressure. Similar differences exist but are not as systematic in the overlying, more heterogeneous fluvial zone, whereas the more homogeneous marine sandstones are almost isotropic at reservoir conditions (Teufel and Warpinski, 1984).

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* Note that the rock-property measurements presented in Figures 20, 22-25 were made on vertically oriented samples; i.e., perpendicular to bedding.

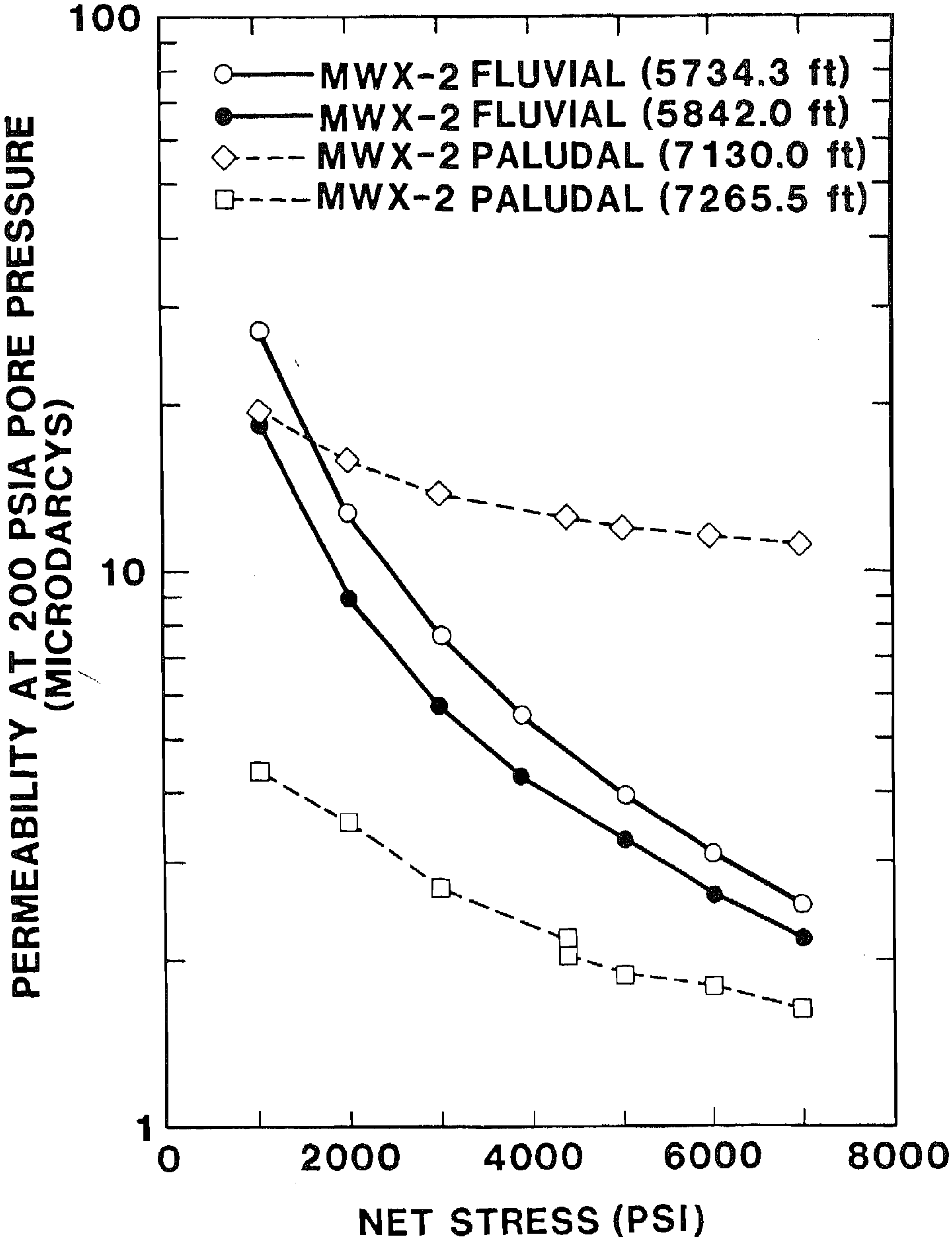


Figure 19. Cation Exchange Capacity in the Corcoran and Cozzette Sandstones Varies Closely as a Function of Clay Content (as indicated by the gamma ray log)

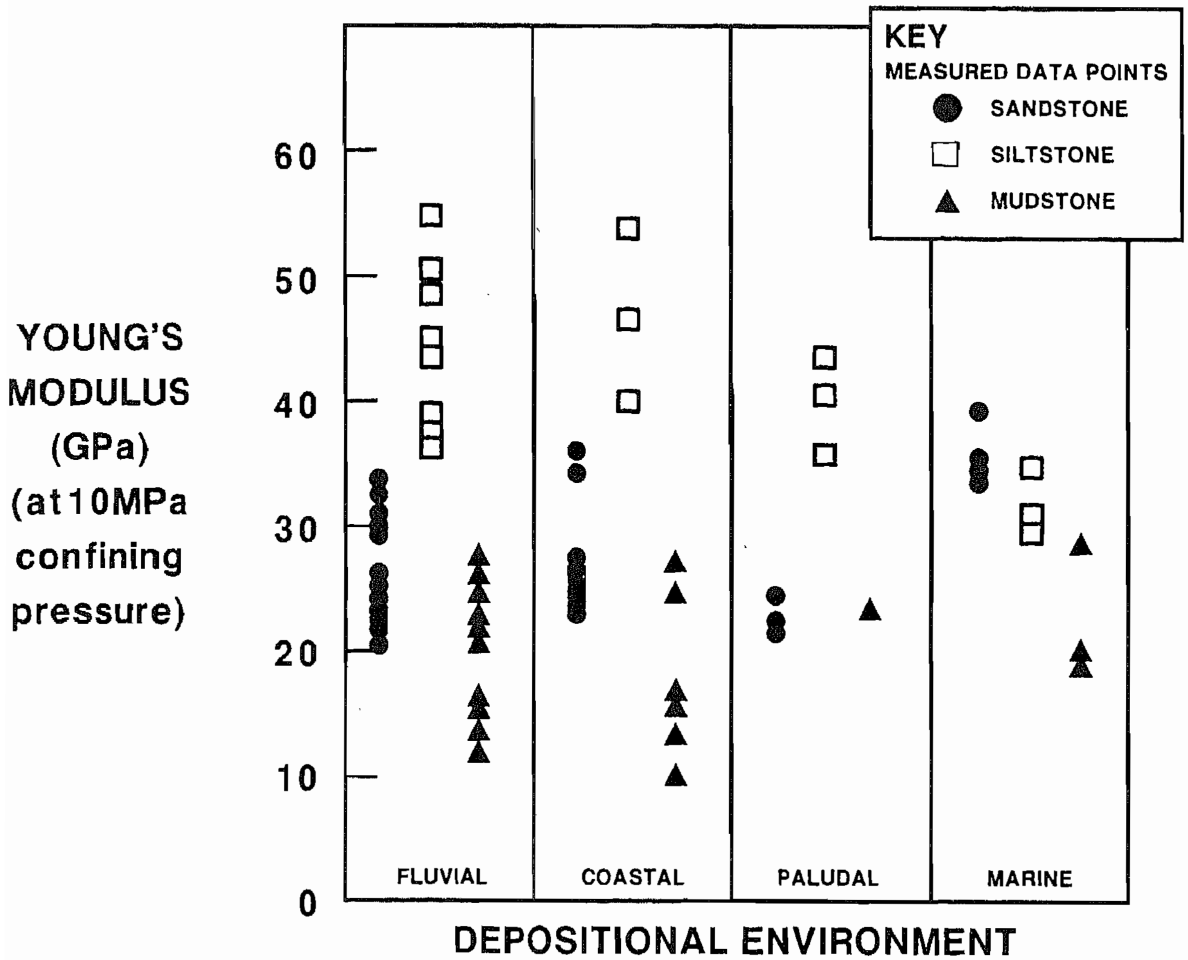


Figure 20. Comparison of Measurements of Young's Moduli by Lithology and Depositional Environment

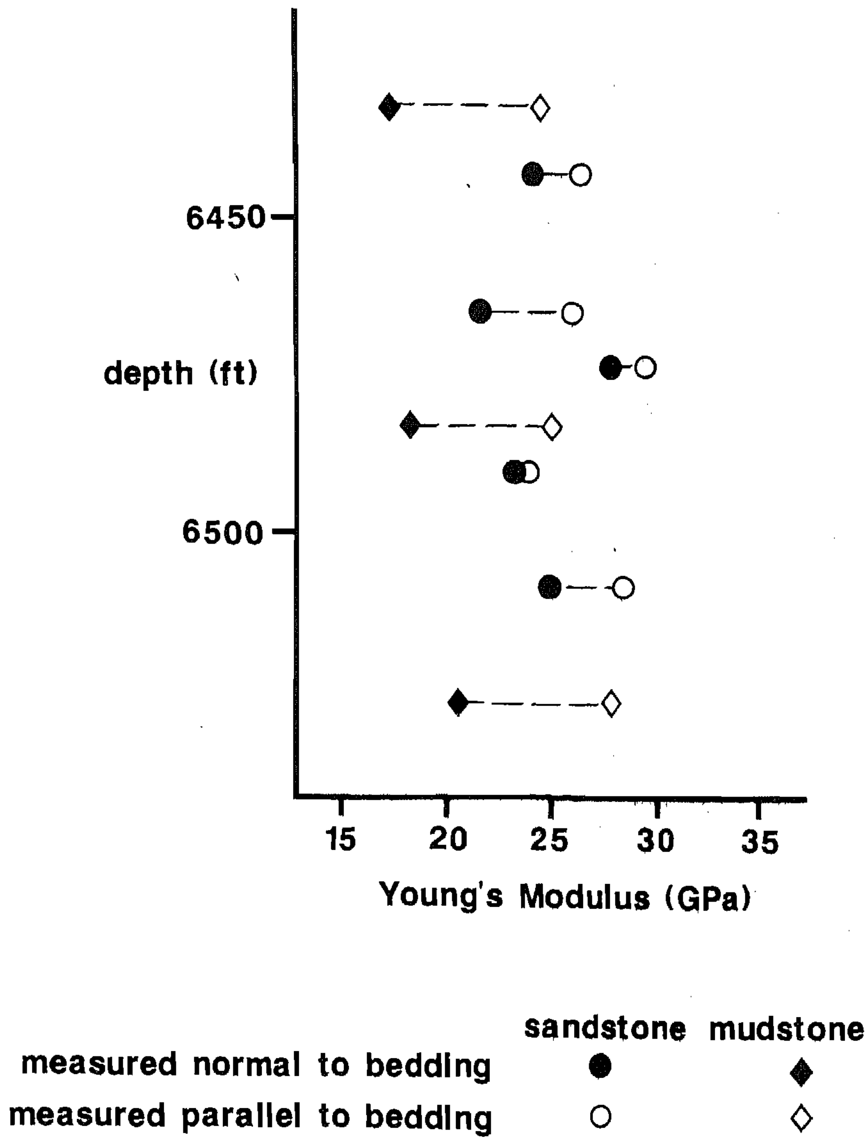


Figure 21. Differences of Young's Modulus Measured Parallel and Normal to Bedding (from Teufel, personal communication, June 1988)

Poisson's Ratio

Poisson's ratio of all lithologies ranges from about 0.15-0.3, and does not change with confining pressure (RE/SPEC, 1982, 1984). Neither does it change significantly with depositional environment, lithology, or confining stress (Figure 22), although the coastal and marine siltstones have relatively low values. Poisson's ratio measured parallel to bedding is commonly a few percent higher than the ratio measured perpendicular to bedding.

Compressive Strength

Compressive strengths of the Mesaverde rocks show a wide range of variability (RE/SPEC, 1982, 1984). The compressive strengths of the paludal reservoir sandstones are on the low end of the scale (Figure 23), again reflecting the difference in paragenesis of these rocks. Compressive strengths of the other reservoir sandstones are comparable to each other, but there is considerable scatter in the measurements, reflecting lithologic heterogeneity. Compressive strengths of the nonmarine siltstones tend to be higher than those of the associated sandstones, whereas the reverse appears to be true in the marine section.

Tensile Strength

Measurements of the tensile strength (Brazilian test) of Mesaverde rocks show variability of similar scale and relationships as measurements of compressive strength (Figure 24). Siltstones are the strongest lithology in all environments except possibly the coastal, whereas the mudstones are the weakest lithology in all environments except the paludal (where, in contrast to the other zones, the sandstones are the weakest lithology).

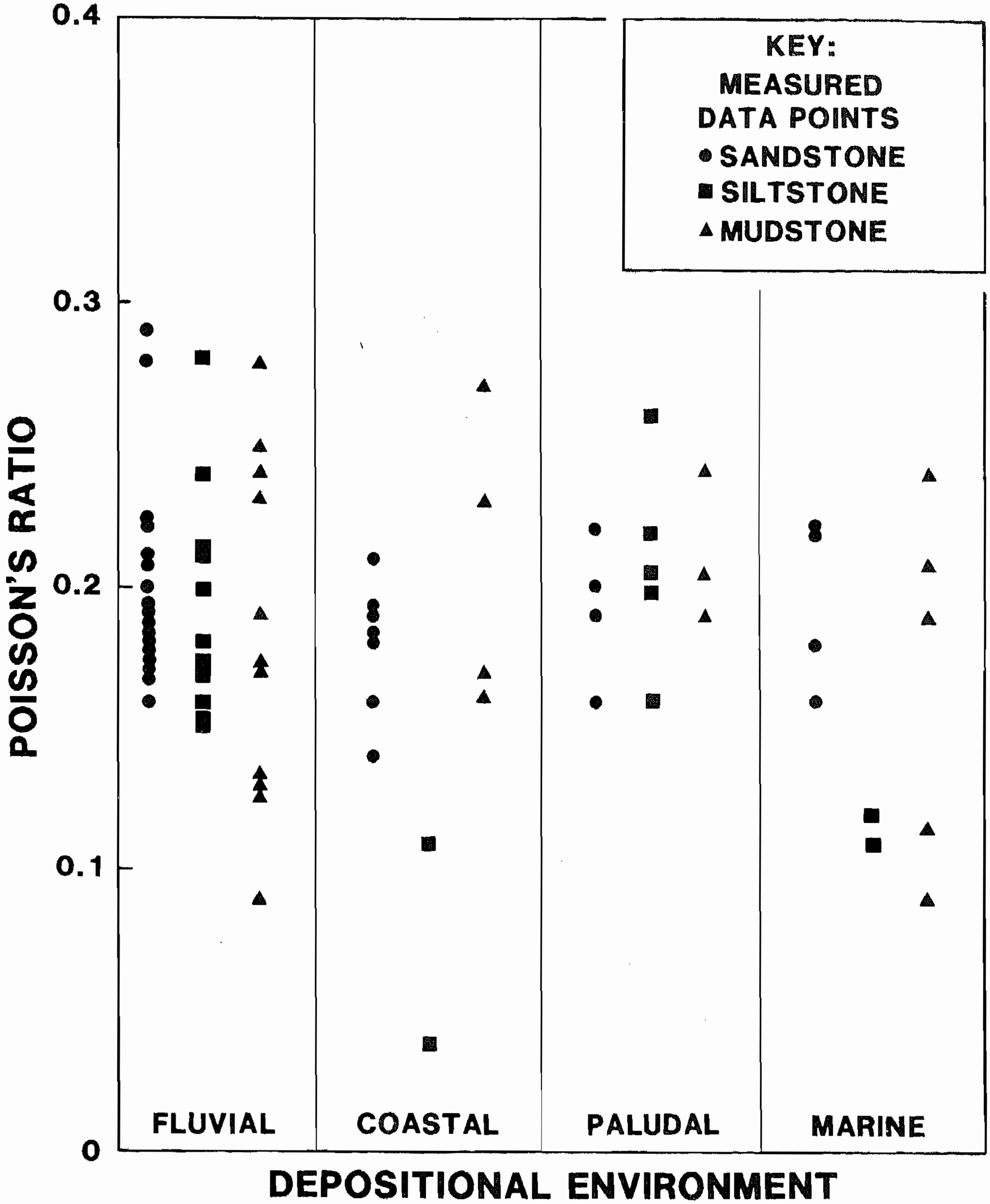


Figure 22. Measurements of Poisson's Ratio by Lithology and Depositional Environment

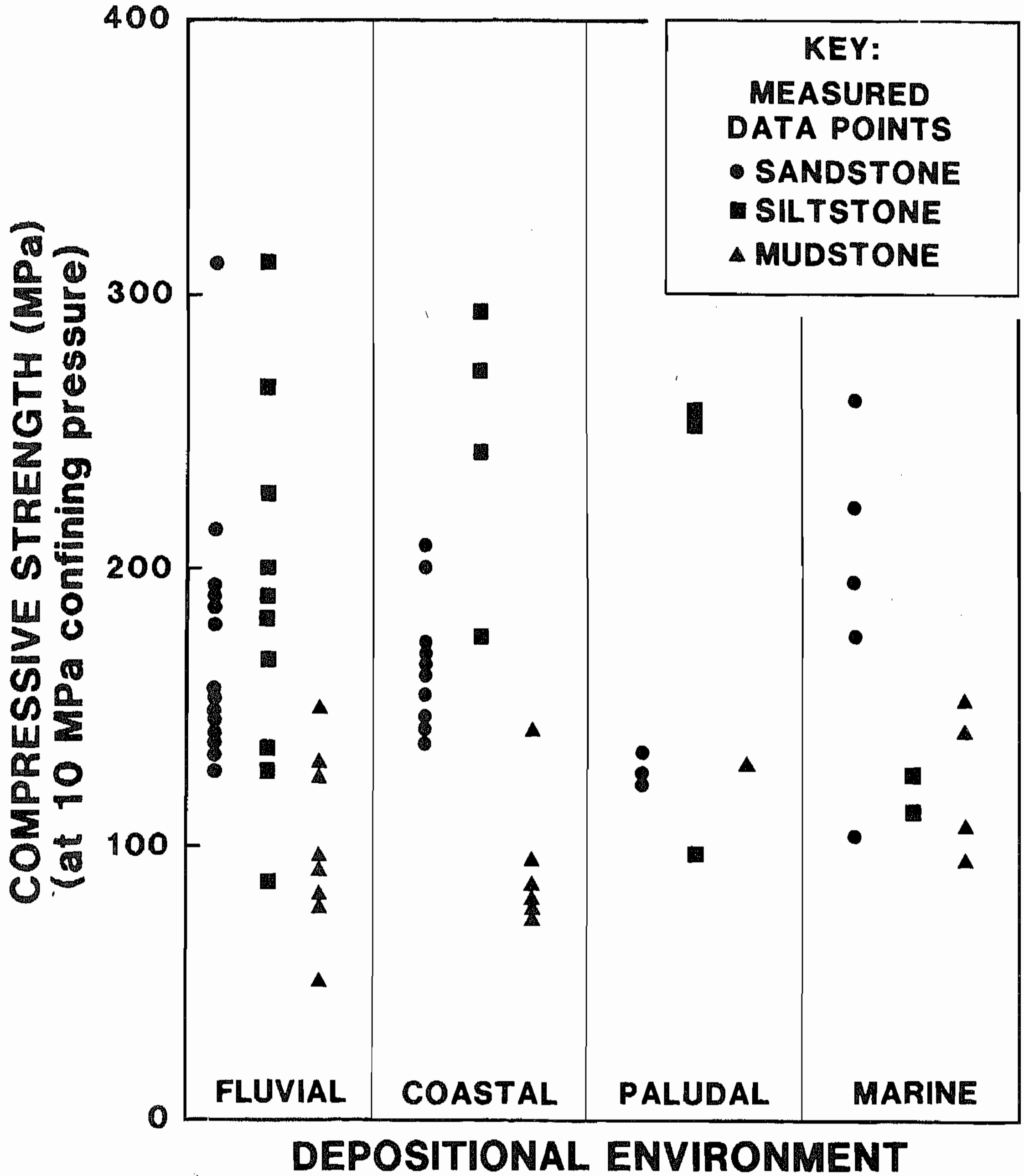


Figure 23. Measurements of Compressive Strengths by Lithology and Depositional Environment

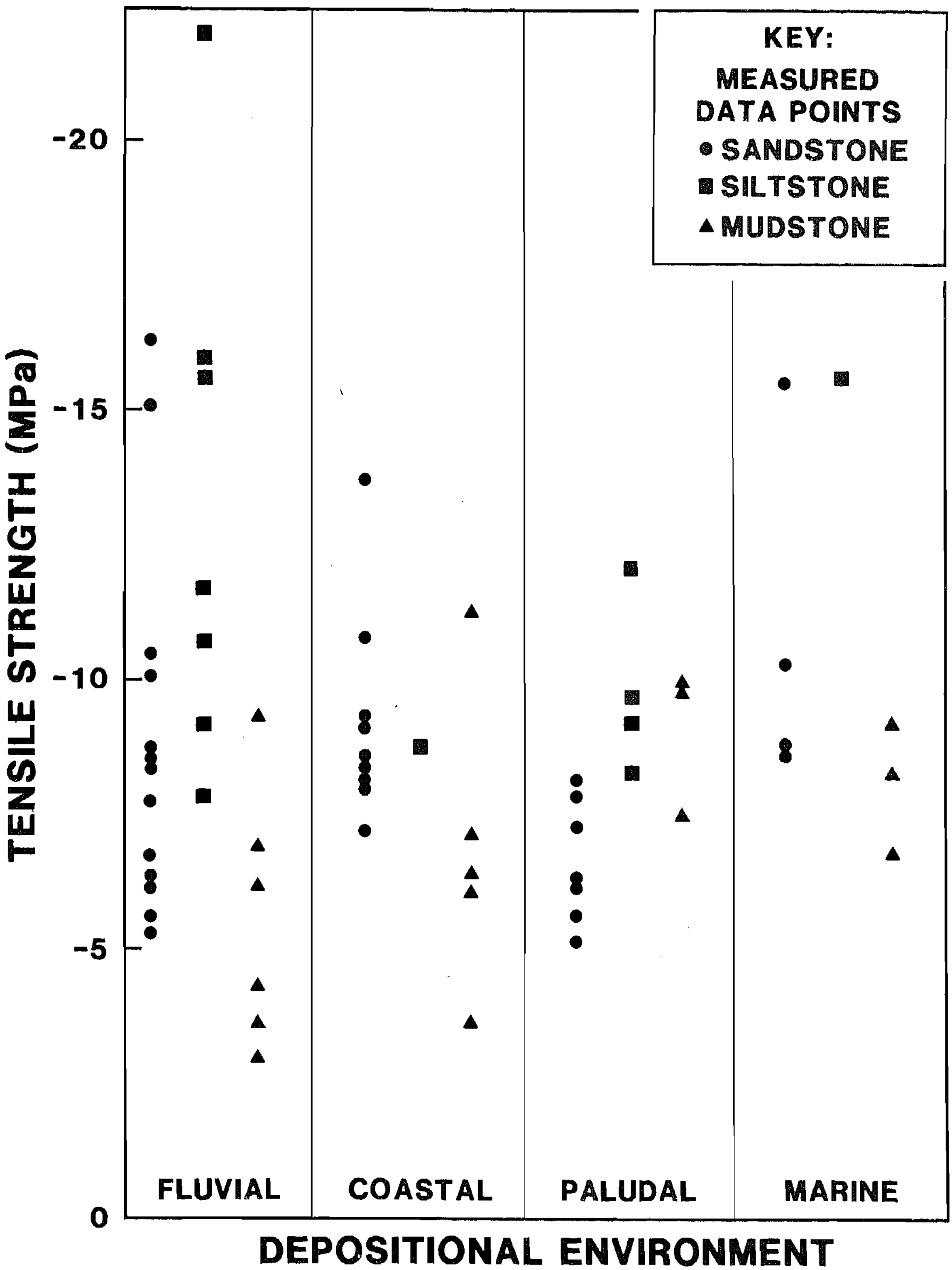


Figure 24. Measurements of Tensile Strength by Lithology and Depositional Environment

Fracture Toughness

Fracture toughness (Figure 25) ranges from 0.69-2.40 $MPa.m^{1/2}$ for sandstones, and from 0.17-2.61 $MPa.m^{1/2}$ for nonreservoir rocks. Siltstones are toughest, except in the paludal zone, whereas the mudstones are weakest. The mudstones (shales) of the marine zone, however, are apparently as tough as the other lithologies in that zone. For fracture toughness, at least, there is a distinction between the behavior of true shales of the marine zone, and the more amorphous and heterogeneous mudstones in the nonmarine strata.

USE AND APPLICATION OF MULTIWELL EXPERIMENT CORE PROPERTIES

Core data were used at every stage of production testing and completion, and are presently being used in paleostress and fracture genesis modeling at the MWX site and in the basin. During the drilling of the first MWX well, the initial designations of the reservoirs of interest were made using routine core analyses, especially porosities and water saturations. In order to accurately model the reservoirs to predict and describe production performance in these unconventional reservoirs, however, it was necessary to conduct special reservoir core analyses on the matrix rock, i.e., to measure permeabilities and capillary pressures at restored pressure conditions.

Rock and reservoir properties vary significantly with lithology, with changes in the Late Cretaceous environment in which the sandstones were deposited, and with the subsequent diagenetic environments. Although documented locally at the MWX site, such variability is probably common to all Mesaverde facies in the Rocky Mountain region. Marine and the coal-bearing paludal intervals display the most obviously different characteristics, due primarily to high-energy depositional conditions in the former case, and to differences in the local geochemical environment of diagenesis created by the presence of coals in the latter case. Many of the characteristics of the other reservoirs can also be attributed to

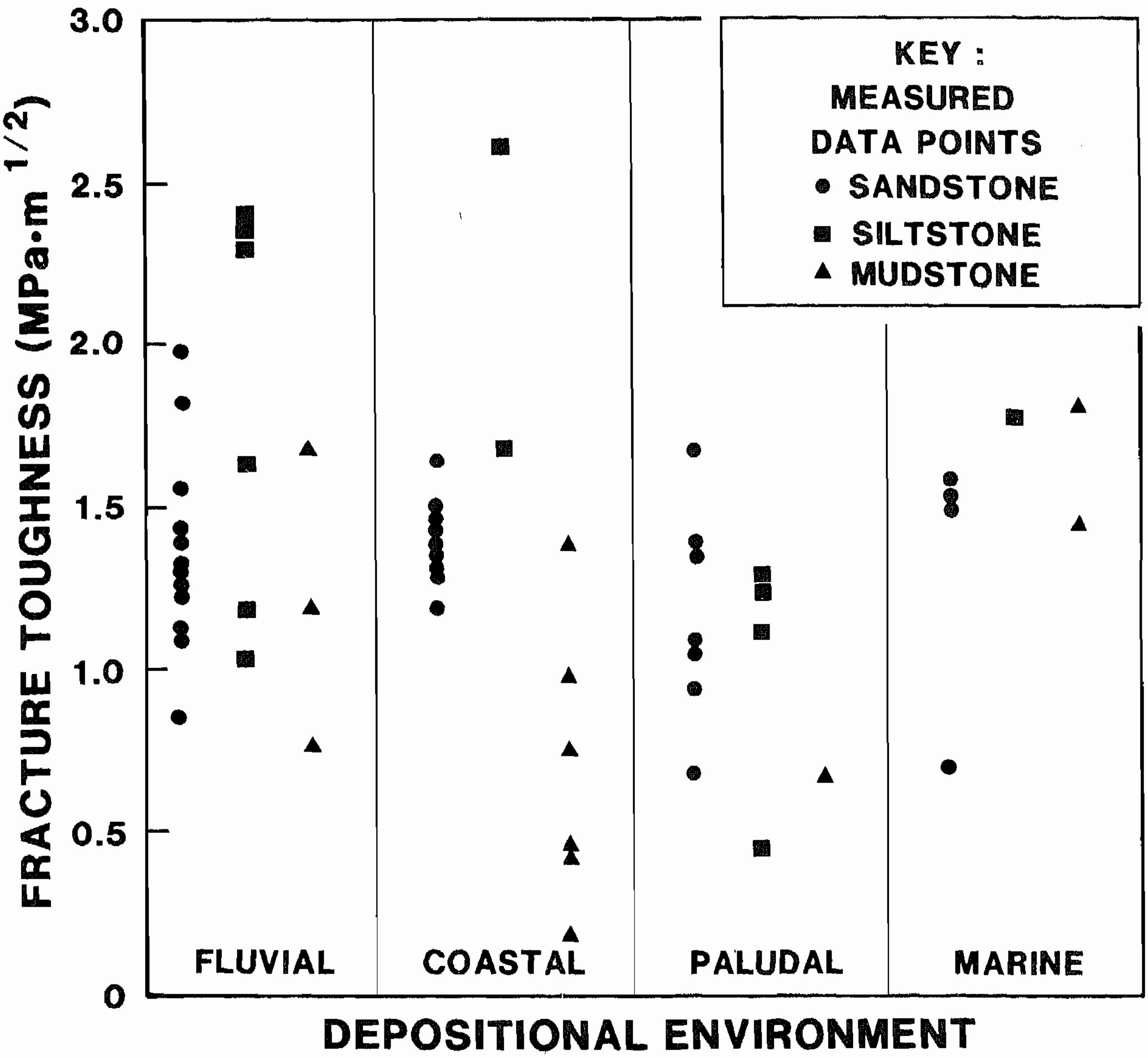


Figure 25. Measurements of Fracture Toughness by Lithology and Depositional Environment

depositional environment, such as the winnowing and sorting of grain sizes and composition that occurred in the high-energy, shallow-marine environment.

Petrology controls not only porosity and permeability, but stress sensitivity as well. The sensitivity of permeability to stress varies inversely with grain size: the sandstones with larger grain sizes (i.e., that contain more of the ductile rock fragments) are more stress sensitive. Finer-grained sandstones are less stress sensitive. Permeability stress sensitivity and pore-volume compressibility also vary as a function of depositional environment (Soeder and Randolph, 1984; Kilmer et al., 1987): paludal sandstones with a relatively strong dolomite framework, and fine-grained, cleaner marine sandstones are least stress sensitive. Because the permeabilities of these tight sands are usually strongly pressure dependent, these measurements had to be at the appropriate confining pressures. (The permeabilities derived from routine core analyses were measured at only 200 psi confining pressure, therefore those data could only be construed as rough qualitative indicators of in situ permeabilities.) Moreover the permeabilities in these tight sands were extremely dependent on water saturation.

The permeabilities measured from reservoir testing were at least one to three orders of magnitude higher than the corresponding matrix-rock data. Consequently, dry and water-saturated permeability measurements were made on core samples containing natural fractures. The measured permeability from naturally fractured core samples is considerably higher than the matrix-rock values, and helps to reconcile the large disparity between matrix and formation test permeabilities. It also provided one of the strongest indications of the importance of natural fractures in production from certain tight gas sandstone formations.

Petrology varies as a function of depositional environment, and controls most of the parameters described here. Young's Modulus, Poisson's Ratio, and the different types of rock strength measurements are all dependent on the composition of the rock. These in turn control parameters such as the closure stresses in the formation and the anisotropy of rock properties. Young's Modulus measured at different angles to bedding varies markedly in mudstones and somewhat in sandstones. Poisson's ratio varies only slightly in this respect.

For Mesaverde sandstone reservoirs at the MWX site, the dominant controls on gas production potential are reservoir size, reservoir pressure, lithologic heterogeneity, and distribution/frequency/connectivity of the natural fracture system (Northrop, 1988). However, the smaller-scale rock and reservoir properties described here play an important role in the volume of reserves, and in the design of drilling and stimulation fluids and techniques.

For example, acid stimulations and many commonly used stimulation fluids react adversely with several of the petrologic components of the Mesaverde reservoirs described here, especially the iron-bearing chlorites. Nonreactive nitrogen-foam stimulations have been the most successful at the MWX site. Mineralogy and clay analyses are also important to the determination of the presence/absence of swelling clays that would present problems during the stimulation, and for predicting possible damage from migrating fines.

The largest reservoirs are the marine blanket sandstones, and sustainable production occurs from these units--despite their low permeability--because of the presence of natural fractures. The formation of these fractures was controlled by rock properties: rocks with high elastic modulus (sandstones and siltstones) are fractured, whereas mudstones are not. Thus fracture permeability distribution is a function of the distribution of rock properties. Similarly, the extent of hydraulic fractures for stimulation is controlled by the in situ stresses that are governed largely by rock properties.

Many of the properties described here are important to the interpreta- ... ehole geophysical logs. Cation exchange capacity (CEC) and water resistivity profiles are necessary to understanding self-potential logs that often give ambiguous readings in tight formations. Cation exchange measurements and other electrical properties were used as inputs to the Waxman-Smits formalisms in log analysis. CEC measurements also provided a rough indication of the amount and activity of the existing clays in a formation.

Mechanical rock properties are important inputs to predicting the behavior of hydraulic fractures, the modeling of the genesis of natural fractures, and in situ stress modeling. Young's modulus was used in hydraulic fracture length and width predictions. Under certain conditions, fracture toughness measurements are useful in predicting hydraulic fracture heights. Tensile and compressive strengths were used in estimating the paleostress behavior of the rock at the MWX site. Poisson's ratios were used in modeling present in situ stresses.

Capillary measurements helped provide an indication of the formation's susceptibility to invasion and damage when drilling or conducting a stimulation with water-based fluids. These measurements are also useful in predicting the clean-up time of the matrix rock after a stimulation. Furthermore it appears that the capillary pressure provides an indication of the ability of the matrix rock to keep the natural fractures free of water at existing reservoir conditions, and of the ability of the matrix rock to help mitigate fluid damage to the narrow natural fractures occurring at MWX. Capillary measurements are especially important in low-permeability reservoirs.

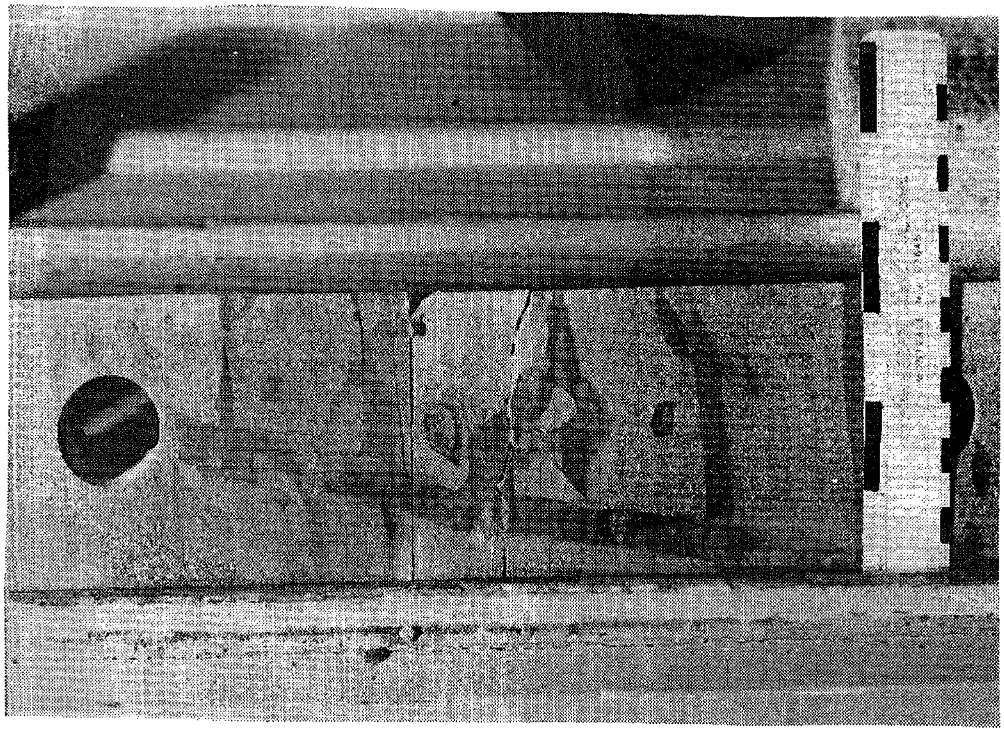
SUMMARY AND CONCLUSION

The study of the petrological and petrophysical properties of the tight Mesaverde sandstones at the MWX site was large enough in size and breadth that a comprehensive summary can be made of these respective properties. Many aspects of the petrophysical properties of the different reservoirs of the formation can be explained in terms of their particular depositional environments. This report presented the stratigraphy, depositional environments, petrological properties, and the petrophysical properties of the formation at the Multiwell site. The petrological characteristics of each depositional environment (marine, paludal, coastal, fluvial) were presented in detail, highlighting the unique features for each environment.

The reservoir properties of the rock were summarized for each of the depositional environments. The petrological characteristics can reasonably explain some of the variation, especially of two critical parameters: porosity and permeability. Petrology studies also show why the measured values for these sandstones are less than those of conventional sandstones. Petrological characteristics help to explain the variation of the CEC values with depositional environment, as well as the general characteristics of capillary pressure curves for tight sandstone core.

The mechanical rock properties were presented for the different depositional environments. For Young's modulus, a general trend of the measured values is seen with depositional environment. The petrological properties of the rock account for some of the differences between environments noted in the sandstones, siltstones, and mudstones for Young's modulus, compressive strength, tensile strength, and fracture toughness. Exact correlation of these properties with depositional environment is still uncertain, however. The measured values of the Poisson's ratio seem to be independent of lithology and confining pressures. These tight sandstones are complex in many aspects, hence simple correlation between all sets of petrological and petrophysical properties is not to be expected.

The petrophysical properties obtained from the Multiwell Experiment core analyses provide the most thorough description of Mesaverde reservoir characteristics available in the Piceance basin. This data base is one of the important outputs of the Multiwell Experiment (MWX). The properties presented here were used to describe the reservoir, to model in situ stress, and to plan and predict the stimulations of selected sands at the Multiwell site.



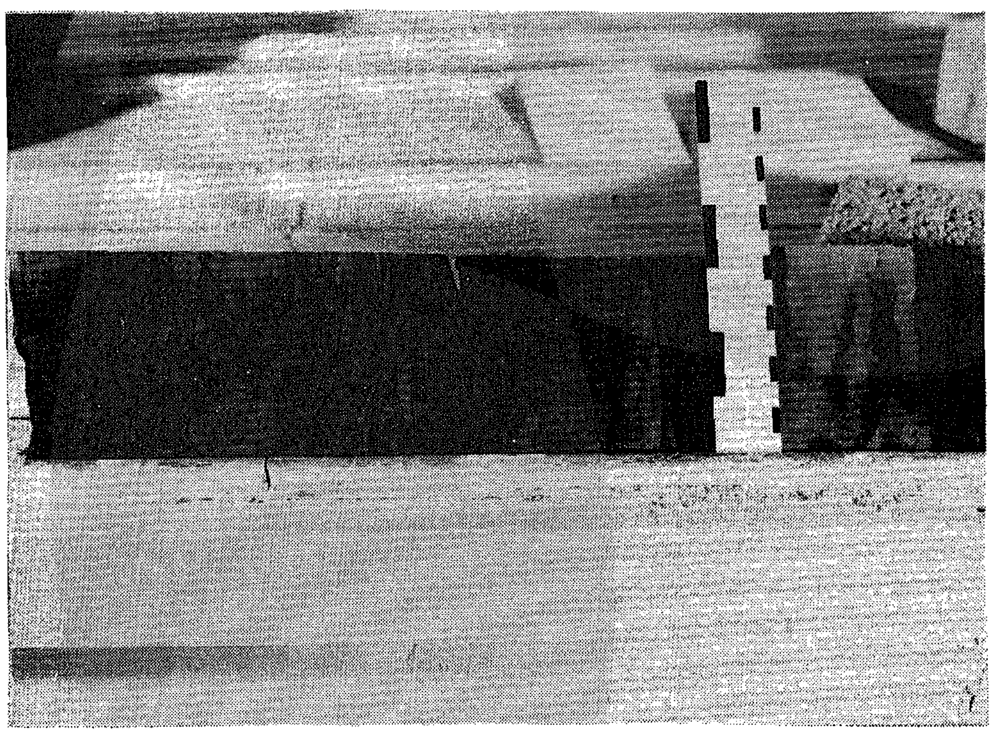
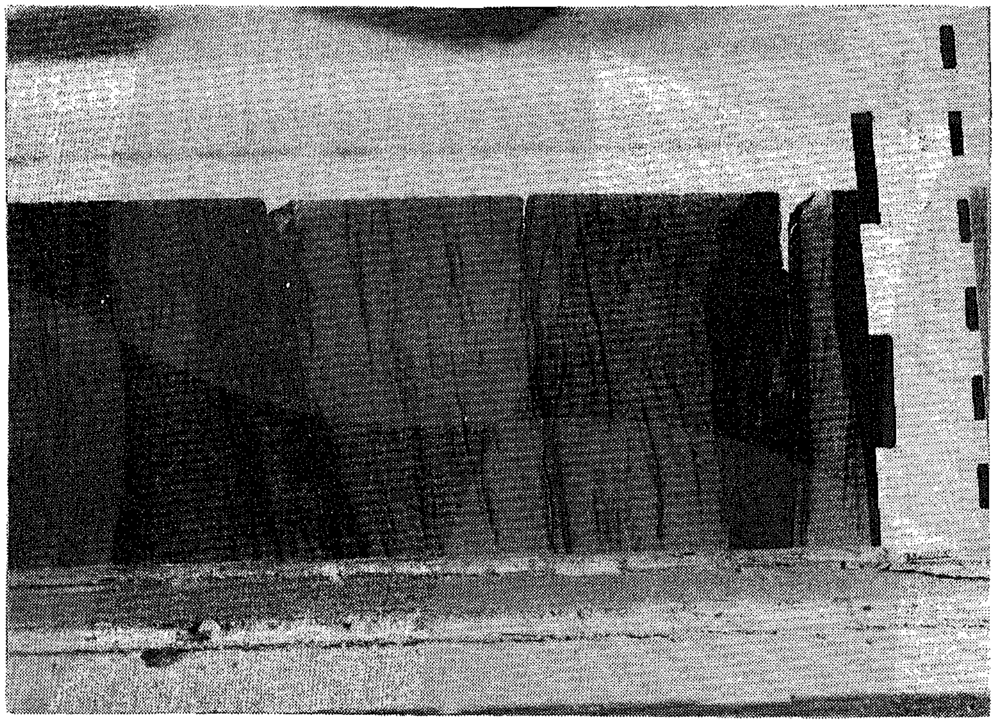


Plate 1A Photographs of Slabbed Core From the Marine Zone: a - Upper Shoreface: Burrowed, Cross- and Parallel-Bedded Sandstone; b - Lower Shoreface: Burrowed, Thin-Bedded Sandstones and Shales (inch/centimeter scale, upsection to left)



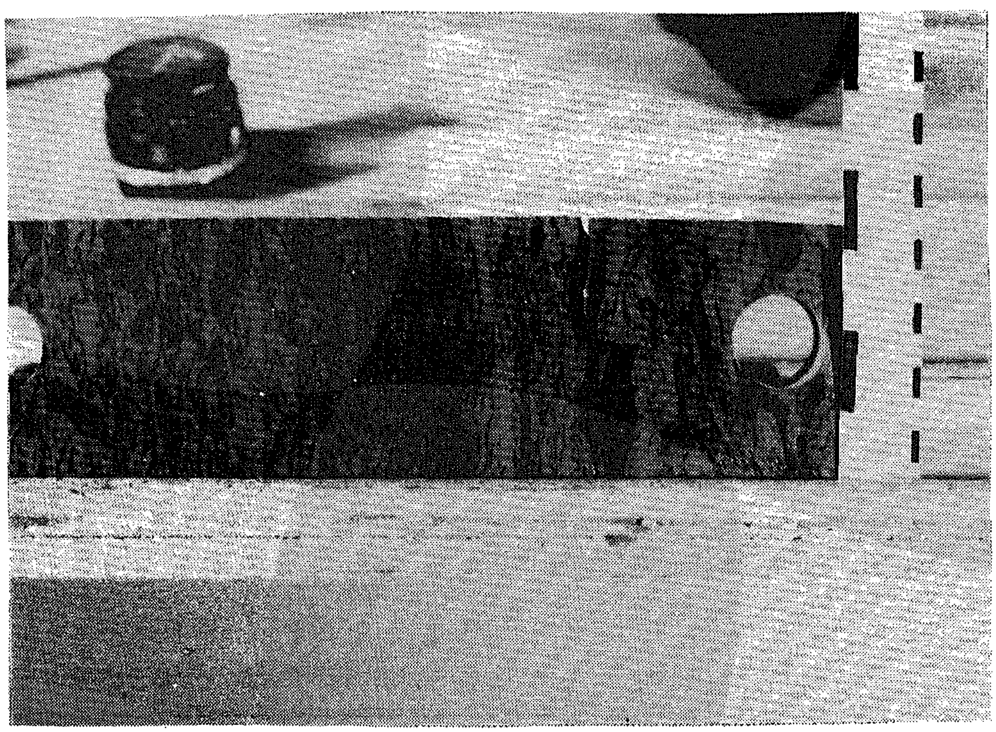
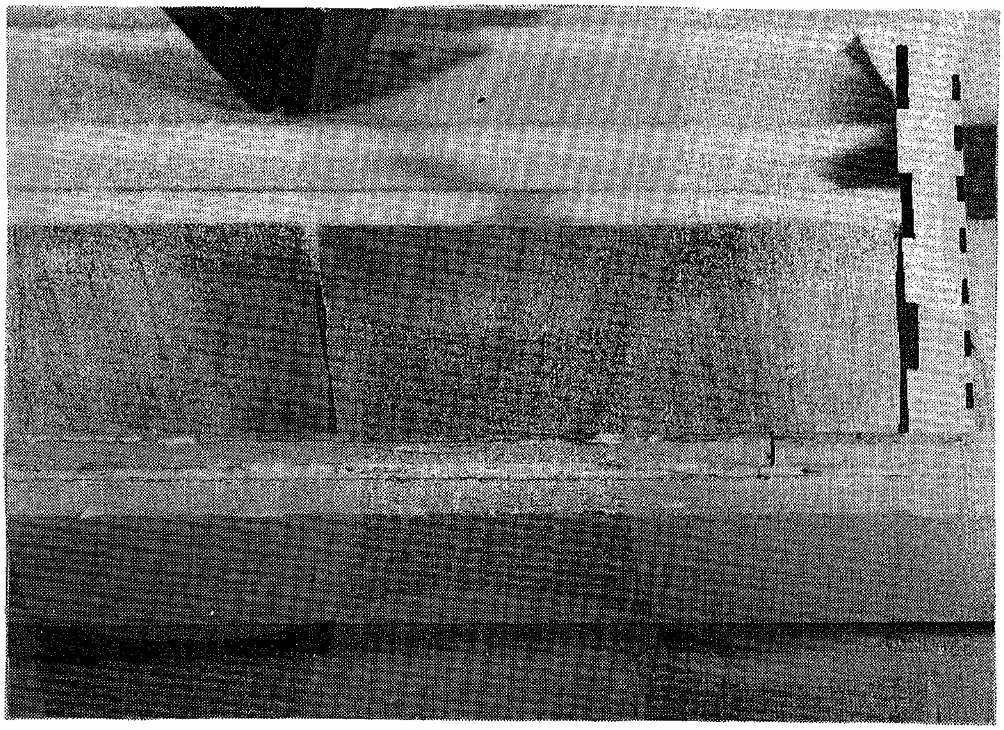


Plate 1B Photographs of Slabbed Core From the Paludal Zone: a - Distal Splay: Thin-Bedded, Rippled Sandstone with Muddy Drapes; b - Proximal Splay or Crevasse Channel: Ripup Clasts in Sandstone Matrix (inch/centimeter scale, upsection to left)



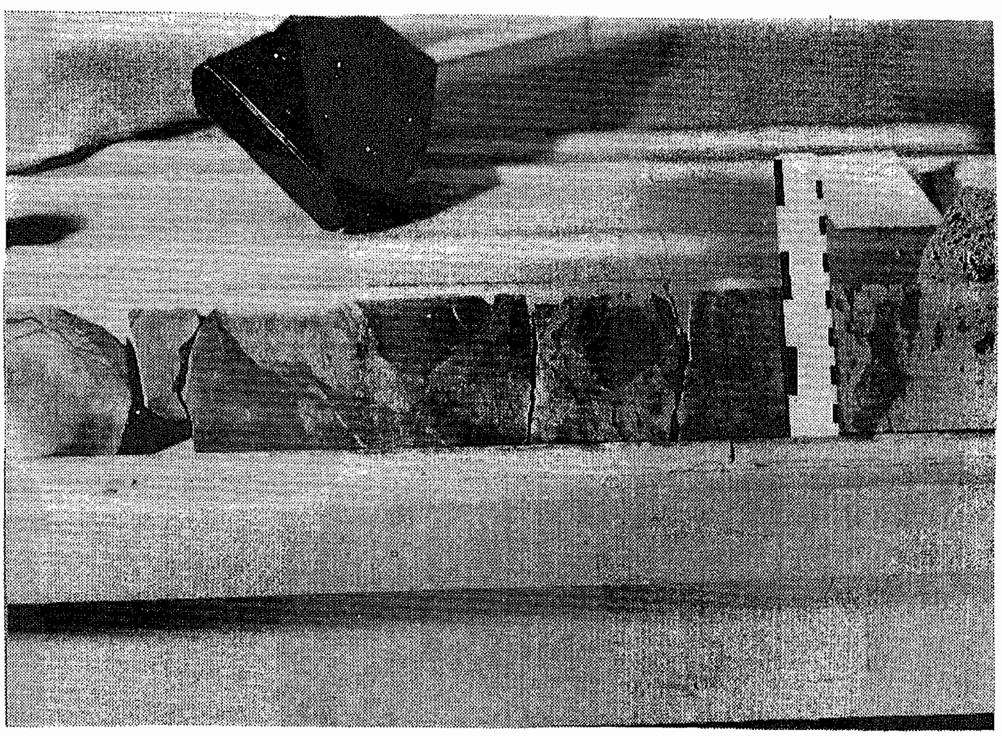
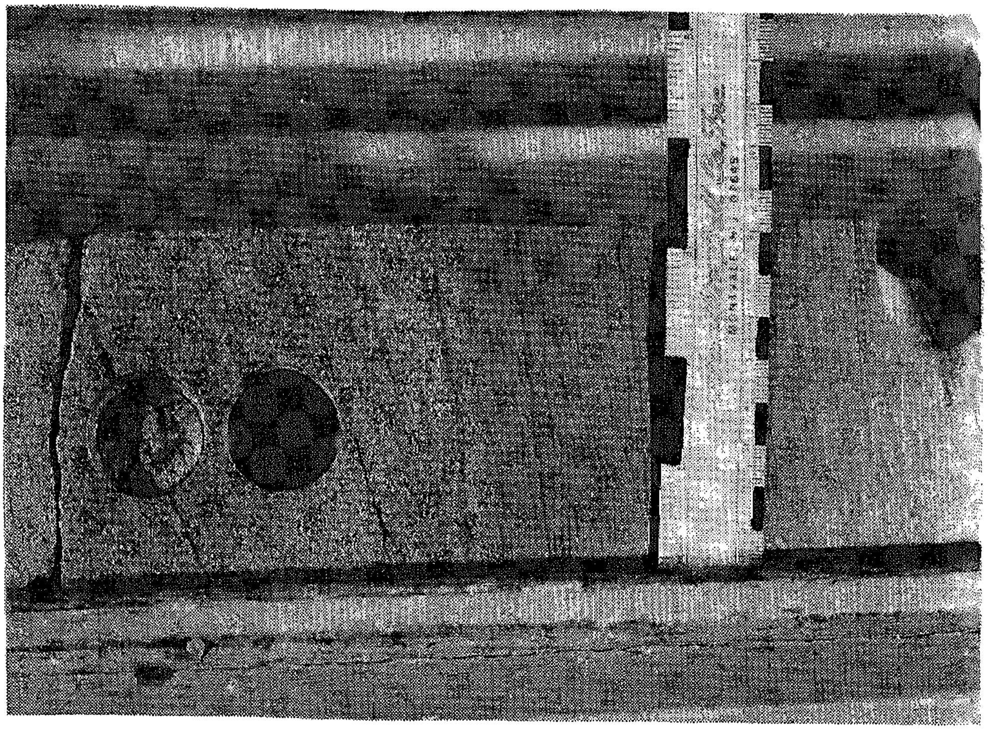


Plate 1C Photographs of Slabbed Core From the Coastal Zone: a - Channel: Cross-Bedded Sandstone; b - Overbank: Siderite Nodules, Sandstone, and Mudstone in a Soft-Sediment Deformation Mixture (inch/centimeter scale, upsection to left)



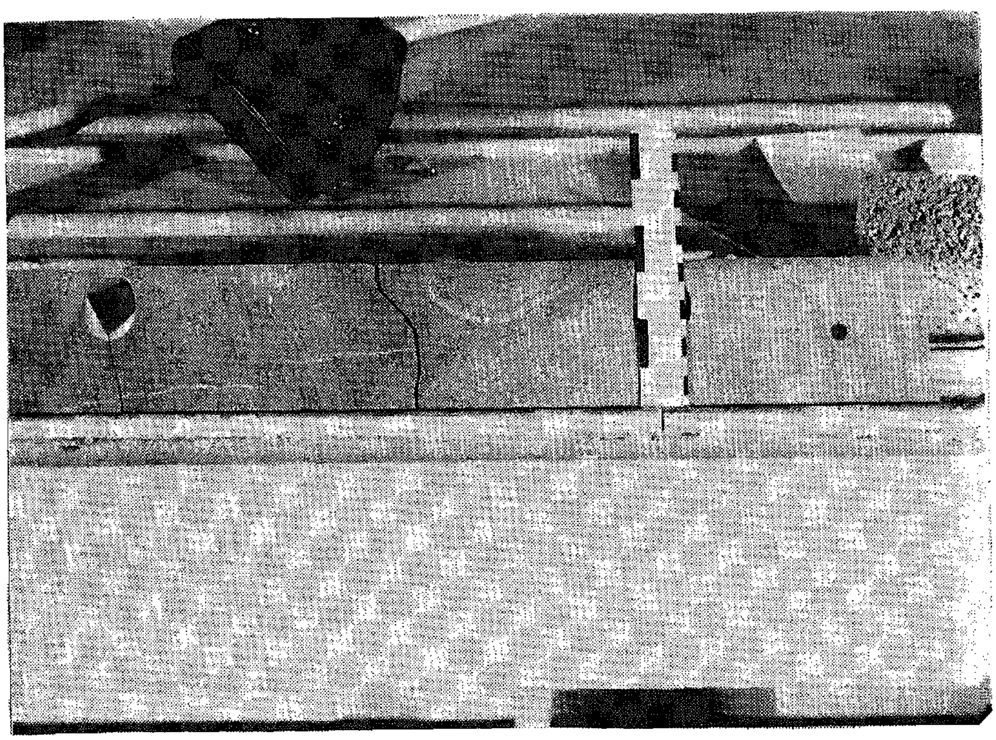
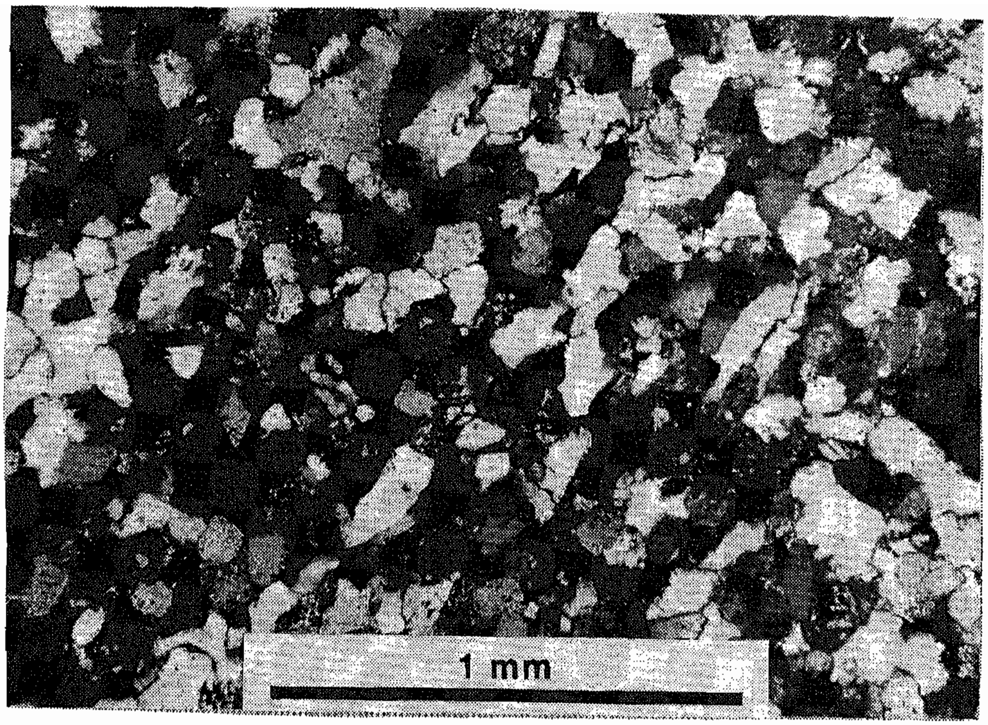


Plate 1D Photographs of Slabbed Core From Meander-Belt Sandstones in the Fluvial Zone: a) Lower-Point-Bar Coarse, Cross-Bedded Sandstone Overlying Upper-Point-Bar Rippled Sandstone; b) Soft-Sediment Deformation and Fracture in Channel Sandstone (inch/centimeter scale, upsection to left)



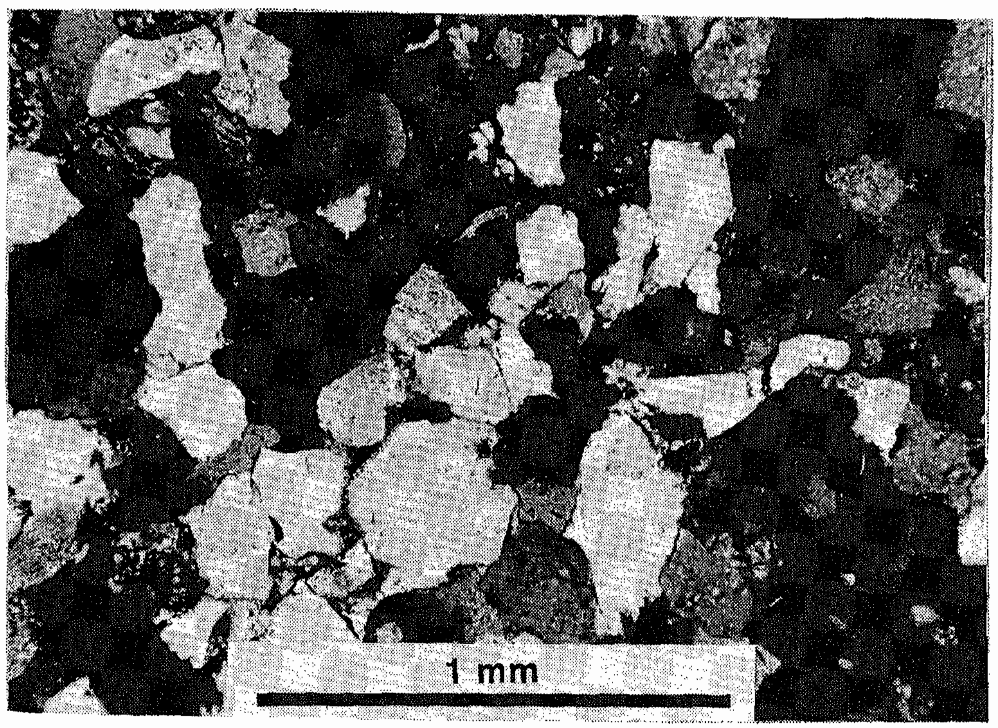


Plate 2A Thin-Section Photomicrographs of Sandstone Reservoirs in the Marine Zone: Polarized Light, Impregnated with Blue Epoxy

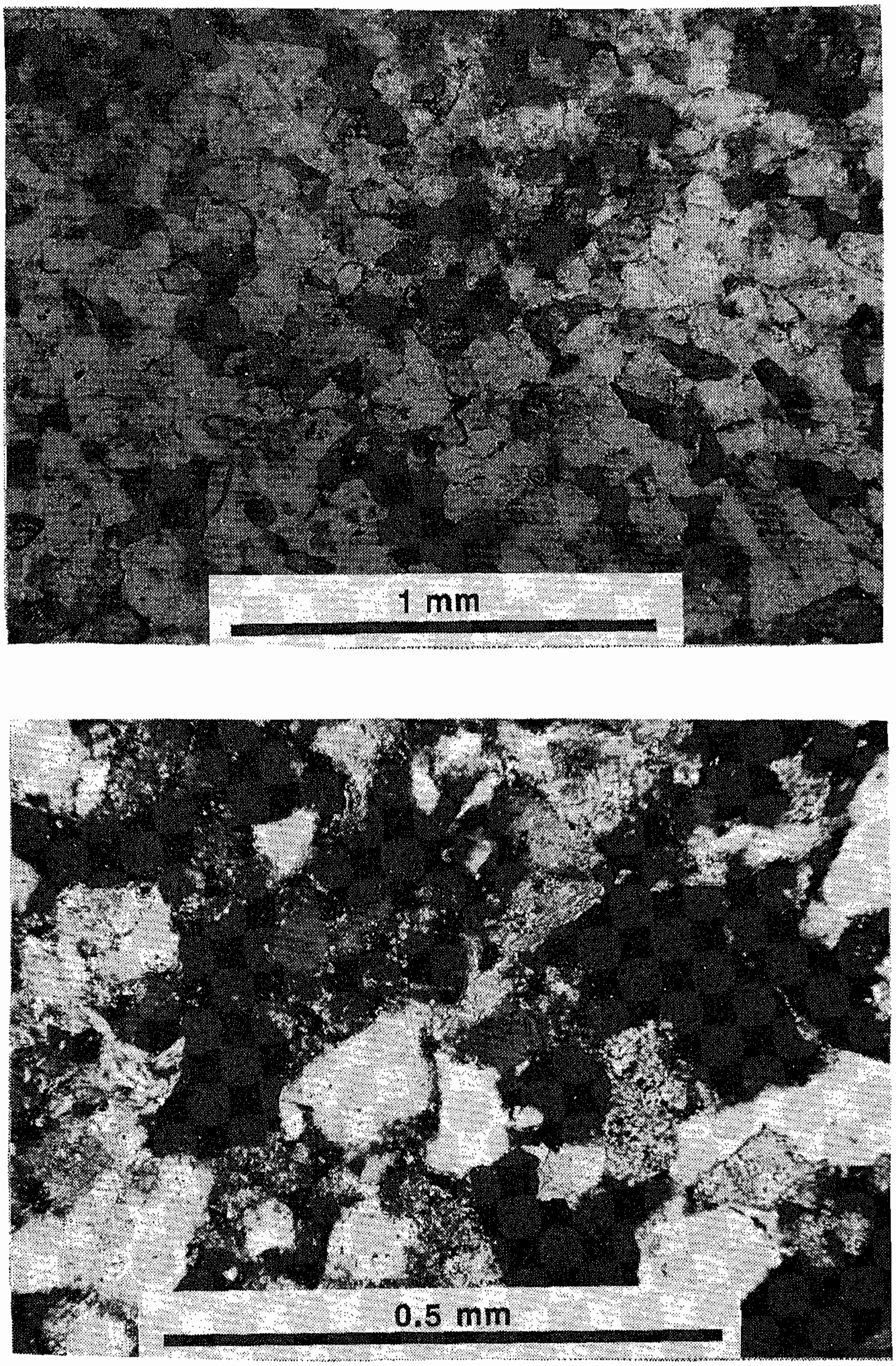


Plate 2B Thin-Section Photomicrographs Showing Relatively High Porosity (Blue-Stained Epoxy) and Dissolved Feldspars in Paludal Sandstones: a - plane light; b - polarized light (different rock)

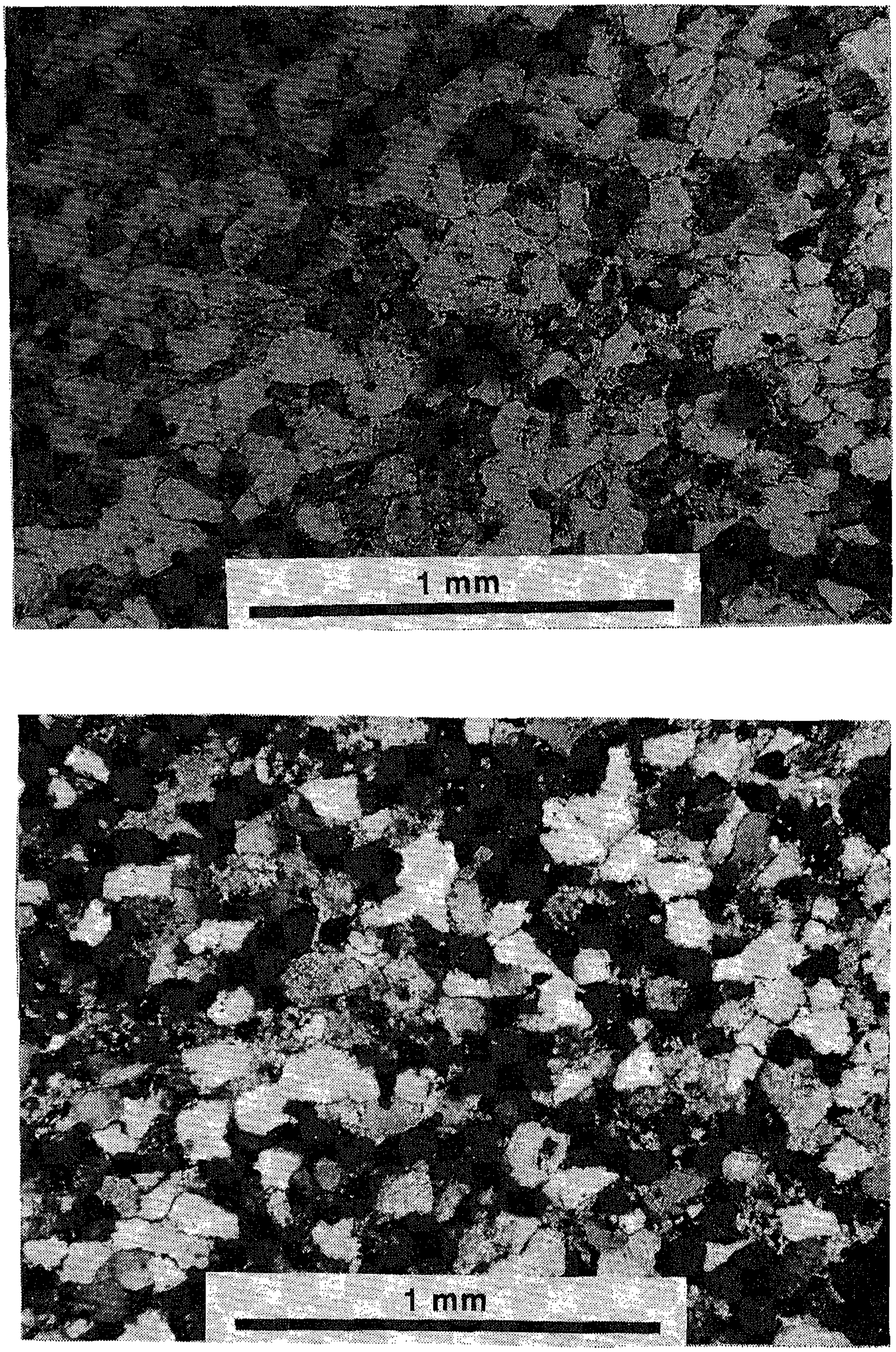


Plate 2C Thin-Section Photomicrographs From the Reservoir Sandstones in the Coastal Zone (Impregnated with Blue Epoxy): a - plain light; b - same rock, polarized light

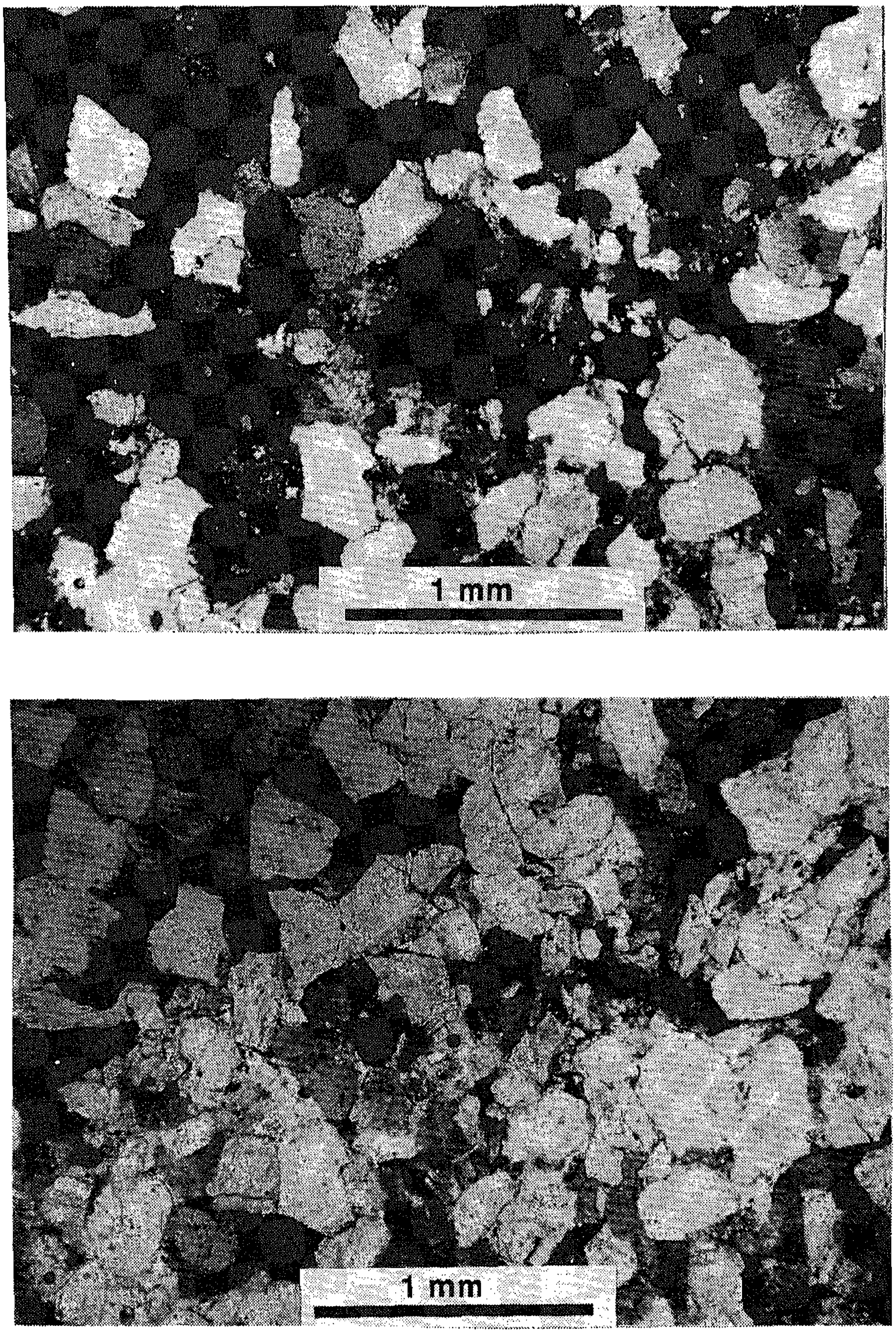


Plate 2D Thin-Section Photomicrographs From Reservoir Sandstones in the Fluvial Zone (Impregnated with Blue Epoxy): a - polarized light; b - same rock, plain light

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