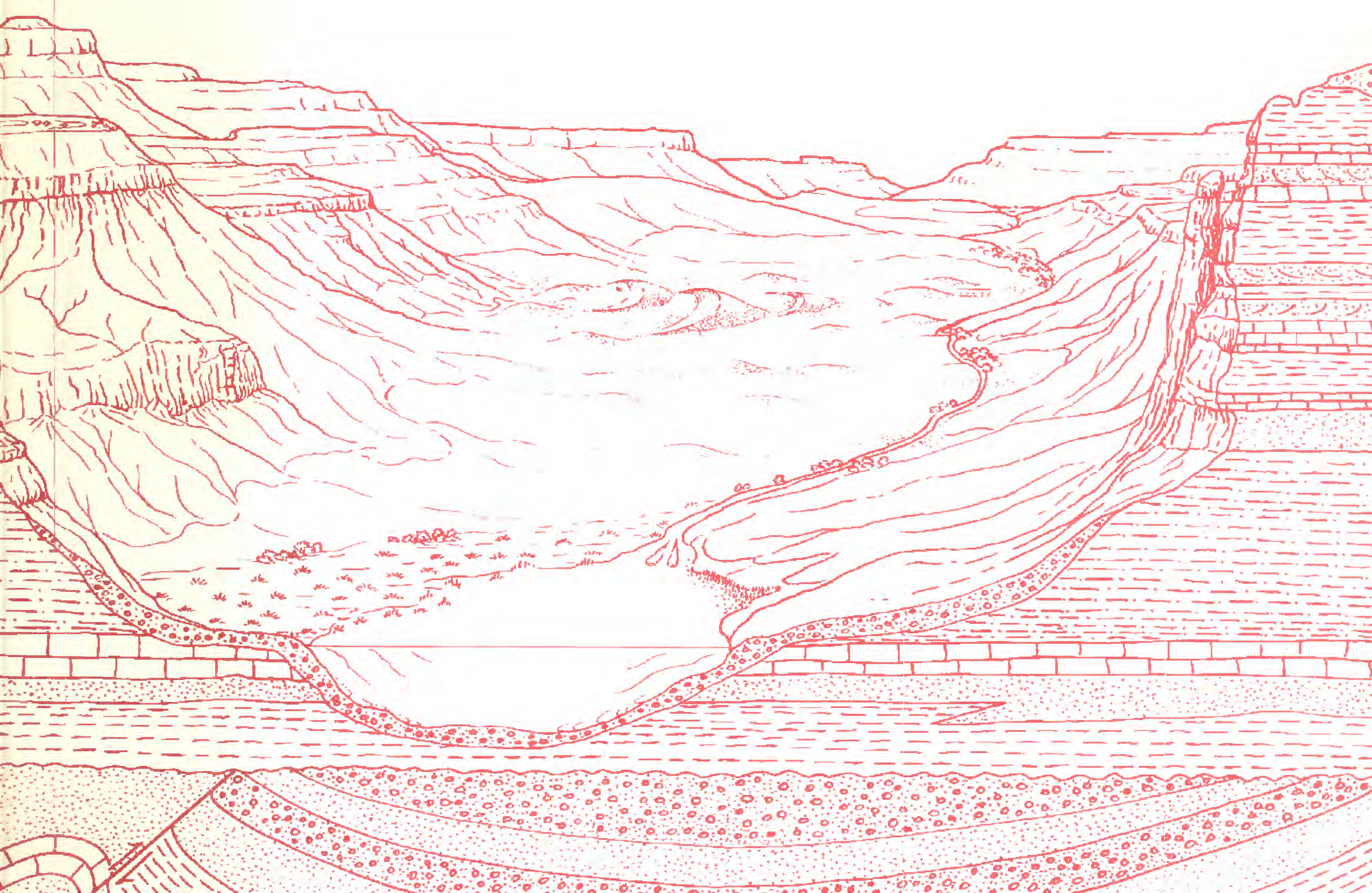
Petrology and Reservoir Paragenesis in the Sussex "B" Sandstone of the Upper Cretaceous Cody Shale, House Creek and Porcupine Fields, Powder River Basin, Wyoming

U.S. GEOLOGICAL SURVEY BULLETIN 1917-G



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Chapter G

Petrology and Reservoir Paragenesis in the Sussex "B" Sandstone of the Upper Cretaceous Cody Shale, House Creek and Porcupine Fields, Powder River Basin, Wyoming

By DEBRA K. HIGLEY

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1917

EVOLUTION OF SEDIMENTARY BASINS—POWDER RIVER BASIN

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U.S. GEOLOGICAL SURVEY
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Petrology and Reservoir Paragenesis in the Sussex "B" Sandstone of the Upper Cretaceous Cody Shale, House Creek and Porcupine Fields, Powder River Basin, Wyoming

By Debra K. Higley

Abstract

Oil is produced in the House Creek and Porcupine fields in the Powder River Basin from central-ridge and ridge-margin facies of the Sussex "B" sandstone, Sussex Sandstone Member of the Upper Cretaceous Cody Shale. Mudstone forms overlying and updip reservoir seals in these fields. Hydrocarbons are also trapped by a thin, areally discontinuous chert pebble sandstone that may represent an unconformity surface.

Macroscopic reservoir heterogeneity results from interbedding of reservoir sandstones with inter-ridge and low-energy ridge-margin sandstones. This interbedding forms sedimentologic permeability boundaries that isolate and compartmentalize individual sand bodies. Ductile deformation of glauconite, which is concentrated in reservoir sandstone trough cross-bedding ripple laminae, results in minor permeability boundaries to fluid flow.

Microscopic heterogeneity and porosity loss in the Sussex "B" sandstone results primarily from highly variable amounts and distributions of quartz and calcite cements. Minus-cement porosity that averages 30.2 percent for non-bioturbated sandstones suggests a compactional volume decrease of 5–10 percent porosity prior to lithification. Compactional processes in the Sussex "B" sandstone are important only in bioturbated sandstone—these are found in mainly inter-ridge and low-energy ridge-margin depositional environments.

Oil-producing sandstones are commonly cemented by quartz, which averages about 8 volume percent of the rock. These sandstones contain only minor amounts of carbonate cement. However, the volumetrically most important cement in non-productive Sussex "B" sandstone is calcite. Authigenic kaolinite, illite-smectite, and chlorite influence reservoir properties by occluding pore spaces and pore throats. Most porosity in reservoir sandstones is primary; however, secondary porosity is created by dissolution of plagioclase and other unstable lithic grains and by dissolution of carbonate cements that filled pore spaces and replaced lithic grains and overgrowths. Microporosity is present within chert grains and clays.

INTRODUCTION

Using petrologic and sedimentologic studies, this paper characterizes the influence of sedimentologic and petrologic variations on reservoir heterogeneity in the Sussex "B" sandstone in the House Creek and Porcupine fields, Powder River Basin, Wyoming. Effects of authigenic minerals on reservoir properties are described in detail for selected inter-ridge and ridge facies sandstones.

The House Creek and Porcupine fields are about 1 mi (1.6 km) wide and have a combined length of more than 36 mi (58 km). The fields form a major ridge system that is composed mainly of coalescing small- to medium-scale subaqueous dunes. The House Creek and Porcupine fields, and the ridge facies they outline, trend about N. 40° W., approximately parallel to basin structure contours (fig. 1).

The Sussex "B" sandstone is as much as 45 ft (14 m) thick, ranges in depth from about 7,000 to 9,000 ft (2,100–2,700 m), and is one of as many as twelve separate sandstone bodies that are located at different vertical and lateral positions within the Sussex Sandstone Member of the Upper Cretaceous Cody Shale (Anderman, 1976; Crews and

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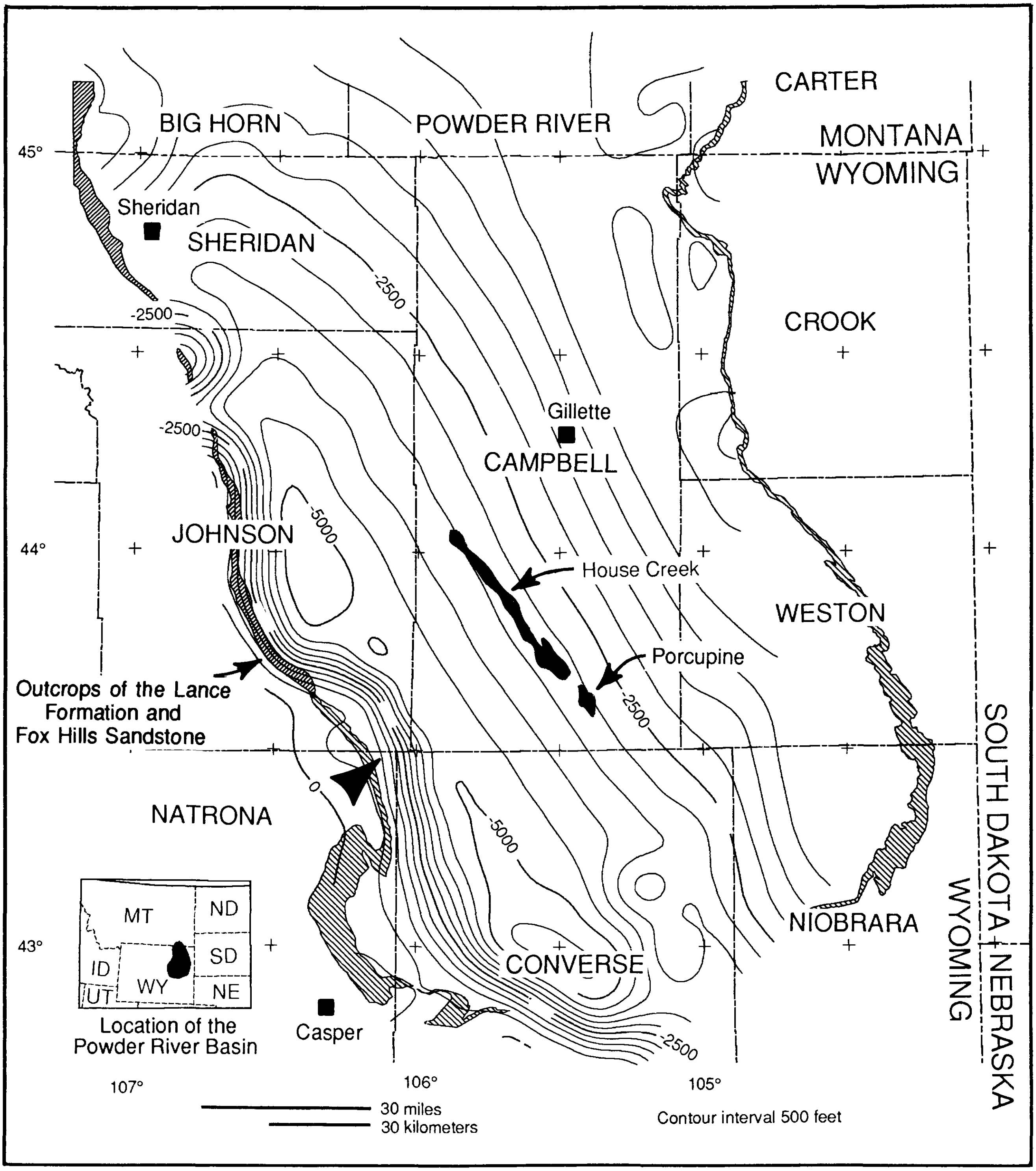


Figure 1. Powder River Basin structure map. Contours drawn on the top of the Sussex Sandstone Member of the Upper Cretaceous Cody Shale and its equivalents. Locations of the Salt Creek outcrop (large arrow) and House Creek and Porcupine fields are shown. Datum is mean sea level.

others, 1976). Oil is stratigraphically trapped in the Sussex "B" sandstone by overlying mudstone and ferroan calcite-cemented sandstone and by a lateral change from permeable sandstone to relatively impermeable mudstone. Approximately 21 million barrels of oil (MMBO) and 19 million cubic feet of gas (MMCFG) have been produced from the House Creek field, and more than 3 MMBO and 5 MMCFG have been produced from all reservoirs within the Porcupine field (as of December 1989). Porcupine field production is from the Muddy Sandstone Member of the Lower

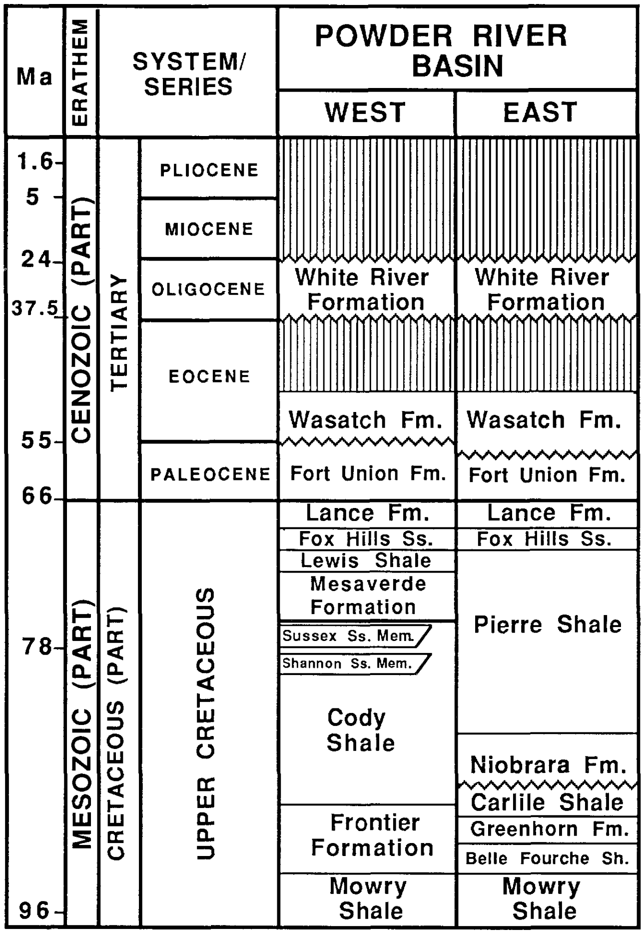


Figure 2. Generalized stratigraphic section showing nomenclature and correlations of Upper Cretaceous and Tertiary rocks in the Powder River Basin of Wyoming and Montana. Unconformities indicated by vertical ruled pattern and (or) jagged lines.

Cretaceous Thermopolis Shale, the Sussex "B" sandstone, and the Turner Sandy Member of the Upper Cretaceous Carlile Shale (fig. 2) (Lawyer and others, 1981). The mean reservoir porosity and permeability of pay sandstones in the House Creek field are 13 percent and 15 millidarcies (md), and the thickness of perforated sandstones ranges from 2 to 32 ft (0.6–10 m) (Sabel, 1985). Reservoir porosity in the Porcupine field is 8–12 percent (Lawyer and others, 1981).

Facies assignments were determined from outcrop and core studies and by correlation of stratigraphic data to geophysical well logs. Sussex "B" core from 21 wells was described (Higley, 1988); these cores are located at the U.S. Geological Survey core library in Denver, Colorado. Cores from 10 wells located in and near the House Creek and Porcupine oil fields were sampled for petrographic analysis (table 1). Thin sections of 54 samples, X-ray diffraction analyses, and scanning electron microscope studies were used to determine reservoir paragenesis, sandstone porosity, and mineralogic constituents of the Sussex "B" sandstone in the study area.

GEOLOGIC SETTING

The Powder River Basin is a Laramide-style structural basin with a steeply dipping western flank and a gently dipping eastern flank. The Cody Shale, including the Sussex Sandstone Member and its equivalents, underlies most of the basin and outcrops along the western flank, west of the Lance Formation and Fox Hills Sandstone outcrops shown on figure 1. Sandstone body and basin geometry indicate that the Sussex "B" sandstone was deposited as a narrow, low-relief, marine ridge complex in a shallow, offshore marine setting within the narrow Campanian seaway (Asquith, 1970; Berg, 1975; Hobson and others, 1982). This seaway extended from the Arctic to the Gulf of Mexico.

Sussex Sandstone Member deposition may represent transgressive marine reworking by oceanic, storm, and tidal currents of residual sand sheets that were deposited during a previous progradation (Hobson and others, 1982). Berg (1975), Brenner (1978), and Hobson and others (1982) believe that the Sussex Sandstone Member was deposited more than 100 mi (160 km) east of the Upper Cretaceous Eagle Sandstone shoreline as marine topsets in a progradation of marine shelf, slope, and basin sediments. Hobson and others (1982) further postulate that the sources of the sandstone for the Sussex Sandstone Member were the nearshore marine and deltaic sediments of the Eagle Sandstone. Brenner (1978) used core and well-log studies to hypothesize that Sussex Sandstone Member ridge facies were reworked and shaped by storm and tidal currents. Deposition in water as deep as 100–200 ft (30–60 m) is inferred based on *Haplophragmoides* and *Reophax* foraminiferal tests (Berg, 1975) and on the presence of trace fossils from oxygenated water (including *Skolithos*, *Chondrites*, *Diplocraterion*, and *Arenicolites*). Asquith (1970) inferred water depths as shallow as 50 ft (15 m) for sandstone deposition.

SANDSTONE DIAGENESIS

The Sussex "B" sandstone is a very fine to medium-grained litharenite to feldspathic litharenite (Folk, 1970). Reservoir sandstones are composed of moderately sorted to fairly well sorted subangular to subrounded grains that commonly exhibit well-developed quartz overgrowths. Included in table 2 are average volume percentages of minerals and rock fragments determined from point-count data of 54 thin sections for all sedimentary facies of the Sussex "B" sandstone in the area of the House Creek and Porcupine fields. Porosity and mineralogic determinations were derived from more than 300 point-count measurements. Thin sections were stained for calcite, potassium feldspar, plagioclase, and iron. Mineralogical compositions were verified by X-ray diffraction and SEM analysis.

Table 1. Names and locations of wells sampled for petrographic analysis, Sussex "B" sandstone, Sussex Sandstone Member of the Upper Cretaceous Cody Shale

[HC, House Creek field; P, Porcupine field; *, estimated depth to top of Sussex "B" sandstone. Leaders (--) indicate that well is not within House Creek or Porcupine fields]

Well name	Field name	Location (Section, township, range)	Depth to top of Sussex "B" (in feet)	
			Core	Well log
14–9 Federal	P	9, T. 42 N., R. 71 W.	7,781	7,778
1 Campbell	P	21, T. 42 N., R. 71 W.	7,700	7,708
1 Government Miles "A"	HC	9, T. 44 N., R. 73 W.	8,189	8,190
1 Mandell Federal	HC	22, T. 44 N., R. 73 W.	8,166	8,174
1–23 House Creek Federal	HC	23, T. 44 N., R. 73 W.	8,238	8,240
1 Empire–Federal "C"	HC	29, T. 45 N., R. 73 W.	8,006	8,004
32–1 Marguiss "B"	HC	32, T. 45 N., R. 73 W.	7,980	7,998
2 House Creek Federal	HC	13, T. 45 N., R. 74 W.	8,175	8,175
1 Red Unit	--	26, T, 48 N., R. 79 W.	9,028*	9,028
1–11 Ucross State	--	11, T. 52 N., R. 81 W.	8,233*	8,245

Table 2. Selected thin-section point-count data for depositional facies of the Sussex "B" sandstone, Sussex Sandstone Member of the Upper Cretaceous Cody Shale, Powder River Basin, Wyoming

[Data represent average volume percentages for number of thin sections listed. N, number of thin sections studied; qtz, quartz; poly-x qtz, polycrystalline quartz; ms, mudstone; sid, siderite; chl, chlorite; cmt, cement; cly clay; frag, fragments; -cmt por, minus-cement porosity]

Facies	N	Framework grains				Mainly detrital matrix					Cements, clays, porosity								
		Qtz	Poly-x qtz	Feld-spar	Rock frag	Glauc-onite	Matrix Ms	Matrix Cly	Drapes Ms	Drapes Sid	Pyr-ite	Chl rims	Qtz cmt	Chert cmt	Feld-spar	Carb-onate	Kaol-inite	Poro-sity	–Cmt por
All facies	54	31.1	2.9	6.3	13.2	5.1	3.0	5.9	1.8	0.9	0.6	0.9	7.7	2.1	1.5	10.6	0.8	5.4	29.6
Chert pebble sandstone	3	26.8	0.8	3.5	36.3	3.0	0.0	2.1	0.0	0.0	0.2	0.0	1.9	0.0	0.2	20.9	0.0	1.6	24.8
Central-ridge sandstone	17	32.2	2.9	5.7	14.1	4.7	0.7	3.9	2.1	2.9	0.3	0.8	8.5	2.1	1.3	9.5	0.4	7.7	30.7
High-energy ridge margin	8	30.0	2.7	7.1	11.0	5.5	2.8	3.8	1.2	0.1	1.3	1.3	8.5	2.2	1.6	14.3	0.5	6.1	35.8
Low-energy ridge margin	3	26.8	3.1	8.5	11.8	6.7	1.4	7.6	1.2	0.8	1.0	1.1	11.3	1.9	3.8	9.7	0.9	2.4	32.1
Wavy-bedded inter-ridge	6	31.5	2.1	6.9	10.2	6.9	3.2	5.1	0.0	0.0	0.4	1.8	7.9	2.2	2.2	11.9	1.6	5.9	33.9
Inter-ridge sandstone	10	30.7	2.8	7.4	11.1	5.5	3.3	7.2	3.2	0.2	0.7	0.7	8.3	2.2	1.5	8.5	1.3	5.4	28.7
Inter-ridge siltstone	7	33.3	2.3	5.3	9.9	3.4	10.3	13.3	3.3	0.2	0.6	0.6	4.5	2.6	0.7	6.8	0.6	2.1	18.6

Quartz grains in the Sussex "B" sandstone are almost entirely monocrystalline. Chert averages 5.8 percent by volume for the 54 samples and is included with mudstone clasts and minor amounts of sedimentary and volcanic rock fragments as part of the rock fragment category (table 2). Feldspar consists almost entirely of plagioclase (primarily albite); potassium feldspar is rare. The detrital matrix category contains mudstone and clay matrix categories (table 2). Clay matrix represents undifferentiated clays of mixed authigenic and detrital origin. Authigenic clay matrix may have formed by precipitation of clays into primary and secondary pore spaces and (or) by minor replacement of glauconite and lithic grains by illitic clay. X-ray diffraction analysis indicates that separates of clay from the Sussex "B" sandstone are composed of illite, ordered and random-layer illite-smectite, iron-rich chlorite or chamosite, glauconite, and kaolinite. The minus-cement porosity category (table 2) combines intergranular primary porosity and secondary porosity (in addition to authigenic cements and clays) as an estimate of the amount of porosity at the time of lithification.

Reservoir Paragenesis

Reservoir paragenesis of the Sussex "B" sandstone in the House Creek and Porcupine fields is shown on figure 3. The inferred principal diagenetic events are:

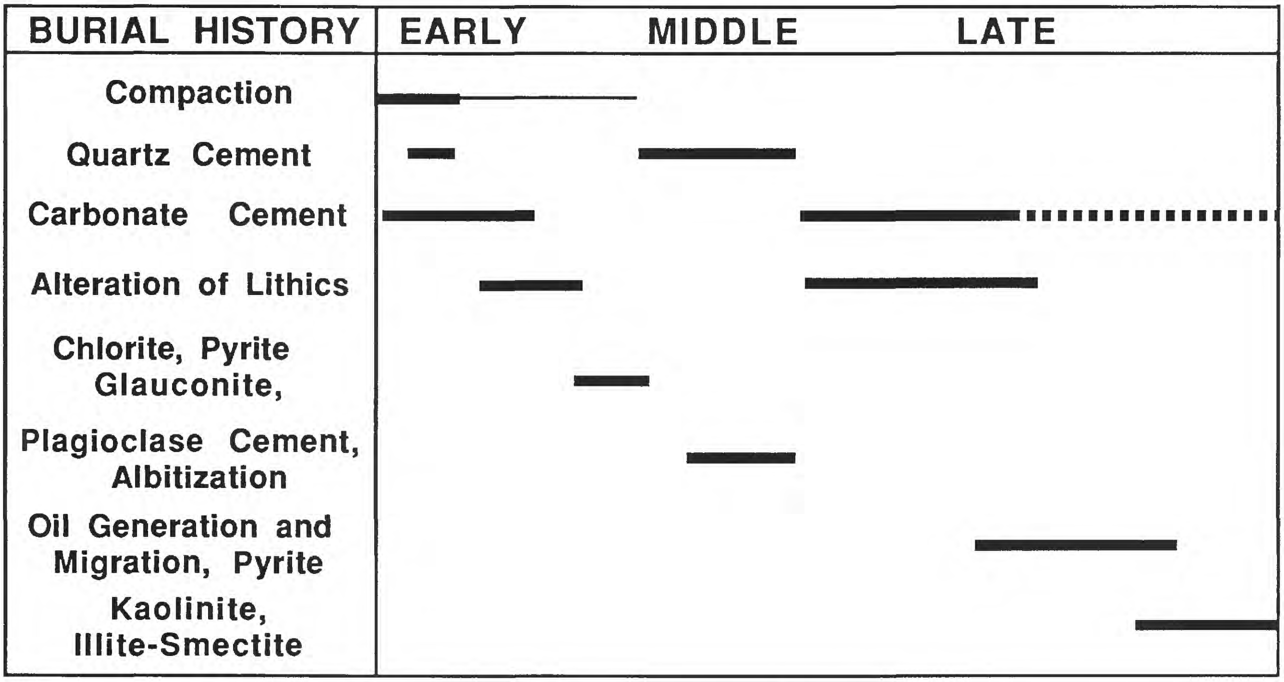
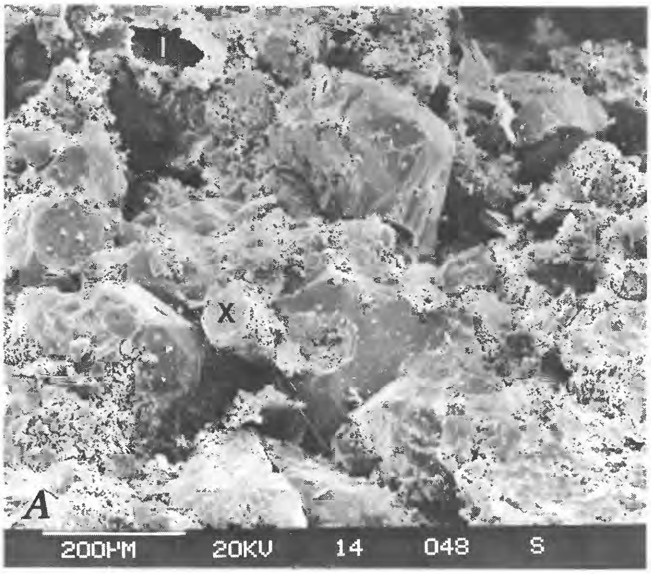


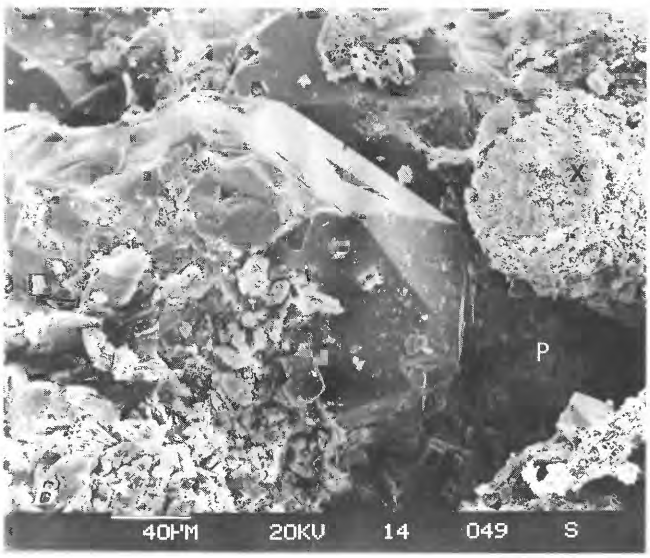
Figure 3. Generalized paragenetic sequence of the Upper Cretaceous Sussex "B" sandstone in the House Creek and Porcupine fields. Dashed line indicates dissolution of calcite and ferroan calcite cements.

1. Calcite precipitated during two major diagenetic events and is present primarily as poikilotopic crystals (fig. 4*C*). Siderite cementation occurred during the very early compactional history of the Sussex "B" sandstone. Dolomite and rare ankerite precipitated during the later stage of carbonate cementation and commonly occur as scattered rhombs. The average for all facies of 10.6 volume percent carbonate cement includes a mean 8.6 percent calcite and ferroan calcite and 2.0 percent dolomite and ferroan dolomite (determined from thin sections stained for calcite and iron).
2. An early stage of quartz cementation is characterized by minor syntaxial overgrowths, many of which are meniscal in appearance. Early quartz precipitation is interrupted by cementation by poikilotopic and radial-fibrous calcite.
3. Glauconite grains represent early diagenetic alteration of fecal pellets and biotite. The presence of glauconite, in addition to pyrite and chlorite, indicates reducing conditions in marine pore fluids.
4. Pyrite as framboids and minor euhedral crystals is present within organic-rich mudstone laminae and later hydrocarbons.
5. Rims of chlorite grow perpendicular to quartz grain surfaces. Chlorite crystals coat grains, are intergrown with, and may partially replace the quartz overgrowths of stage 6, below.
6. Syntaxial quartz overgrowths precipitate (figs. 4, 5*A*). This represents the major quartz cementation event.
7. Authigenic feldspar is present as plagioclase overgrowths on albite grains and as minor amounts of pore-filling cement. Grains and overgrowths commonly exhibit albite twinning. Most albite appears detrital; however, chessboard twinning of some grains indicates albitization. Dissolution of plagioclase occurred during two stages: the first stage occurred prior to overgrowth formation, and the second stage may be related to changes in pore fluids that were associated with hydrocarbon generation and migration. Plagioclase may exhibit extensive replacement by calcite and dolomite cements; replacement by calcite occurred during both stages of carbonate cementation.
8. Oil from the House Creek and Porcupine fields migrated updip and up-fracture during early Eocene to Miocene time (Nuccio, 1990; Momper and Williams, 1984). Cores of organic-rich marine shale, adjacent to the Sussex "B" sandstone, were sampled from 6 locations across the fields. Samples range in depth from 7,776 to 9,803 ft (2,370–2,988 m). Vitrinite reflectance values range from 0.51 to 0.58 percent, suggesting that hydrocarbon source rocks are only marginally mature for oil generation.
9. Following the onset of oil migration, kaolinite and minor amounts of associated illite-smectite precipitated in pore spaces (figs. 4, 5).

Porosity Relationships

Porosity and permeability increase generally upward from inter-ridge to central-ridge facies, reflecting depositional energy trends in the Sussex "B" sandstone. Increase in porosity is usually accompanied by an increase in





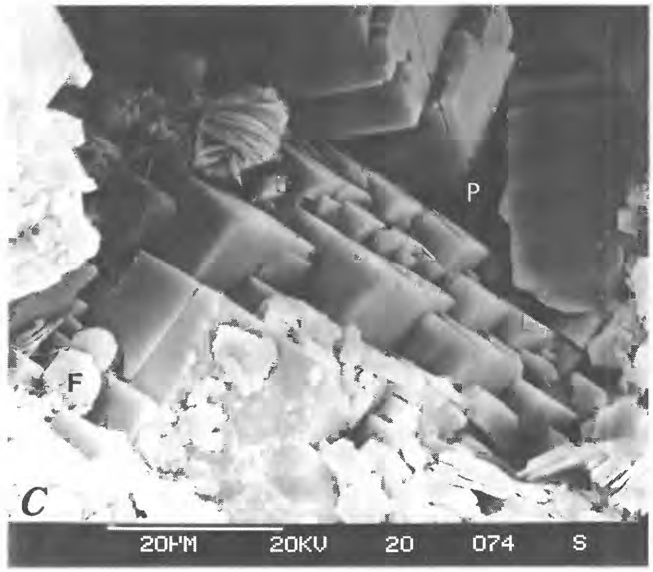
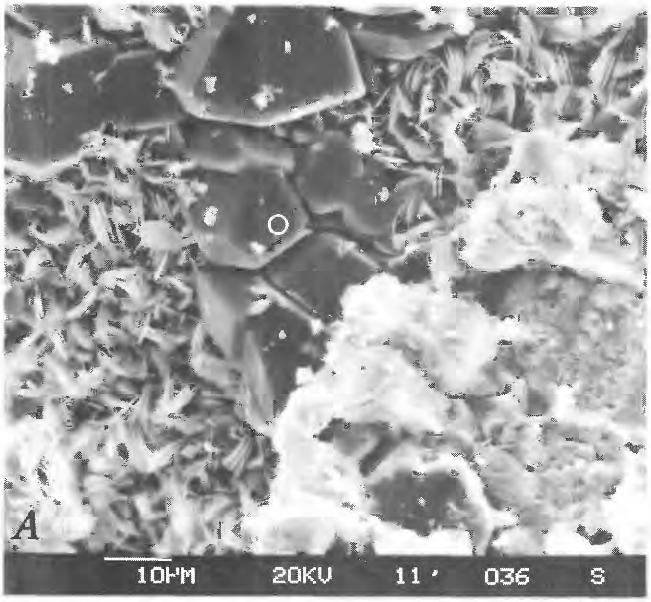


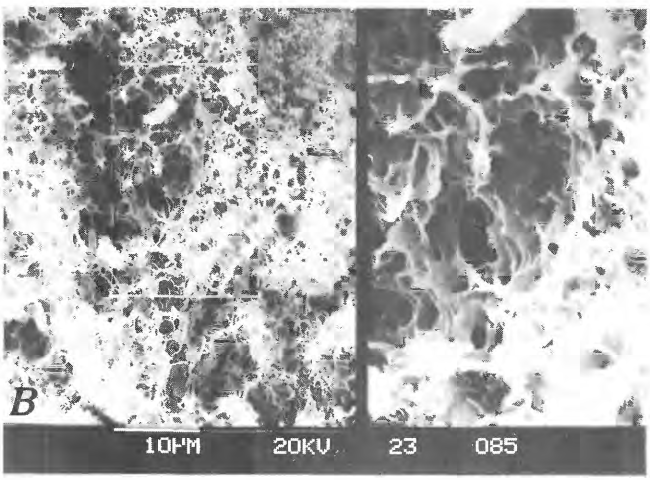
Figure 4 (above and facing column). SEM photomicrographs of: *A*, fine- to medium-grained trough cross-bedded sandstone from an oil-productive interval at 8,197.5 ft (2,498.6 m), No. 1 Government Miles "A" well. Sandstone has well-developed quartz overgrowths and moderate intergranular porosity (17.5 percent thin-section porosity). Porosity is mostly primary; however, secondary porosity results from dissolution of lithic grains (rim of chlorite and illitic clay (I)), and microporosity is present within clays. X is a fossil fragment. *B*, Close-up view of figure 4*A* shows a pore (P), adjacent quartz overgrowth and grain, a fossil fragment (X), and kaolinite. *C*, Poikilotopic calcite cement fills the pore space (P) in this inter-ridge sandstone from the No. 14–9 Federal well. Later chlorite rosettes and pyrite framboids (F) are present on calcite.

permeability, although scatter in the data is considerable (fig. 6*A*). Porosity relationships are complex—petrology and diagenesis may vary greatly across small distances. The greatest amounts of porosity are present in central-ridge and high-energy ridge-margin facies. Lower depositional energy facies may contain moderate amounts of porosity; however, these thin, porous beds exhibit a spotty distribution and sedimentologic isolation that precludes their development as reservoir sandstones. Vertical stacking of thin beds of carbonate-cemented and non-cemented zones is common in the Sussex "B" sandstone; this may reflect isolation of cemented zones from migrating fluids that dissolved carbonate cements in other sandstone beds.

Porosity is mainly of the primary intergranular type; however, secondary porosity is present as corroded and dissolved lithic grains, and microporosity exists within chert and clays (fig. 4). Intergranular plus intragranular porosity in studied thin sections may total as much as 17.5 percent. Average porosity for all studied thin sections is 5.2 percent; 3.4 percent of this is primary intergranular, and as much as 1.9 percent is secondary and intragranular porosity. Average porosity values for Sussex "B" facies are listed in table 2. Thin-section porosity values are lower than core and average reservoir porosity values for two main reasons: (1) Microporosity is not included in thin-section estimates but is measured by core analysis. The amount of microporosity may be considerable because clays comprise an average of 12 percent by volume of the Sussex "B." The percentage of microporosity should decrease up-section because the amounts of suspended-load sediment and most clays decrease upward. (2) Three-dimensional effects of thin sections influence point-count results.

Sussex "B" sediment compaction was slowed by two processes: early calcite cementation and later formation of quartz overgrowths (fig. 3). Pryor (1973) analyzed porosity and permeability within unconsolidated beach sands of the Gulf Coast and found that depositional porosity of beach sands ranges from 39 to 56 percent, decreasing rapidly with burial. Initial porosity within central-ridge facies sandstone was probably 35–40 percent. Sussex "B" sandstone samples that contain the early calcite cement have minus-cement porosity (MCP) values of as much as 50.2 percent—in this





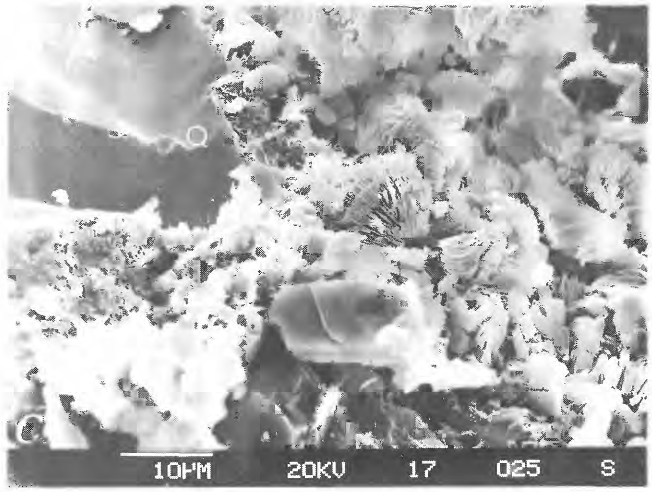


Figure 5 (above and facing column). SEM photomicrographs of authigenic clays in Sussex "B" sandstone. *A*, Chlorite rims a quartz grain in oil-productive central-ridge facies sandstone from 8,171.3 ft. (2,490.6m) depth, No. 1 Mandell Federal oil well. Quartz cement (O) overlies, and is intergrown with, chlorite. Quartz overgrowths have well-defined crystal faces that interlock and coalesce. *B*, Illite-smectite coats a pore; sample is from No. 1 Campbell well at a depth of 7,723.7 ft (2,354.2 m) in a planar-tabular cross-bedded ridge-margin sandstone. Close-up view is located within inset. *C*, Kaolinite covers a fractured quartz grain (Q) and fills porosity in a wavy-bedded inter-ridge sandstone at 8,245 ft. (2,513 m) depth in the No. 1–23 House Creek Federal well. Minor amounts of illitic clay are present as "wispy" coatings on grains and kaolinite.

case, calcite cement is 46.2 volume percent. This MCP value is misleading because early calcite within some intervals is moderately to highly displacive (fig. 7*A*), and calcite also partly to totally replaced some lithic grains. This results in substantial overestimation of porosity at the time of early calcite cementation. Diagenesis is commonly "frozen" within units that contain pervasive early calcite cement, suggesting that some permeability is required for calcite dissolution and for precipitation of later authigenic minerals.

Two periods of quartz cementation are shown on figure 3. Early quartz cementation is characterized by scattered, minor, poorly developed overgrowths; later overgrowths are well-developed and commonly have grain-coating chlorite rims (figs. 7*B*, 7*E*). Some sandstone beds contain pervasive quartz cement (more than 12 volume percent) and display minimal evidence of prior cementation by calcite (fig. 6*B*). Therefore, the average 30 percent MCP in these intervals reflects porosity at the time of quartz cementation. Also, those intervals with the greatest porosity are generally quartz cemented and contain only minor amounts of calcite cement (fig. 6*C*). Dissolution of pore-filling and replacive carbonate cements near maximum burial depths restored primary porosity and created locally extensive secondary porosity.

A second stage of carbonate cementation followed precipitation of well-developed quartz and feldspar overgrowths (fig. 7*E*). Samples that exhibit this stage of carbonate cementation commonly contain intermediate amounts of the quartz and later calcite cements and are shown near the center of figure 6*B*. These later calcite and ferroan carbonate cements are commonly poikilotopic, with minor rhombs, and may be highly replacive of feldspar grains and overgrowths, glauconite, and rock fragments.

PETROLOGIC CHARACTERISTICS OF SANDSTONE FACIES

Facies assignments are based on core, well log, and outcrop studies. They are partly based on an evaluation of the Shannon Sandstone Member (fig. 2) in the Powder River Basin (Tillman and Martinsen, 1984) and on the Sussex Sandstone Member facies descriptions of Berg (1975) (fig. 8). The Sussex "B" sandstone is generally composed of

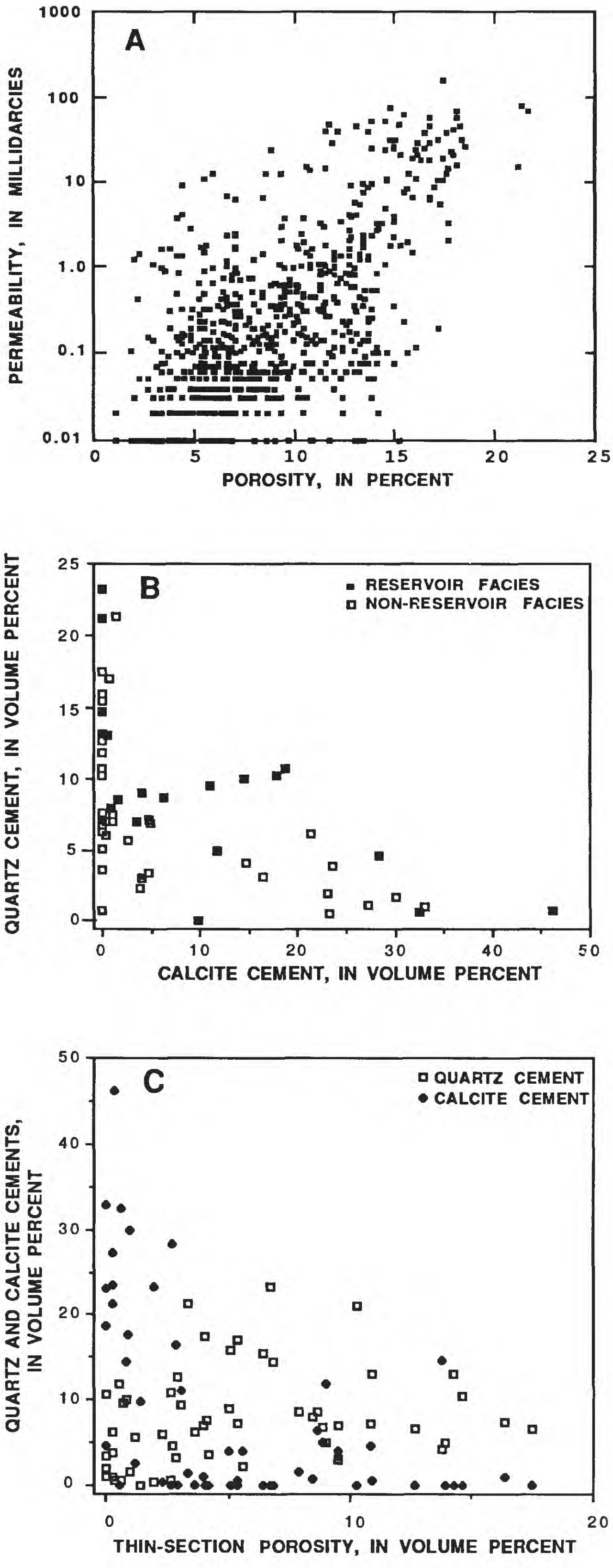
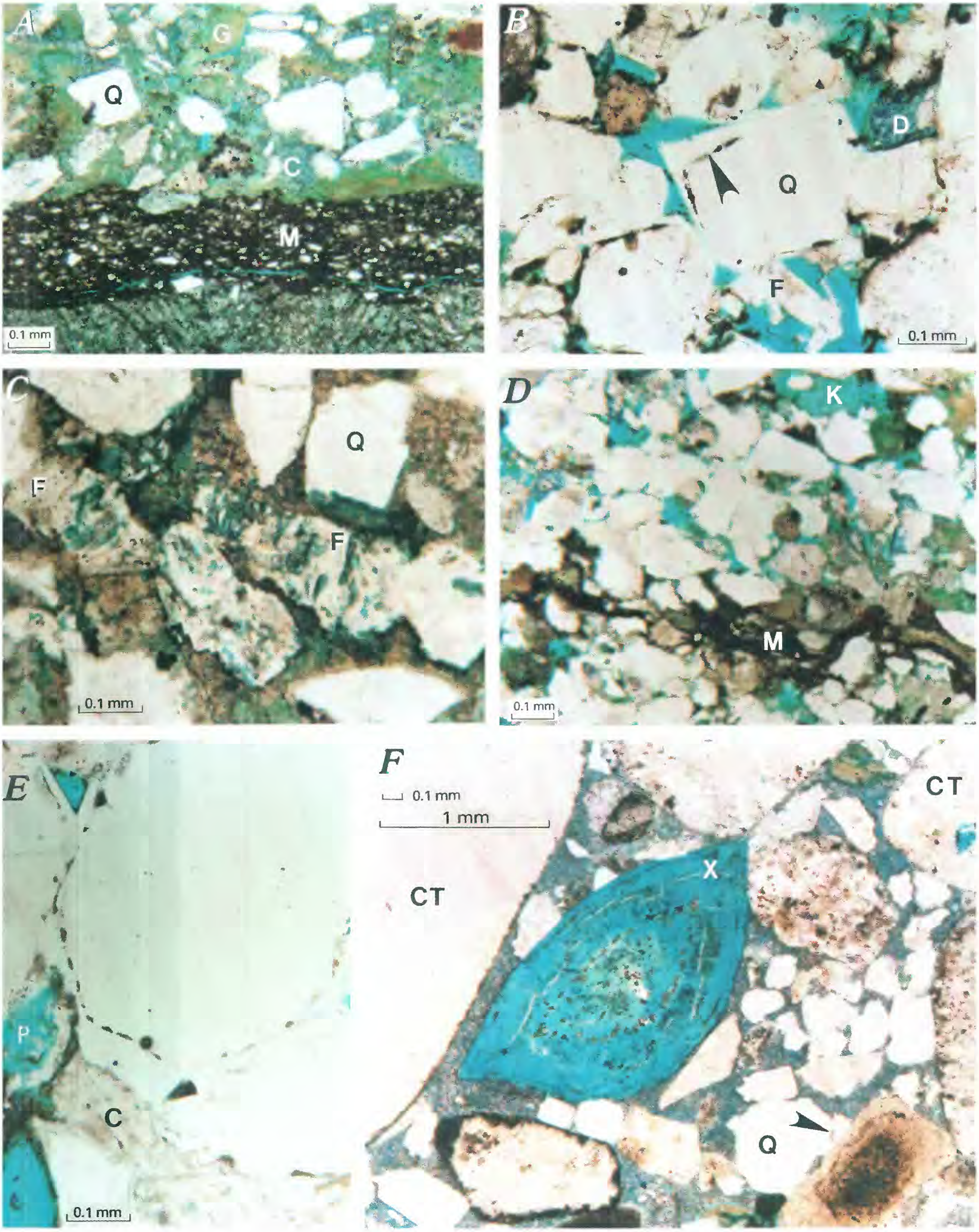


Figure 6 (facing column). Crossplots showing porosity, permeability, and cement relationships. *A*, Increase in core porosity is generally accompanied by increasing permeability, although considerable scatter is present. Graph represents core porosity and permeability for 792 samples of Sussex "B" sandstone from 30 drillholes across the study area. *B* and *C*, Volume percentages of intergranular plus intragranular porosity and quartz and calcite cements were determined for 54 samples by thin-section petrology methods. Amounts of cements are highly variable, although certain trends are present. *B*, The central-ridge and high-energy ridge-margin reservoir facies generally contain 8 percent or greater quartz cement and highly variable amounts of calcite cement. Samples that contain large amounts of quartz cement (more than 12 percent) commonly have minimal calcite and ferroan calcite cement. *C*, Amounts of calcite cement in excess of 15 percent are generally associated with low porosity. Quartz-cemented sandstone with minor cementation by calcite exhibits the greatest porosity—within these intervals, calcite cementation was minor, or porosity was restored by extensive late-stage dissolution of calcite.

Figure 7 (facing page). Photomicrographs showing paragenesis and porosity evolution in the Sussex "B" sandstone. Ferroan carbonates are stained blue. Blue epoxy fills pore spaces. Scale bars are 0.1mm. Transmitted light. *A*, Precipitation of "early" radial-fibrous calcite (C) results in a moderately replacive and highly displacive fabric with "floating" quartz grains (Q), minor deformation of glauconite (G) and mudstone clasts (M), and very low porosity (which is present as shrinkage cracks in mudstone and glauconite). The chevron pattern below the mudstone results from nucleation of calcite within mudstone layers and separation of laminae. This high-energy ridge-margin sandstone is at 7,723.7 ft (2,354.2 m) depth in the No. 1 Campbell well. *B*, Oil-stained chlorite rims are beneath well-developed quartz overgrowths (arrow) in this sandstone from 8,012.7 ft (2,442.3 m) depth, No. 1 Empire-Federal "C" well. Remnants of late dolomite (D) partly fill pores. Authigenic albite (F) is located within a secondary pore space. *C*, Ferroan calcite (dark blue) peripherally replaces grains and fills dissolution pores in plagioclase (F). This inter-ridge sandstone was sampled from 7,797.6 ft (2,376.7 m) depth, No. 14–9 Federal well. *D*, Soft-sediment deformation of glauconite and mudstone (M) that is concentrated in a ripple lamina creates a permeability boundary in this sandstone from 8,014 ft (2,443 m) depth, No. 1 Empire-Federal "C" well. Kaolinite (K) fills a secondary pore. *E*, Late-stage calcite (C) covers quartz overgrowths in a sandstone from 8,167 ft (2,489 m), No. 1 Federal well. Porosity includes primary (triangular pore) and dissolution (P) pores. *F*, Chert pebble sandstone from 7,781.8 ft (2,371.8 m) in the No. 14–9 Federal well. Grain sorting is distinctly bimodal. Quartz grains are located in ferroan calcite cement between chert pebbles (CT). Quartz overgrowths are minor (arrow) and partially replaced by calcite. Porosity is present within a chert grain and as a dissolved foraminifera test (X). Scales are 0.1 and 1.0 mm.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one coarsening-upward marine ridge sequence, although there may be as many as three coarsening-upward progressions within it. The lower contact is transitional. The upper contact of the Sussex "B" sandstone grades rapidly upward into bioturbated siltstone and mudstone of inter-ridge or offshore depositional environments. Internal contacts of low-energy sandstones are sharp to gradational and nonerosional; higher energy ridge facies commonly have basal and internal scour contacts. The term bioturbated is used here to indicate sediments that contain more than 75 percent burrowing; almost all primary depositional features are destroyed by biologic activity and only relict, commonly ripple-laminated, bedding is preserved.

Inter-Ridge Facies

The Sussex "B" sandstone body includes interbedded and basal sheet sand of inter-ridge and offshore origin. This sandstone body is more than 7 mi (11 km) wide, and the thickest section is southwest of the House Creek producing area (Beaumont and others, 1980). Inter-ridge facies were probably deposited as sheet sands during periods of low- to moderate-energy oceanic and tidal currents; they may represent transgressive marine reworking of underlying nearshore and offshore marine sediments (Hobson and others, 1982). Inter-ridge strata are divided into three facies on the basis of: (1) degree of biologic activity, (2) type of sedimentary structures, and (3) differences in inferred depositional energy. Facies are generally less than 5 ft (1.5 m) thick; they are thinly bedded and are commonly interstratified. Wavy-bedded inter-ridge sandstone is distinguished from other inter-ridge sandstone by low biologic activity and predominantly wavy bedding. Biologic activity in other inter-ridge sandstone and siltstone facies may completely destroy bedforms.

Inter-ridge facies have generally low potential as reservoir rocks because of low porosity and numerous permeability boundaries; low porosity and permeability results from: (1) pervasive cementation by calcite and ferroan calcite, (2) cementation by quartz, or (3) by compaction and soft-sediment deformation. Within any interval, one of these three processes generally predominates.

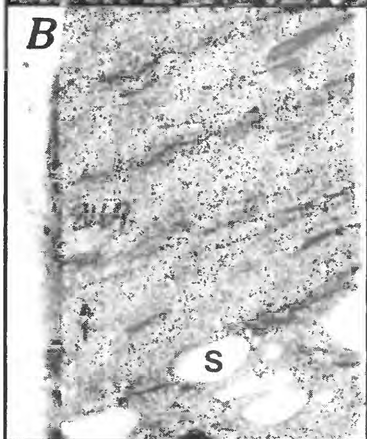
Inter-Ridge Sandstone and Siltstone

Inter-ridge facies grade upward from bioturbated siltstone and shale to burrowed and bioturbated very fine grained ripple-laminated sandstone (fig. 8*E*). Sandstone may exhibit flaser bedding. Individual beds are several inches to 1 ft (4–30 cm) thick; they have tabular to lenticular geometry and can generally be traced more than 100 ft (30 m) across the length of the Salt Creek outcrop. Upwardly increasing depositional energy conditions are reflected by: (1) an upward increase in sandstone grain size, (2) the upward transition from mudstone (which may exhibit "sand-starved" ripple lamination) to sandstone (which may be burrowed, with tabular bedding, and small-scale ripple laminae), to burrowed small- to medium-scale ripple-laminated bed sets, and (3) by the upward transition from a zone of mainly horizontal and back-fill burrows (*Planolites*, *Teichichnus*) to rocks that include some vertical burrows (*Skolithos*, *Arenicolites*).

Thin-section porosity of seven inter-ridge siltstone and ten inter-ridge sandstone samples averages 2.0 percent and 5.4 percent, respectively, although porosity in inter-ridge sandstone is as great as 13.8 percent. More than half of the porosity is secondary intergranular and intragranular. Pore spaces are commonly pervasively cemented by quartz or calcite. Numerous mudstone drapes between these thinly bedded sandstones are effective boundaries to fluid flow: in the absence of fractures, these boundaries hydraulically isolate these facies from central-ridge and ridge-margin sandstone facies. This isolation would aid in secondary recovery of oil where reservoir facies overlie, and are not interbedded with, inter-ridge facies. Interbedding results in barriers to vertical flow of fluids in reservoir sandstones.

Bioturbated siltstone and mudstone are the only Sussex units in which compaction was a more important process than cementation for reducing porosity; glauconite and other soft-sediment grains are commonly extensively deformed (fig. 9*C*). Inter-ridge siltstone facies contain the least minus-cement porosity (18.6 percent) of the units studied (table 2). Porosity at the time of deposition was less for the siltstone unit than other facies mainly because of larger amounts of suspended-load sediment and poor sorting due to biologic and depositional processes.

Figure 8 (facing page). Sedimentologic, petrologic, and reservoir characteristics of Sussex "B" sandstone facies. Core width is about 3.5 in (9 cm). *A*, Core photograph of chert pebble sandstone which erosionally overlies medium-grained sandstone of the central-ridge facies (arrow at contact), 7,782 ft (2,372 m) depth, No. 14–9 Federal well. *B*, Core photograph of trough cross-bedded medium-grained central-ridge sandstone from 8,169 ft (2,490 m) depth in the No. 1 Mandell Federal well. Large siderite (S) clasts are located on trough cross-bedding. Glauconite is concentrated in dark lineations. *C*, Outcrop of low-energy ridge-margin sandstone exhibits dips of 1°–15° on trough and planar-tangential cross-bedding. Low-angle dips and lateral and vertical facies gradations into inter-ridge sandstone characterize this unit. The thin-bedded inter-ridge sandstone lenses above this unit are highly burrowed. A siderite drape marks the boundary between the ridge-margin sandstone and underlying slope-forming bioturbated sandstone and siltstone. Outcrop location is east of the Salt Creek anticline in SW¼ sec. 7, T. 40 N., R. 78 W. *D*, Core of wavy-bedded inter-ridge sandstone at 8,194 ft (2,498 m) depth in the No. 1 Mandell Federal well. A ripple reactivation surface is present to the right of a siderite-cemented sandstone lamina (S). *E*, Extensively *Teichichnus* burrowed inter-ridge siltstone core exhibits minor, relict ripple laminae. Core width is about 2 in (5 cm). Sample location is 8,038 ft (2,449 m) depth in the No. 1 Empire-Federal "C" well.

SUSSEX "B" FACIES	SEDIMENTOLOGY	PETROLOGY	RESERVOIR CHARACTERISTICS
A 	Chert pebble (CP) sandstone: a thin, lenticular, areally discontinuous, trough and planar-tangential bedded, very coarse grained sandstone. CP erosionally overlies ridge-facies sandstone. Sandstone may contain fossil debris.	CP composition is different than other Sussex "B" facies. CP contains 32% chert granules (4% for other facies). Diagenesis is commonly frozen by early carbonate cement. Porosity is secondary, resulting mainly from dissolution of calcite, shell debris, and chert.	The CP sandstone has low reservoir potential because it is thin, discontinuous, and completely cemented by calcite with negligible primary porosity and very minor secondary porosity. Because of the low porosity and permeability, it is a reservoir seal.
B 	Central-ridge (CR) and high-energy ridge-margin (HRM) sandstone: lenticular, fine to medium-grained, with moderate-angle trough crossbedding and minor planar-tabular and planar-tangential bedding. Rip-up clasts of mudstone and siderite may be present on cross-bedding. Facies have erosional contacts and contain only minor burrowing.	CR and HRM are quartz- and carbonate-cemented, glauconitic, quartzose sandstones. Oil-productive sandstone is quartz cemented (8% average) with negligible calcite; dissolution of lithics and of replacive carbonate cements restores primary porosity and generates locally extensive secondary porosity.	CR and HRM sandstone have good to excellent reservoir potential and would be a hydrologic flow unit. These facies have the greatest porosity and permeability. Maximum facies distribution corresponds to field outlines. Ductile deformation of mudstone and glauconite, which are concentrated in ripple laminae, are minor barriers to fluid flow, and interbedding with low porosity and permeability inter-ridge sandstone may result in isolation and compartmentalization of sandstones.
C 	Low-energy ridge-margin (LRM) sandstone: very fine to fine-grained, ripple-laminated, and low-angle trough and planar bedded sandstone. Contacts are gradational to erosional. LRM is interbedded with IR and commonly grades upward into HRM sandstone. LRM may contain 0-25% burrows.	LRM sandstone shares similarities to IR and HRM sandstones; similar bedform types have similar petrology. Core evaluation indicates LRM facies are mainly calcite cemented.	LRM sandstone has low to moderate reservoir potential. Bioturbation and interbedding with lower depositional energy facies decreases reservoir potential. Because of the variation in bedforms, this sandstone is the most heterogeneous; trough cross-bedded units exhibit similar petrology to CR and HRM facies; ripple-laminated sandstone is similar to non-bioturbated inter-ridge facies; and bioturbated sandstone has low porosity due to compaction.
D 	Inter-ridge (IR) sandstone: Facies include wavy-bedded subfacies. Very fine to fine-grained , thinly-bedded, mainly tabular bedded sandstone. Bedforms are ripple laminated with low to extensive burrowing. Individual sandstone beds are segregated by thin mudstone drapes. Internal and bounding contacts are gradational to sharp and non-erosional.	IR sandstone contains variable but commonly pervasive amounts of quartz and calcite cement. Bioturbated sandstone exhibits extensive early porosity loss through compaction. Stacked sets of thin sandstones, which are variably cemented by carbonate and quartz, are common.	IR sandstone has low reservoir potential. Numerous thin mudstone drapes are effective permeability barriers to recovery of oil. Degree of cementation is highly variable in these units; however, core examination indicates that sandstones are commonly extensively cemented by carbonate and, to a lesser extent, quartz; this results in decrease of effective porosity and permeability.
E 	Inter-ridge (BIR) siltstone: tabular siltstone to very fine grained sandstone. Sedimentary structures are commonly destroyed by biologic activity.	BIR is the only facies in which compactional processes predominate. BIR contains abundant ductile grains. Cements are minor.	BIR facies have very low reservoir potential due to extensive compaction and very low porosity and permeability. Interbedding with reservoir facies results in permeability boundaries to vertical flow.

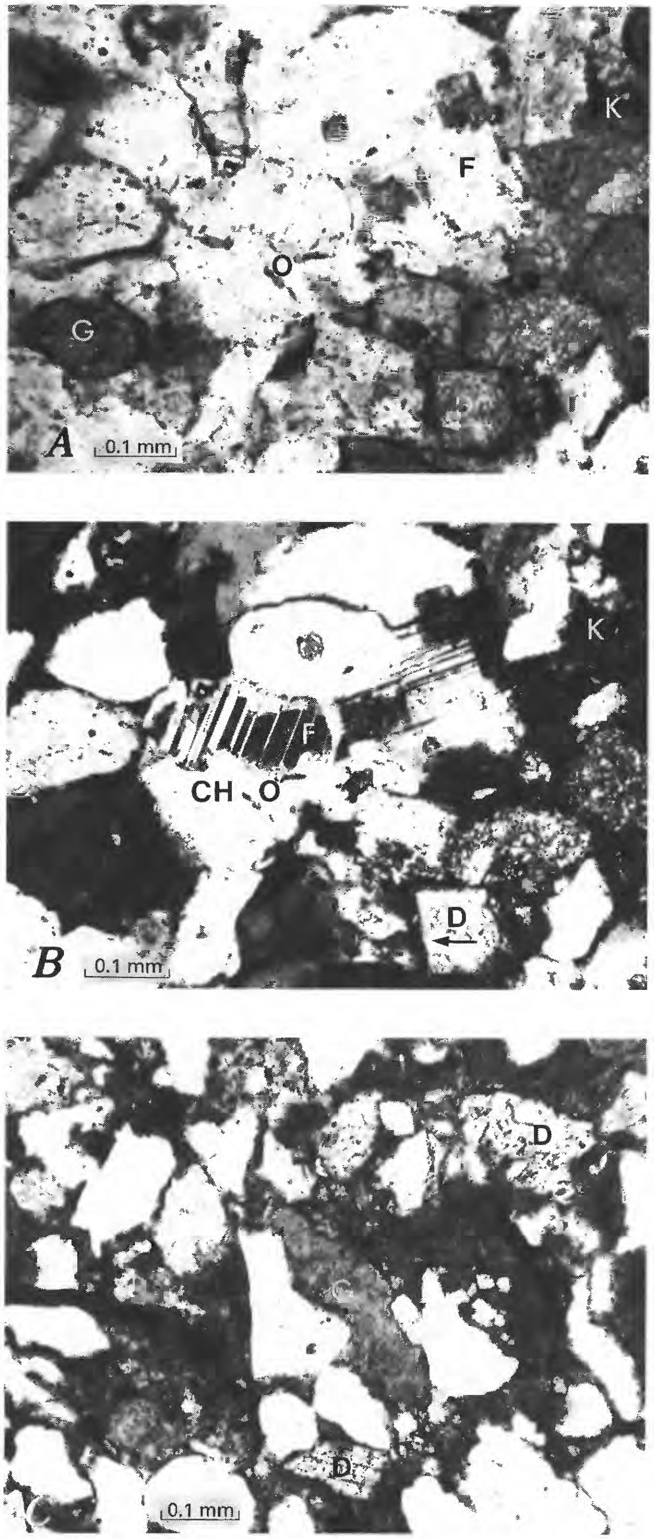


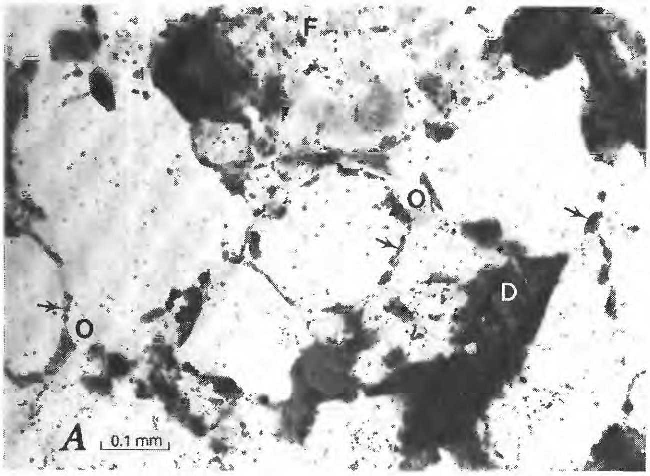
Figure 9 (facing column). Compaction and cementation relationships in inter-ridge facies. Scale bars are 0.1 mm. *A* and *B*, Transmitted and plane-polarized light views of an oil-stained wavy-bedded inter-ridge sandstone from 8,244 ft (2,513 m) depth in the No. 1–23 House Creek Federal well. This interval contains extensive (16.9 volume percent) quartz cement (O) that results in a close, interlocking framework with low porosity (5.4 percent thin-section) and low permeability. Cementation occurred prior to significant amounts of sediment compaction as indicated by undeformed glauconite (G) grains and minus-cement porosity of 38 percent. Peripheral dissolution of the albite grains (F) occurred prior to precipitation of overgrowths. Late-diagenetic dolomite and ferroan dolomite (D), comprising 2.3 volume percent, precipitated in available pores and automorphically replaced lithic grains. Grains, overgrowths, and dolomite rhombs are coated with later bitumen (arrows). Microporosity is present in authigenic kaolinite (K) and amounts to 2.7 percent, *C*, Transmitted light view of a bioturbated, very fine grained inter-ridge sandstone at 7,809.1 ft (2,380.2 m) depth, No. 14–9 Federal well. The glauconite grain (G) is deformed around adjacent quartz grains. CH is chlorite grain. Carbonate is present as scattered dolomite rhombs (D). Dolomite (upper right) replaces a quartz grain.

Wavy-Bedded Inter-Ridge Sandstone

Wavy-bedded inter-ridge sandstone is composed of thinly bedded, cyclical mudstone-drape sandstone sets (fig. 8*D*). Individual sets are generally less than 0.3 ft (0.1 m) thick and consist of fairly well sorted sandstone that exhibits small- to large-scale oscillation and current ripples; they are separated from other sandstone sets by mudstone drapes 0.01–0.1 inch (0.25–2.5 mm) thick. Grain-size grading is uncommon in this sandstone. Internal contacts are sharp, wavy, and non-erosional; sandstone structure is preserved by mudstone drapes. This facies is interbedded with other inter-ridge facies and with ridge-margin facies. The wavy-bedded inter-ridge sandstone unit differs from other inter-ridge sandstones because it is essentially non-burrowed: sandstone samples contain no more than 10 percent vertical and horizontal burrows. Mudstone drapes also display limited biological activity—they contain minor *Planolites* burrows and rare back-filled burrows.

The presence of rhythmic sandstone and mudstone sets suggests that periods of low- to moderate-energy wave motion were separated by slack water periods during which deposition of suspended load was rapid enough to prevent significant amounts of reworking by biologic activity. Reactivation surfaces (fig. 8*D*) within some sandstone sets indicate flow reversals—this suggests the influence of tides.

The wavy-bedded sandstone has limited potential as a petroleum reservoir. Primary and secondary oil recovery is adversely affected by numerous mudstone drapes that are effective boundaries to vertical and lateral fluid flow. Sandstone thin-section porosity averages 5.9 percent and may be as much as 13.9 percent. Sandstone is commonly pervasively cemented by quartz (fig. 9) or carbonate. Approximately half of the porosity is secondary and intragranular and results mainly from: (1) dissolution of plagioclase, or (2) replacement of feldspar, quartz, rock fragment, and glauconite grains by calcite, followed by carbonate dissolution.



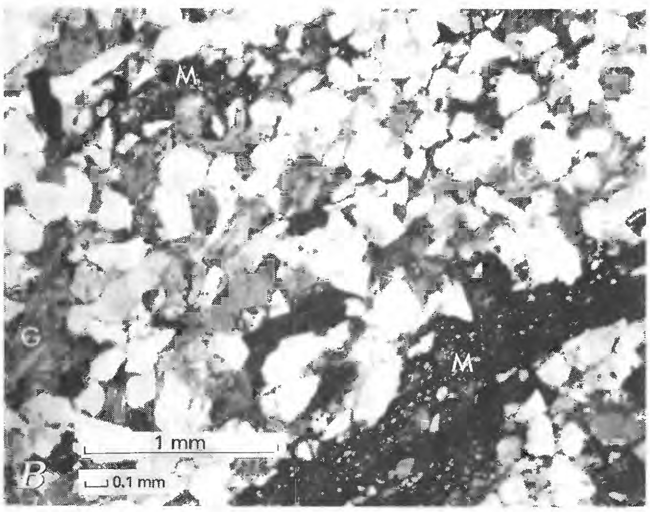


Figure 10. Transmitted light photomicrographs of low-energy ridge-margin sandstone showing two processes resulting in porosity reduction. *A*, Ripple-laminated sandstone in the No. 1 Campbell well (7,704.3 ft depth) contains 17.4 percent quartz cement (O) that results in a volumetric decrease in porosity to 4.1 percent. F is feldspar grain. Chlorite rims (arrows) comprise 2 volume percent of this interval. Abundant clay matrix and minor dolomite rhombs (D) fill remaining pore spaces. Scale bar is 0.1 mm. *B*, This flaser-bedded unit is a ripple-laminated sandstone from 7,793.2 ft (2,375.4 m) in the No. 14–9 Federal well. Extensive mechanical deformation of glauconite (G) (10.3 percent by volume) reduced porosity to 4.1 percent intergranular and 20.7 percent minus-cement porosity. Mudstone laminae (M) are oil stained. This interval probably traps hydrocarbons in the underlying perforated interval in the well. Scale bars are 1.0 and 0.1 mm.

Ridge-Margin and Central-Ridge Sandstone

Ridge-margin and central-ridge sandstones are the reservoir facies in the House Creek and Porcupine fields. These facies generally grade upward from sets of low-energy ridge-margin sandstone to high-energy ridge-margin and central-ridge sandstone. Low-energy ridge-margin sandstones include sedimentologic and petrologic characteristics of inter-ridge and ridge facies and represent a transition zone between them. High-energy ridge-margin and central-ridge sandstones are described together because they are almost identical petrologically.

Low-Energy Ridge-Margin Sandstone

Low-energy ridge-margin sandstones have a combined thickness of much as 8 ft (2.4 m) and consist of fine-grained trough or planar-tangential cross-beds that are interbedded with massive, wavy-bedded, and ripple-laminated sandstone (fig. 8*C*). Contacts between sets are generally transitional, and, partly because of erosion by higher-energy facies, the sets may be only a few inches (cm) thick. Low-energy ridge-margin sandstones have low to moderate reservoir potential. This sandstone is sedimentologically more heterogeneous than that of the central-ridge or high-energy ridge-margin facies: individual sandstone sets are thinner and are frequently bounded by mudstone drapes—this facies is interbedded with inter-ridge sandstones and commonly contains greater amounts of carbonate cement and clay matrix.

Low-energy ridge-margin sandstones are moderately to highly glauconitic (3–13 percent) with minor, small clasts of mudstone rip-up and siderite. Drapes of mudstone are 0.01–0.1 inch (0.25–2.54 mm) thick and may contain horizontal sand-filled burrows of *Planolites*. Sandstone generally contains less than 10 percent, vertical, U-shaped, and horizontal burrows of *Arenicolites*, *Skolithos*, *Chondrites*, *Diplocraterion*, and *Terrebellina*.

Evaluation of Sussex "B" core indicates that pore spaces in non-oil-productive sandstones are commonly filled with calcite cement. Extreme ranges in amounts and types of cement are characteristic of this facies and may reflect the interbedding of low and moderate depositional energy sandstone (fig. 10).

Central-Ridge and High-Energy Ridge-Margin Sandstone

Central-ridge and high-energy ridge-margin sandstones are the primary oil reservoir facies of the Sussex "B" sandstone. High-energy ridge-margin and central-ridge facies are grouped together because of very similar petrology and sedimentology: these facies form a hydrologic flow unit. High-energy ridge-margin sandstone is more heterogeneous than central-ridge sandstone because it contains more carbonate cement and exhibits greater interbedding with sandstones and siltstones of lower depositional energy.

The areal distribution of ridge facies sandstones in the House Creek field has been mapped and described by Berg (1975), Brenner (1978), and Hobson and others (1982); the distribution corresponds generally to the field outlines shown on figure 1. The central-ridge and high-energy ridge-margin facies in the House Creek and Porcupine fields are as much as 20 ft (6 m) thick. Individual trough cross-bedded sets fine upward, are commonly less than 1 ft (0.3 m) thick, and are truncated at their upper surfaces. Sandstones exhibit small- to medium-scale trough cross-bedding with minor planar-tabular and planar-tangential bedding; dip angles on trough cross-bedding are mainly 20° to 35° (fig. 8*B*). These facies were deposited primarily as small- to medium-sized subaqueous dunes. Biologic activity results in as much as 10 percent horizontal burrows in mudstone drapes. Uncommon vertical burrows of *Skolithos*, *Arenicolites*, and *Diplocraterion* may be present near the top of the trough sets or may penetrate into central-ridge sandstones where they are overlain by lower energy sandstone units. The vertical trace fossils were formed by suspension-feeding organisms, and burrows generally display evidence of rapid sediment deposition. Glauconite is concentrated within discrete trough cross-bedding ripple-laminae sets (dark lines on fig. 8*B*). Extensive soft-sediment deformation within these laminae may result in minor permeability barriers to vertical fluid flow (fig. 7*D*). Fluid should preferentially flow parallel to the long axes of trough cross-beds. Mudstone is present mainly as drapes on trough bedding planes; suspended-load sedimentation on dunes occurred primarily during slack water periods. Also present on the trough bedding planes are mudstone rip-up clasts and siderite clasts that may be as much as 3 inches (8 cm) long and 1 inch (3 cm) wide. Core and outcrop studies indicate that sources of the clasts are siderite drapes and siderite-cemented sandstone; these are present in many of the facies located within and below the Sussex interval (fig. 8*D*). These siderite drapes may have been eroded by storm currents or other strong currents; the rounded clasts were subsequently deposited on subaqueous dunes. The volume percent for siderite drapes in central-ridge sandstone (table 2) is anomalously large, primarily because of preferential sampling of some intervals containing the drapes.

Central-ridge and high-energy ridge-margin facies sandstones are fine to medium grained. Grains generally exhibit long and straight or point contacts with other grains. Cementation by quartz and calcite are important porosity reduction processes in central-ridge and high-energy ridge-margin facies—this is indicated by Sussex "B" sandstone average minus-cement porosity values of 30.7 and 35.8 percent, respectively (table 2). Quartz cement averages 8.5 volume percent in both facies and ranges from 0.7 to 23.2 volume percent. Thin-section porosity averages 7.7 and 6.1 percent for central-ridge and high-energy ridge-margin sandstones; this is less than the average reservoir porosity of 13 percent. Microporosity was not measured during thin-section point counting, resulting in low values relative to core porosity. Central-ridge and high-energy ridge-margin facies also average 9.5 and 14.3 volume percent carbonate cement, respectively, and oil is present mainly in those rock intervals in which calcite is absent or in which calcite dissolution has restored porosity and created secondary pore spaces. The rare potassium feldspar grains generally are extensively corroded and are sometimes closely associated with pore-filling authigenic kaolinite. Plagioclase content ranges from 2.3 to 11.5 volume percent, and grains may exhibit extensive dissolution (fig. 7*C*) and minor to extensive replacement by calcite and dolomite. Secondary porosity results mainly from dissolution of: (1) plagioclase, (2) calcite that filled intragranular pore spaces and replaced feldspar and, (3), to a lesser extent, calcite that replaced rock fragments, quartz grains and overgrowths, and glauconite.

Chert Pebble Sandstone

Where present, chert pebble sandstone is the upper contact of the Sussex "B" sandstone (fig. 8*A*) and represents the highest depositional energy conditions of the facies studied (Hobson and others, 1982). This chert pebble sandstone facies is generally less than 1 ft (0.3 m) thick and is areally discontinuous across the House Creek and Porcupine fields. Cores from at least five of the 21 Sussex "B" wells in the area of the House Creek field and one well in the Porcupine field contain this chert unit (several of the cored sections did not include the upper contact). This sandstone is indistinguishable on well logs from underlying facies; it contains pervasive calcite cement and is not a reservoir for oil. However, where this unit is present, it acts as a seal that traps hydrocarbons in underlying reservoir sandstones.

The chert pebble sandstone exhibits distinct bimodal sorting and consists of medium-sized grains of subangular quartz and granule-sized grains of well-rounded chert that are 0.05–0.2 inch (1–5 mm) in diameter. This facies erosionally overlies central-ridge facies sandstones and is transitionally overlain by a unit that consists of offshore marine mudstone to very fine grained sandstone. The chert pebble sandstone facies exhibits small- to medium-scale trough cross-bedding and minor planar-tabular cross-bedding. Individual trough cross-sets are several inches to 1 ft (0.08–0.3 m) thick, fine upward, and have truncated upper surfaces. Glauconite, mudstone rip-up, and other soft sediment grains were winnowed from the sandstone and are concentrated within trough-laminae sets. The source of the chert is probably limestone that was replaced by chert and subsequently eroded—this is indicated by inclusions of carbonate in chert, pseudomorphs after dolomite, and burrows and fossil fragments that are replaced by chert and chalcedony.

The chert pebble sandstone may have been deposited by high-energy storm currents. The sandstone may also have resulted from an event in which the pebbles were introduced by channelized flow (Berg, 1975) and reworked into the chert sandstone. However, the chert pebble sandstone probably represents a winnowed lag deposit on an unconformity surface: the unit is widely distributed across the House Creek and Porcupine fields, erosional surfaces show low relief (less than 1 m), and deep channels are absent. Foraminiferal tests and bone fragments are occasionally preserved. Also, this unit is petrologically different from other facies of the Sussex: the chert pebble sandstone consists of 32.4 percent by volume chert pebbles (rock fragment category), whereas chert grains average 4.2 percent in the other facies. Chert grains in this unit exhibit coatings of oxidized iron (fig. 7*F*); this is unlike grains in the other units. Grain-to-grain contacts within this facies are point and long-straight contacts. Quartz grains incorporated from underlying central-ridge facies sandstones commonly "float" in a matrix of carbonate cement (fig. 7*F*). Because of high depositional energy conditions, the sandstone does not contain burrows or tracks.

Porosity in the chert pebble sandstone is commonly secondary, resulting mainly from dissolution of lithic grains and fossil fragments (fig. 7*F*). Cementation is the major process of porosity reduction. Compactional loss of porosity results primarily from rearrangement and closer packing of lithic grains. The 24.8 percent average minus-cement porosity represents about a 5–10 percent loss of porosity from the initial depositional porosity. Initial porosity was probably less in this facies than in other facies because of bimodal sorting.

In core and thin sections, this chert pebble sandstone is completely cemented by calcite and ferroan calcite. Average calcite cement comprises 20.9 volume percent. This sandstone would have excellent porosity and permeability and would be a reservoir facies if the calcite cement were removed. Paragenesis is commonly "frozen" because of early calcite cementation. Kaolinite and illite-smectite (which precipitated in other sandstone facies after calcite dissolution) are rare in the chert pebble sandstone facies.

CONCLUSIONS

The Sussex "B" sandstone is composed generally of a coarsening-upward sequence of inter-ridge to central-ridge sandstones; the best developed reservoir sandstones are located at the top of each sequence. Sandstones are very fine to medium-grained litharenites to feldspathic litharenites. Porosity relationships are complex and consist of primary porosity, secondary porosity, and microporosity. Porosity is commonly greatest within the high depositional energy central-ridge and ridge-margin facies: these are the reservoir sandstones of the House Creek and Porcupine fields. Reservoir properties are controlled by: (1) types and amounts of cements, (2) enhancement of porosity through dissolution of carbonate cements, (3) sedimentologic factors that influence fluid flow and the degree of sediment compaction, and (4) amounts of pore-filling and grain-coating clays. Fluid flow during oil production is slowed by the numerous permeability boundaries created by interbedding of inter-ridge with ridge facies sandstones and by numerous mudstone drapes.

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