Sedimentological Descriptions and Depositional Interpretations, in Sequence Stratigraphic Context, of Two 300–Meter Cores from the Upper Cretaceous Straight Cliffs Formation, Kaiparowits Plateau, Kane County, Utah

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By Robert D. Hettinger

SEDIMENTOLOGIC AND STRATIGRAPHIC INVESTIGATIONS OF
COAL-BEARING STRATA IN THE UPPER CRETACEOUS
STRAIGHT CLIFFS FORMATION, KAIPAROWITS PLATEAU, UTAH

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ABSTRACT

In 1991, the U.S. Geological Survey drilled two wells in the Kaiparowits Plateau, Utah, and retrieved two 300-meter cores from upper Turonian to lower Campanian strata of the Straight Cliffs Formation. Detailed analyses of the cores document details of published sequence stratigraphic models and provide new insight into controls on peat accumulation.

Along the northeast flank of the plateau, the entire 250-meter-thick John Henry Member of the Straight Cliffs Formation consists of coarsening-upward shoreface parasequences that accreted along the transgressive maxima of a third-order marine cycle. The shoreface deposits are characterized by swaley and hummocky cross-stratified sandstone and mudrock containing marine fossils. Core retrieved 5 kilometers inland (southwest) of the shoreface stack contains coeval strata that are 58 percent tidal, 23 percent coastal plain, and 19 percent shoreface in origin. Tidally influenced strata comprise heterolithic units characterized by trough and planar tabular crossbedded and cross-laminated sandstone, wavy and lenticular bedding, double mud drapes, *Teredolites* borings, and oyster shell fragments. Coastal plain strata are characterized by rooted and convoluted mudrock, cross-laminated and trough-crossbedded sandstone, and coal beds that are as much as 3.5 meters thick. Fifteen kilometers inland from the shoreface stack, a second core of coeval rocks is 68 percent coastal plain, 30 percent tidal, and 2 percent shoreface in origin. Here, the coastal plain strata include coal beds that are as much as 4.4 meters thick. By contrast, exposures described at the south flank of the plateau, 35 kilometers inland from the shoreface stack, show that the John Henry Member consists entirely of alluvial strata and lacks significant coal.

Sequence stratigraphic interpretations of the core are based on depositional stacking patterns recorded from the core. Sequence boundaries are interpreted from significant basinward shifts of depositional facies. Transgressive and highstand systems tracts are interpreted from retrogradational and progradational stacking patterns, respectively. As much as 28 meters of coal is contained within two highstand systems tracts located adjacent to the marine maxima. Many of the coal beds are closely associated with tidally influenced strata. By contrast, transgressive systems tracts contain less than 2 meters of total coal.

Depositional successions in the core closely match those presented in published regional sequence stratigraphic studies. The combined surface and subsurface studies enhance correlations between shoreface and continental strata and provide a model for making sequence stratigraphic interpretations from limited core data.

INTRODUCTION

In 1991 the USGS (U.S. Geological Survey) drilled two 300-m holes and retrieved nearly 560 m of core from Upper Cretaceous strata in the Kaiparowits Plateau, Utah (fig. 1). The drill holes and respective cores are labeled CT-1-91 and SMP-1-91. Both cores were initiated near the top of the Straight Cliffs Formation, as mapped by Zeller (1978), and Zeller and Vaninetti (1990), and continuous core was retrieved from the Smoky Hollow (upper part), John Henry, and Drip Tank (lower part) Members of the Straight Cliffs Formation at each locality (fig. 2). The core was collected to provide insights into the eustatic, tectonic, and climatic controls on coal accumulation and quality. Palynostratigraphic analysis of the core is reported by D.J. Nichols (in press). Preliminary results of coal and clastic facies analyses related to the core have been published by Hettinger and McCabe (1992a, 1992b), Hettinger (1993), and Pierce and others (1992). This report presents detailed sedimentological descriptions and geophysical logs, as well as depositional and sequence stratigraphic interpretations from cores CT-1-91 and SMP-1-91.

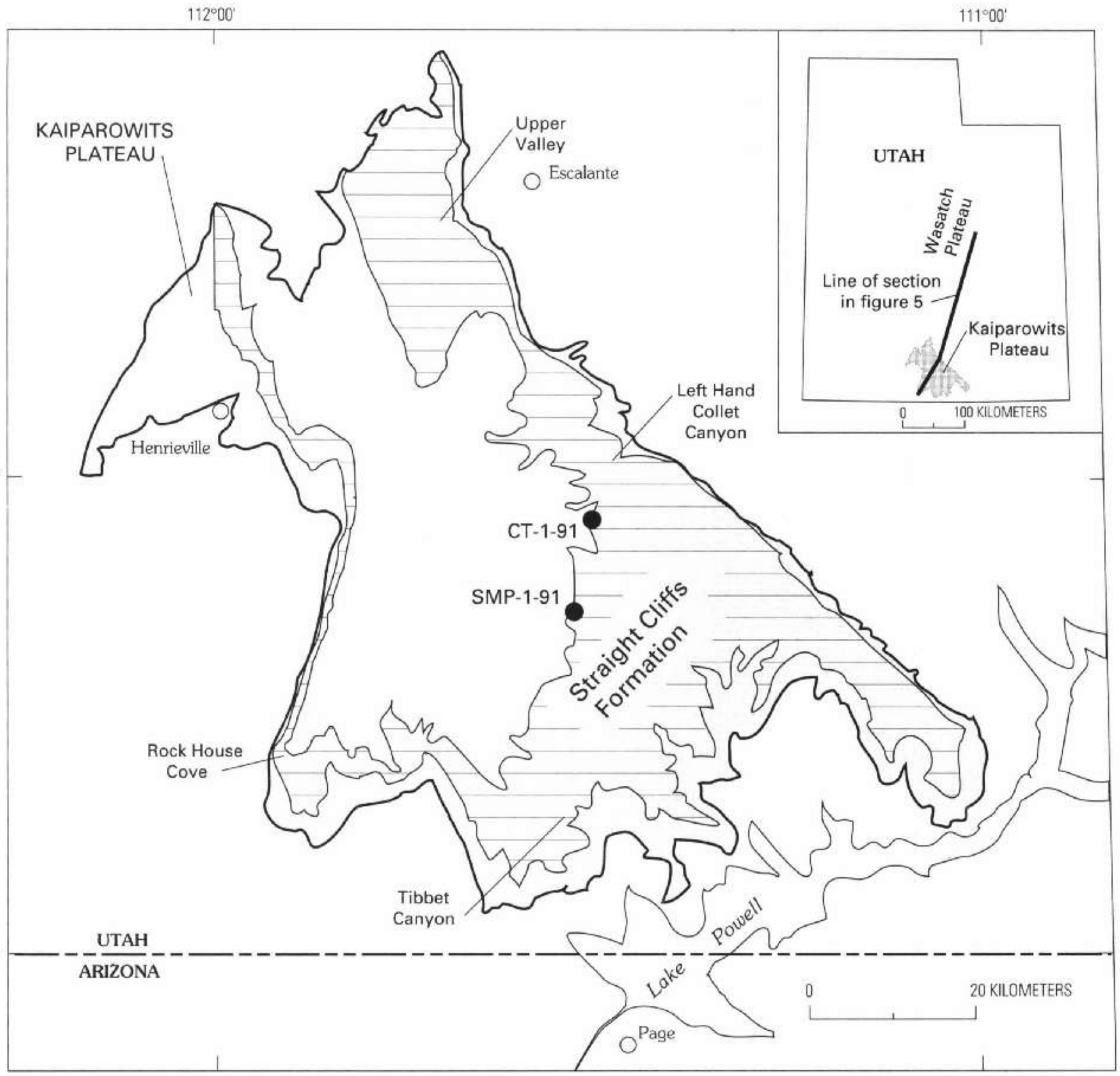


Figure 1. Locations of Kaiparowits Plateau (heavy line outline), core holes CT-1-91 and SMP-1-91, and line of section in figure 5. Outcrops of the Straight Cliffs Formation shown by horizontal line pattern.

The drill holes are located in the interior regions of the Kaiparowits Plateau, in the Collet Top and Ship Mountain Point 7.5′ topographic quadrangles (figs. 3, 4). Drill hole CT-1-91 is located on the southwest limb of the Rees Canyon Anticline, where underlying strata dip less than 1° to the southwest (Zeller, 1978). Drill hole SMP-1-91 is located on the east limb of the Last Chance Syncline, where underlying strata dip approximately 3° to the southwest (Zeller and Vaninetti, 1990). No significant faults have been reported in the vicinity of either drill site.

The drill sites were selected to augment sequence stratigraphic studies of outcrops in Left Hand Collet Canyon, Tibbet Canyon, and Rock House Cove (fig. 1) by Shanley (1991), Shanley and McCabe (1991), McCabe and Shanley (1992), and Shanley and others (1992). The outcrop and drill hole localities are aligned roughly perpendicular to paleoshorelines of the Upper Cretaceous Western Interior seaway as interpreted by Peterson (1969a) and Shanley (1991). The drill sites at CT-1-91 and SMP-1-91 are located about 5 km and 15 km, respectively, inland from a thick stack of shoreface parasequences that comprise the John Henry Member in Left Hand Collet Canyon.

ACKNOWLEDGMENTS

I thank Peter J. McCabe and Diane L. Kamola for the assistance they provided with facies and trace fossil

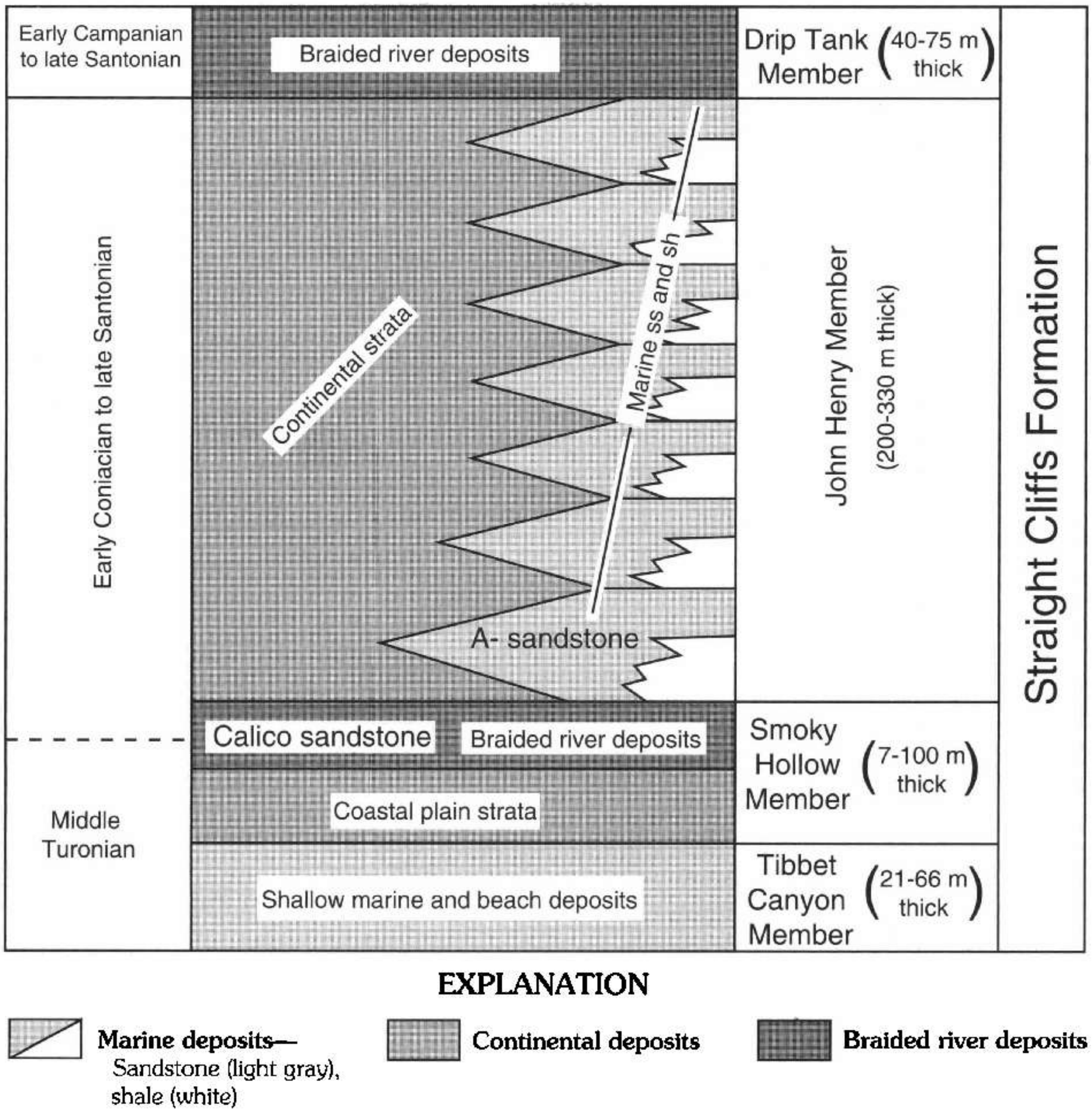


Figure 2. Stratigraphic positions, thicknesses, and depositional settings for members in the Upper Cretaceous Straight Cliffs Formation, modified from Peterson (1969b).

identifications. I thank Bill Whitus, Art Clark, Mark Kirschbaum, and the USGS drill crew for the assistance they provided in the field. I also thank Peter McCabe, Keith Shanley, and Lorna Carter for their reviews of this bulletin.

FIELD WORK

CT-1-91 and SMP-1-91 were drilled during May and June, 1991 with a USGS owned and operated truck mounted rotary/core rig. Drilling was accomplished using compressed air with fresh water injection. Continuous 3-in. (7.6 cm) core was retrieved from each hole using a 20-ft-long (6.1 m), conventional core barrel with a split inner tube sampler. The core was oriented, calibrated, photographed, and briefly described in the field. Down hole depths were marked in 1-ft (0.3 m) increments on the core. Caliper, natural gamma (gamma ray), bulk density, and spontaneous potential (SP) geophysical logs were recorded from each hole and are shown in the appendix of this report. The core holes were filled with fresh water so that spontaneous potential logs could be recorded to the surface (natural ground-water levels were at depths of 804 ft (245 m) in CT-1-91 and 57 ft (17 m) in SMP-1-91).

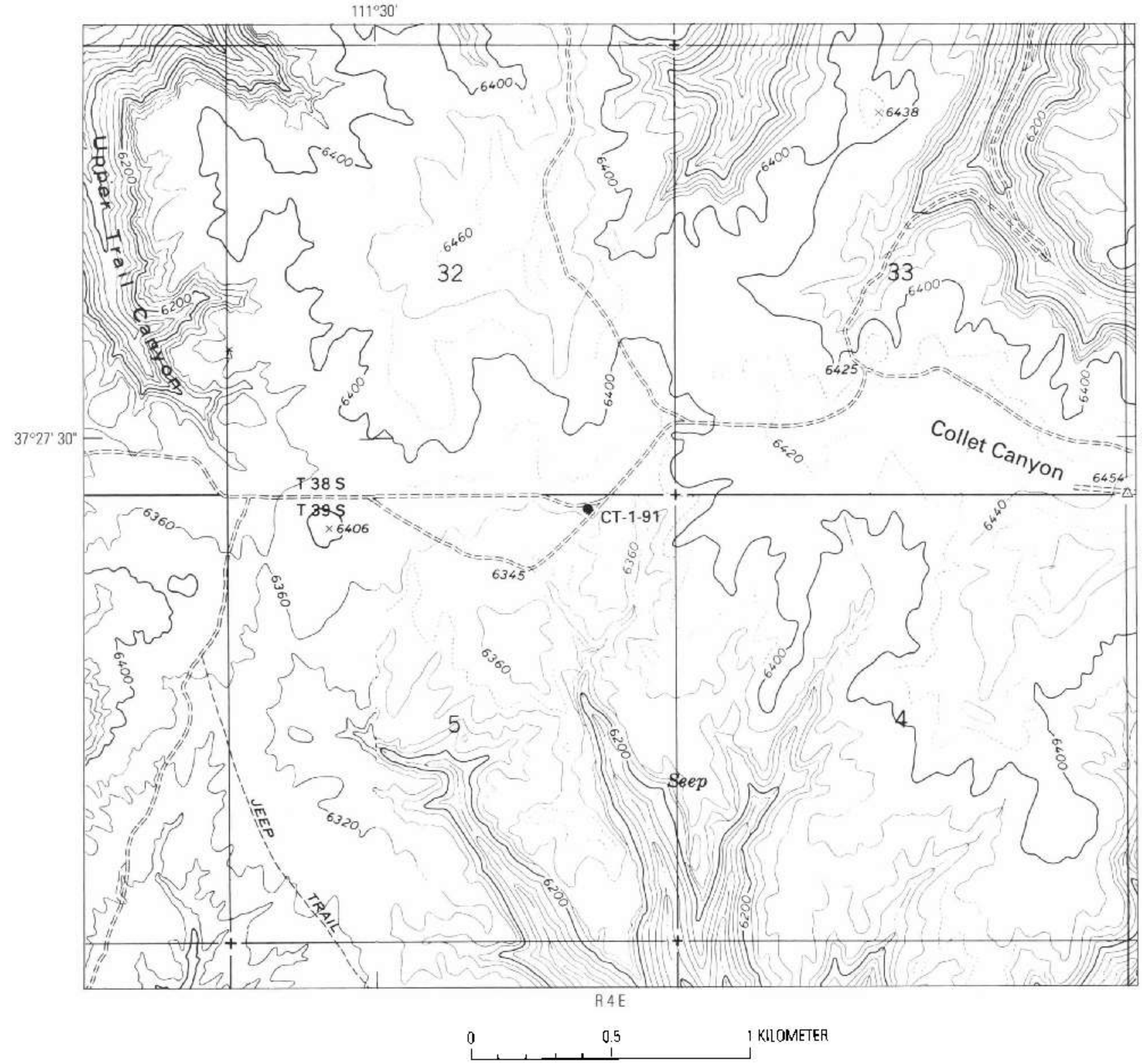


Figure 3. Location of core hole CT-1-91 in the Collet Top 7.5′ topographic quadrangle, Utah. Base from U.S. Geological Survey 1:24,000 Collet Top and Petes Cove, 1968. Contour interval 40 ft. CT-1-91 is located 200 ft (60 m) from the north line and 1,000 ft (305 m) from the east line of sec. 5, T. 39 S., R. 4 E. (lat 37°27′22″ N., long 111°29′27″ W.), at an elevation of 6,370 ft (1,942 m) above mean sea level.

A total of 916 ft (279 m) of core (121 core boxes) were recovered between the depths of 141.1 and 1,057.4 ft (43.0 and 322.7 m) in CT-1-91. A total of 903 ft (275 m) of core (120 boxes) were recovered between the depths of 60.0 and 962.7 ft (18.3 and 293.4 m) in SMP-1-91. All cores of coal beds were placed into airtight plastic bags, and cores of coal beds greater than 1 ft (0.3 m) thick were encased in PVC tubing and sent to the USGS in Reston, Va., for analyses. The remainder of the core was sent to the USGS in Denver, Colo., for analyses. All core and coal splits are stored at the USGS Core Research Library, Building 810, Denver Federal Center, Denver, Colo.

STRATIGRAPHY OF THE STRAIGHT CLIFFS FORMATION

The Upper Cretaceous Straight Cliffs Formation is divided, in ascending order, into the Tibbet Canyon, Smoky Hollow, John Henry, and Drip Tank Members (fig. 2)

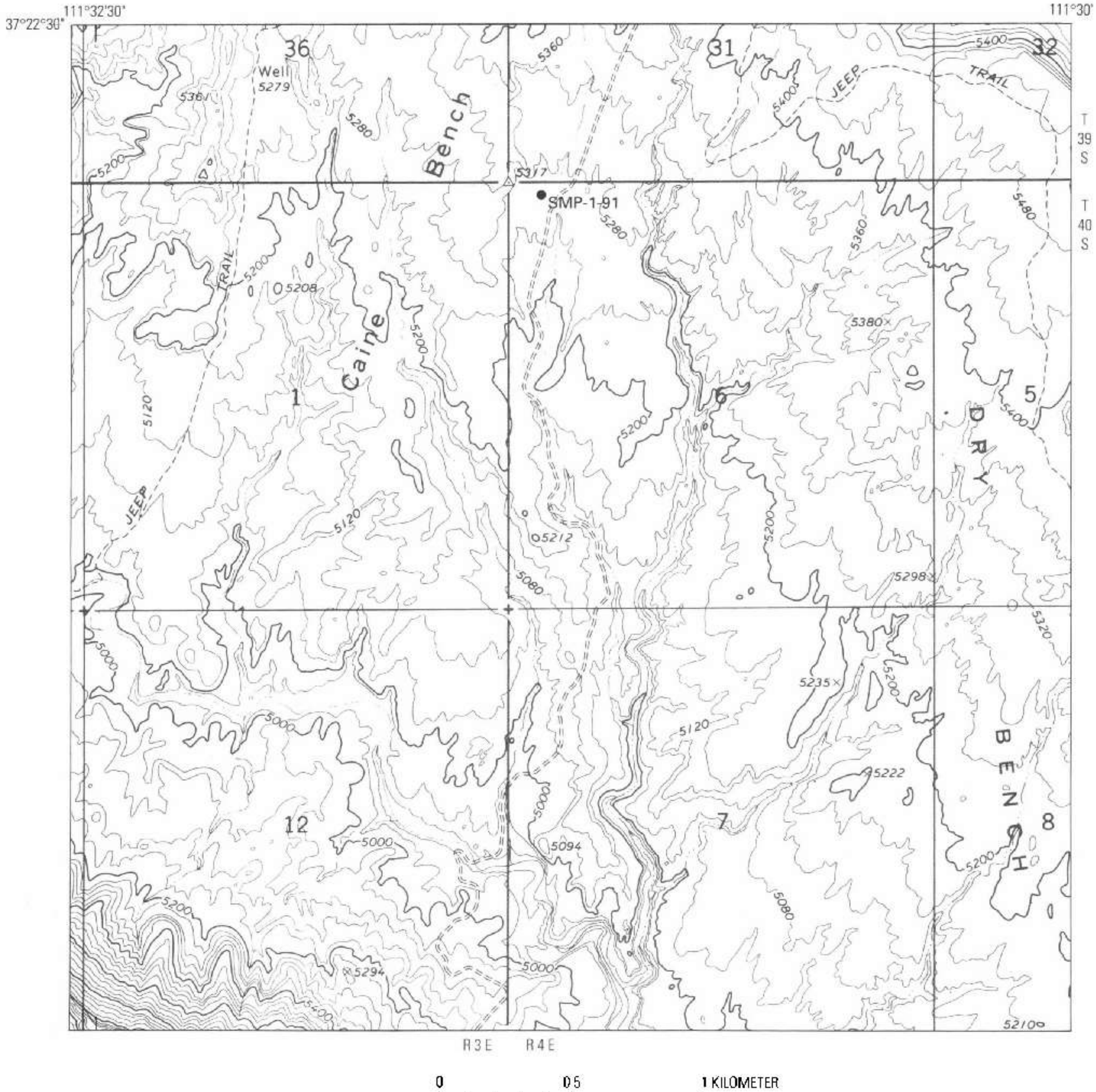


Figure 4. Location of core hole SMP-1-91 in the Ship Mountain Point 7.5' quadrangle, Utah. Base from U.S. Geological Survey, 1968. Contour interval 40 ft. SMP-1-91 is located 200 ft (60 m) from the north line and 400 ft (122 m) from the west line of sec. 6, T. 40 S., R. 4 E. (lat 37°22′09″ N., long 111°31′19″ W.), at an elevation of 5,247 ft (1,599 m) above mean sea level.

(Peterson, 1969b). The members are 21–66 m, 7–100 m, 200–330 m, and 40–75 m thick, respectively. Peterson (1969b) interpreted the Tibbet Canyon Member as a shallow marine and beach deposit; the Smoky Hollow Member as a coastal plain and braided river deposit; the John Henry Member as interbedded marine and continental strata; and the Drip Tank Member as braided river strata. Additionally, Peterson identified two key marker sandstones, the Calico and A- sandstones (fig. 2) (Peterson, 1969a, b). The Calico sandstone is located at the top of the Smoky Hollow Member and is interpreted as a braided river deposit (Peterson, 1969a, b). The A- sandstone is located at the base of the John Henry Member and is interpreted as a marine sandstone (Peterson, 1969a, b). The Tibbet Canyon and Smoky Hollow Members

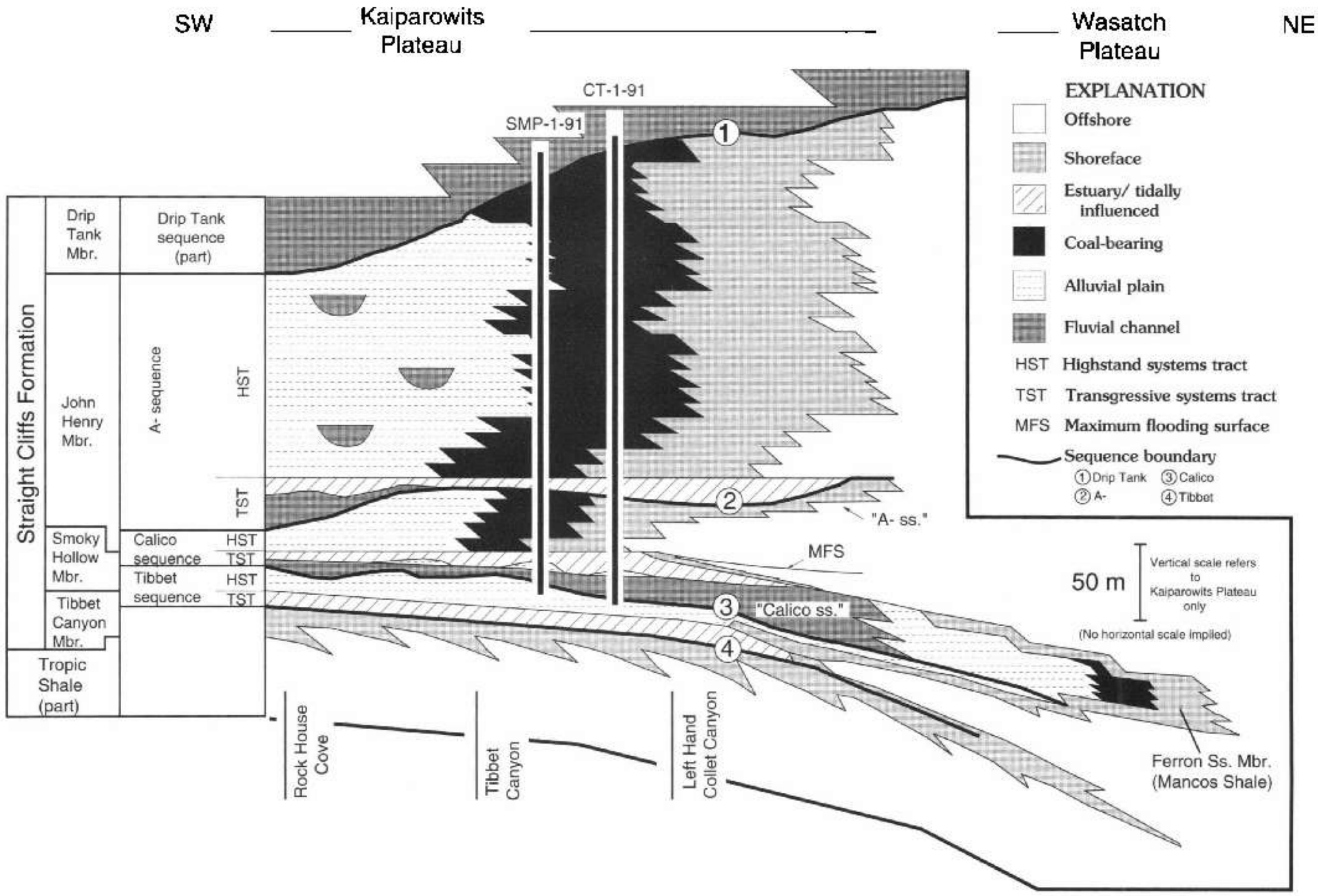


Figure 5. Facies relationships in Turonian through lower Campanian strata of the Kaiparowits and Wasatch Plateaus, Utah. Line of section is shown in figure 1. Core holes are shown with respect to depositional sequences and stratigraphic studies in Left Hand Collet Canyon, Tibbet Canyon, and Rock House Cove (Shanley and McCabe, 1991; Shanley and others, 1992; McCabe and Shanley, 1992). Diagram is modified from Shanley (1991), Shanley and others (1992), and Hettinger and others (1994).

have been dated as middle Turonian (Eaton, 1991); however, an inoceramid fossil[1] recently collected from the upper part of the Smoky Hollow Member indicates an early Coniacian age. The John Henry Member was dated as early Coniacian to late Santonian, and the Drip Tank Member was designated a late Santonian or early Campanian age (Eaton, 1991).

The Straight Cliffs Formation was divided recently into five depositional sequences and associated transgressive and highstand systems tracts (fig. 5) (Shanley and McCabe, 1991). The depositional sequences are each bounded by regional unconformities (sequence boundaries), located within the Tibbet Canyon Member, at the base of the Calico sandstone, within the A- sandstone, and near the base of the Drip Tank Member (fig. 5). The unconformities are named the Tibbet, Calico, A-, and Drip Tank sequence boundaries, respectively (fig. 5) (Shanley and McCabe, 1991). The informally named Tibbet, Calico, A-, and Drip Tank sequences overlie each respective unconformity (fig. 5).

Shanley and McCabe (1991) and Shanley and others (1992) have demonstrated that the arrangement of strata within each depositional sequence occurs within an organized pattern because it is controlled by base-level change. Sequence boundaries are unconformities incised during base-level lowering. These incised valleys are backfilled with an overall deepening-upward succession during the

[1] A fossil that Mark Kirschbaum and I collected from the Smoky Hollow Member of the Straight Cliffs Formation was identified by W.A. Cobban (U.S. Geological Survey, oral commun., 1989) as an inoceramid of Coniacian age. Chris Collom (University of Colorado, oral commun., 1990) further identified the fossil as *Cremnoceramus deformis* of early Coniacian age. The fossil was collected about 4 m below a laterally persistent pebble conglomerate that defines the base of the John Henry Member as mapped by Bowers (1973). The fossil locality is at the 29 m level of measured section 5 of Hettinger and others (1994), and is 2,300 ft (701 m) from the south line and 1,300 ft (396 m) from the west line of section 26, T. 35 S., R. 1 E., Garfield County, Utah. Several additional inoceramids remain at this locality.

Table 1. Grain size, color, thickness, and percent of lithologic components in cores CT-1-91 and SMP-1-91.

Unit	Grain size	Color	Unit thickness	Approximate percent unit in CT-1-91	Approximate percent unit in SMP-1-91
Sandstone	Very fine to very coarse sand, locally granular.	Very light to very dark gray, yellowish gray, brownish gray, greenish gray and orange brown.	< 0.01-27 m.	66	55
Mudrock	Clay and silt	Greenish gray, bluish gray, light to blackish gray, olive gray, and brownish gray.	< 0.01-10 m.	23	30
Coal	- - - -	Dark brownish black and black.	0.1-4.4 m.	7	10
Carbonaceous shale	Clay and silt	Dusky yellow brown, dark brownish black and black.	0.02-1.4 m.	4	4
Mud-clast conglomerate	Intraformational clasts to 7 cm across in a clay or sand matrix.	- - - -	< 0.6 m	< 1	< 1
Conglomerate	Extraformational pebbles to 5 cm across in a sand matrix.	- - - -	< 0.6 m	< 1	- - - -

[Leaders (- - - -) indicate that characteristic is not described for lithologic unit]

subsequent base-level rise. Such back-stepping successions are interpreted as transgressive systems tracts (Shanley and McCabe, 1991). Overlying highstand systems tracts consist of progradational parasequences deposited during a slower rate of rise in base level. Each highstand deposit is subsequently truncated by a sequence boundary unconformity. Thick coals are contained within the coastal plain deposits of the highstand systems tracts.

Depositional facies patterns within each systems tract have been well documented by Shanley and McCabe (1991), Shanley and others (1992), McCabe and Shanley (1992), and Hettinger and others (1994). Rocks overlying each sequence boundary demonstrate an abrupt basinward shift with respect to the underlying strata. For example, the Calico and Drip Tank sequence boundaries each separate fine-grained coastal plain and shoreface strata from overlying coarser grained braided river deposits. The A- sequence boundary separates fine-grained coastal plain and shoreface strata from overlying coarser grained, tidally influenced strata. Rocks within each transgressive systems tract demonstrate back-stepping or landward facies shifts that are capped by marine flooding surfaces. These facies show both an upward and a landward transition from fluvial to estuarine strata and, in the Calico transgressive systems tract, the estuarine strata are capped by shoreface deposits. Tidally influenced and fluvial channel sandstones are typically amalgamated in both transgressive systems tracts. Progradational deposits within the highstand systems tracts are characterized by alluvial strata along the southwest margin of the plateau (Rock House Cove), coal-bearing coastal plain deposits in the central region of the plateau (Tibbet Canyon), and shoreface deposits along the northeast margin of the plateau (Left Hand Collet Canyon) (Shanley and McCabe, 1991; McCabe and Shanley, 1992; Shanley and others, 1992). Channel sandstones within the highstand systems tracts are typically isolated.

CORE DESCRIPTIONS AND FACIES

Lithologies, sedimentological features, fossils, and trace fossils have been described in detail from clean and uncut surfaces of the core and are shown on plate 1. The grain size, color, thickness, and percent of lithologies in each core are summarized in table 1. The characteristics used to identify bivalves and trace fossils are summarized in table 2. Twelve facies are identified in the core on the basis of lithology and sedimentary structures. Characteristics of each facies are summarized in table 3.

Sandstone and mudrock are the major lithologic constituents of each core. CT-1-91 contains about 66 percent sandstone and 23 percent mudrock, whereas SMP-1-91 contains about 55 percent sandstone and 30 percent mudrock. Units of sandstone range from less than 1 cm to as much as 27 m in thickness. Sandstone is very fine

Table 2. Characteristics and identification criteria for bivalves and trace fossils in cores CT-1-91 and SMP-1-91.

Bivalves	Characteristics
Brachidontes	Shells are about 5 cm long and have fine radiating striae and smooth concentric growth lines.
Corbula	Shells are about 1.5 cm across and have smooth concentric growth lines.
Inoceramid	Shell fragments are < 8 cm across and have internal prisms.
Oyster	Shell fragments are < 5 cm across, laminated, and may have a mother of pearl coating.
Trace fossils	**Characteristics**
Cylindrichnus	Burrows are < 0.5 cm in diameter and have thick smooth mud-lined walls and a thin central sand-filled tube.
Ophiomorpha	Burrows are about 0.5-2 cm in diameter, horizontal to oblique, sand filled, and have pelletized linings.
Palaeophycus	Burrows are about 0.5-1.0 cm in diameter, isolated, nearly horizontal, sand filled, and have smooth lined walls.
Planolites	Burrows are < 1 cm in diameter, nearly horizontal, sand filled, and have unlined smooth walls and meniscate fill.
Scoyenia	Burrows are < 0.5 cm in diameter, oblique to vertical, unlined, sand filled, and have a meniscate fill.
Skolithos	Burrows are < 0.5 cm in diameter, nearly vertical, smooth walled, and unbranched.
Teichichnus	Burrows are about 1.5 cm in diameter, horizontal, sand filled, and occur in vertical stacks as much as 5 cm high.
Terebellina	Burrows are < 0.5 cm in diameter, vertical to horizontal, and have a fine-grained infill and white coarser grained lining.
Teredolites	Borings are about 0.5 cm in diameter, club shaped, sand filled, and found in clusters within wood fragments or carbonaceous material.
Thalassinoides	Burrows are about 0.5-1 cm in diameter, horizontal to oblique, sand filled, have smooth lined or unlined walls, and are grouped in clusters that indicate branching.

grained to very coarse grained, locally granular or pebbly, and is either trough or planar tabular cross-stratified (fig. 6), swaley cross-stratified (fig. 7*A*), cross-laminated (fig. 8), horizontally laminated, bioturbated (fig. 9*A*), convolute bedded, or massive. Units of mudrock range from less than 1 cm to 10 m in thickness. Mudrock consists of clay and silt and is either horizontally laminated (fig. 10*A*), massive, convolute bedded, bioturbated, rooted (fig. 10*B*), or mottled. Thinly interbedded or interlaminated units of sandstone and mudrock may exhibit flaser, wavy, lenticular, or streaky bedding (fig. 11*A*, *B*, *C*). Units containing mixed sandstone and mudrock are convolute bedded (fig. 12*A*, *B*) or bioturbated (fig. 9*B*).

Minor lithologic constituents of the core include coal, carbonaceous shale, conglomerate, mud-clast conglomerate, and volcanic ash. Beds of coal range from 0.1 to 4.4 m in thickness and constitute about 7 percent of CT-1-91 and 10 percent of SMP-1-91. Carbonaceous shale consists of clay, silt, and abundant plant fragments. Beds of carbonaceous shale are 0.02–1.4 m thick and make up about 4 percent of each core. Beds of mud-clast conglomerate and conglomerate are less than 0.6 m thick and constitute less than 1 percent of the core. Mud-clast conglomerate contains angular to subrounded interformational mudclasts. Conglomerate is found only in core CT-1-91, and contains subangular to well-rounded extraformational pebbles as

Table 3. Summary of facies in cores CT-1-91 and SMP-1-91.

Facies	Description of sedimentary structures	Grain size	Thickness of facies	Comments
Conglomerate	Conglomerate with a sandstone matrix and conglomeratic sandstone. Extraformational clasts. Either trough or planar tabular cross-bedded or with no stratification.	Pebbles are < 5 cm in diameter. Matrix is fine to coarse sand with scattered granules.	0.06-0.45 m	Inoceramid and oyster shell fragments and plant fragments are common. Pebbles are subangular to well rounded.
Mud-clast conglomerate	Intraformational clasts of mudrock, sandstone, and siltstone in a sandstone matrix. No stratification.	Mudrock clasts are < 7.0 cm in diameter. Matrix is either clay or fine to very coarse sand.	0.06-0.6 m	May have bone fragments, coalified plant fragments, logs with *Teredolites* borings, or rare oyster shell fragments.
Trough and planar tabular crossbedded sandstone	Trough and planar tabular crossbeds; sets are generally 0.03-0.4 m thick. Some beds are as much as 1.1 m thick. Cosets are 0.3 to 6.5 m thick. Trough and planar tabular crossbeds are interpreted from laminae that dip from 10° to 45°. Low angle foresets may be overlain by ripple cross-laminated beds.	Lower fine to upper very coarse sand. May have scattered granules, extraformational pebbles < 4 cm in diameter, and mud clasts < 6 cm in diameter.	0.1-20.0 m	May have bivalve shell fragments, *Teredolites* borings, wood fragments, leaf imprints, or burrow traces. Some bivalves were identified as oysters. Drapes of mud with finely ground plant material are common on foresets and bed tops. Drapes are 0.1-9.0 cm thick. Pyrite concretions are rare.
Horizontally laminated sandstone	Horizontal and subhorizontal lamination. Horizontal and subhorizontal laminated sandstone is interpreted from laminae that dip < 5°.	Lower fine to upper medium sand. Some beds are upper coarse sand and may have scattered granules and extraformational pebbles < 1 cm in diameter.	0.04-1.0 m	Laminae of finely ground plant material are common. May have roots, bivalve shell fragments, and burrows. *Teredolites* borings are rare. Some horizontally laminated sandstones may be toesets of trough and planar tabular beds.
Massive sandstone	Sedimentary structures are generally absent although some relict bedding may be preserved.	Silt to upper fine sand. Some units consist of coarse to upper coarse sand. May have scattered mud clasts < 7 cm in diameter.	0.2-4.2 m	May have roots, plant and wood fragments, coal clasts, *Teredolites* borings, *Ophiomorpha* and *Thalassinoides* burrows, and finely disseminated plant debris. Bivalve shell fragments, bone fragments, and pyrite concretions are rare.
Swaley bedded sandstone	Swaley bedded sandstone is interpreted from thick units of subhorizontally laminated and massive sandstone. Cosets are 0.2-3.5 m thick. Lag containing shell fragments and pebbles may mark base of coset.	Upper very fine to lower medium sand. Sand is generally well sorted but may contain scattered extraformational pebbles < 2 cm in diameter and mud clasts < 3 cm in diameter.	0.6-26.0 m	Inoceramid and oyster shell fragments and *Thalassinoides* and *Ophiomorpha* burrows are common. Shark teeth, bone fragments, wood fragments, and plant debris are rare. Pyrite concretions are rare. Pebbles are subrounded to well rounded.
Cross-laminated sandstone	Ripple cross-laminated sandstone; beds are 0.5-7.0 cm thick. Cosets are 0.1-1.8 m thick. Includes ascending, descending, and climbing ripples. Facies may include some thin beds of horizontally laminated sandstone.	Lower very fine to lower medium sand. Some beds have mudclasts < 1 cm in diameter.	0.1-3.0 m	Burrows, wood fragments, leaf imprints, and *Teredolites* borings are common. Some foresets and bed tops are overlain by drapes of mud or finely ground plant material. Drapes are 0.1-5 cm thick. May contain pyrite concretions.

much as 5 cm in diameter (fig. 7*B*, *C*). A thin bed of volcanic ash is located between the depths of 817.2 and 817.4 ft (249.08 and 249.14 m) in CT-1-91.

Fossils in the core include shells and shell fragments of bivalves, high-spired gastropod shells, ammonite casts, shark teeth, leaf imprints, roots, and fragments of bone, plants, and wood. Resin blebs are also common. Identified bivalve fragments are from oyster (figs. 7*C*, *D*; 10*A*; 12*B*), inoceramid (fig. 7*C*, *D*), *Corbula*, and *Brachidontes* shells.

Trace fossil identifications were made using descriptions and photographs of Chamberlain (1978) and Kamola (1984). *Ophiomorpha* (fig. 9*A*) and *Thalassinoides* burrows and *Teredolites* borings (fig. 13) are common trace fossils. Less common trace fossils include

Table 3. Summary of facies in cores CT-1-91 and SMP-1-91—*Continued*

Facies	Description of sedimentary structures	Grain size	Thickness of facies	Comments
Convoluted bedding	Convoluted units of sandstone, mudrock, or combinations of both.	Mostly clay, silt, and very fine to lower medium sand. Rarely coarse to very coarse sand. May have extraformational pebbles < 2 cm in diameter.	0.04-5.1 m	May have wood fragments, leaf imprints, roots, burrows, coalified plant fragments, and finely disseminated plant debris. Siderite and pyrite concretions are common. Inoceramid and oyster shell fragments constitute as much as 40 percent of some units. Slickensides are rare.
Flaser, wavy, lenticular, and streaky bedding	Alternating beds of cross-laminated sandstone and mudrock. Flaser bedding consists of cross-laminated sandstone with mud streaks on bounding surfaces and some foresets. Wavy and lenticular beds are 0.1-5.0 cm thick. Siltstone and sandstone streaks are generally < 0.2 cm thick and 4 cm long.	Clay, silt and very fine to fine sand.	0.02-2.8 m	*Ophiomorpha, Thalassinoides, Planolites, Scoyenia, Cylindrichnus*, and *Palaeophycus* burrows are common. Units may have oyster shell and wood fragments, and *Teredolites* borings. Streaky-bedded units may contain leaf imprints, resin blebs, and *Corbula* shell fragments. Flaser-bedded units contain > 80 percent sandstone. Wavy- and lenticular-bedded units contain 10-80 percent sandstone. Streaky-bedded units contain < 10 percent sandstone. Contacts between flaser-, wavy-, lenticular-, and streaky-bedded units are commonly gradational. May have siderite and pyrite concretions and synaeresis cracks.
Bioturbated sandstone and mudrock	Beds of sandstone, mudrock, or combinations of both are completely churned by a variety of organisms. Some relict bedding may be preserved.	Mudrock consists of clay and silt. Burrows are generally infilled with fine sand. Sandstone is lower very fine to lower coarse sand.	0.03-5.2 m	*Ophiomorpha* and *Thalassinoides* burrows are common. *Planolites and Teichichnus* burrows are less common. May have roots, finely disseminated plant debris, siderite concretions, resin blebs, and coalified plant fragments and bone fragments. Inoceramid, *Corbula*, oyster, and gastropod shell fragments, ammonite casts, and *Teredolites* borings are common in some thicker beds.
Mudrock	Horizontally laminated or lacking stratification. Beds may be slightly convoluted or mottled.	Clay and silt. May include laminae of fine-grained sandstone or coal.	0.06-10.0 m	Commonly rooted or fossiliferous. Rooted mudrocks are 0.1-10.0 m thick and contain coalified plant debris, resin blebs, roots, wood and bone fragments, burrows, randomly oriented slickensides, and siderite concretions. Fossiliferous mudrocks are 0.06- 2.6 m thick and contain inoceramid, *Corbula*, oyster, *Brachidontes*, or gastropod shell fragments, finely disseminated plant debris, ammonite casts, bone fragments, and synaeresis cracks. Shell fragments may compose as much as 60 percent of some units.
Coal and carbonaceous shale	Coal is faintly banded. Carbonaceous shale is horizontally laminated to massive.	Coal is comprised of variable sized plant fragments. Carbonaceous shale is comprised of clay, silt, and abundant plant fragments of variable size.	Coal is 0.1-4.4 m thick. Carbonaceous shale is 0.02-1.4 m thick.	Coal may have 0.6-15.0 cm thick partings of carbonaceous shale or very fine grained sandstone. Carbonaceous shale may have 1.5 cm thick partings of coal, siltstone, or very fine grained sandstone. Carbonaceous shale may have resin blebs, randomly oriented slickensides, and rare septarian concretions.

Cylindrichnus, *Palaeophycus*, *Planolites*, *Scoyenia*, *Skolithos*, *Teichichnus*, and *Terebellina*.

DEPOSITIONAL INTERPRETATIONS

Facies identified within each core are grouped into four facies assemblages (depositional facies) that are interpreted to have accumulated in either (1) shoreface, (2) tidal, (3) fluvial channel and tidally influenced channel, or (4) floodplain and mire environments. The coeval relationships of these environments are shown in figure 14. Depositional interpretations are identified by color patterns on plate 1.

FACIES ASSEMBLAGE I—SHOREFACE

Description.—Facies assemblage I is dominated by swaley-bedded sandstone (fig. 7*A*) and may include minor thin beds of conglomerate (fig. 7*B*) and trough-crossbedded, cross-laminated or bioturbated sandstone (fig. 9*A*). Intervals

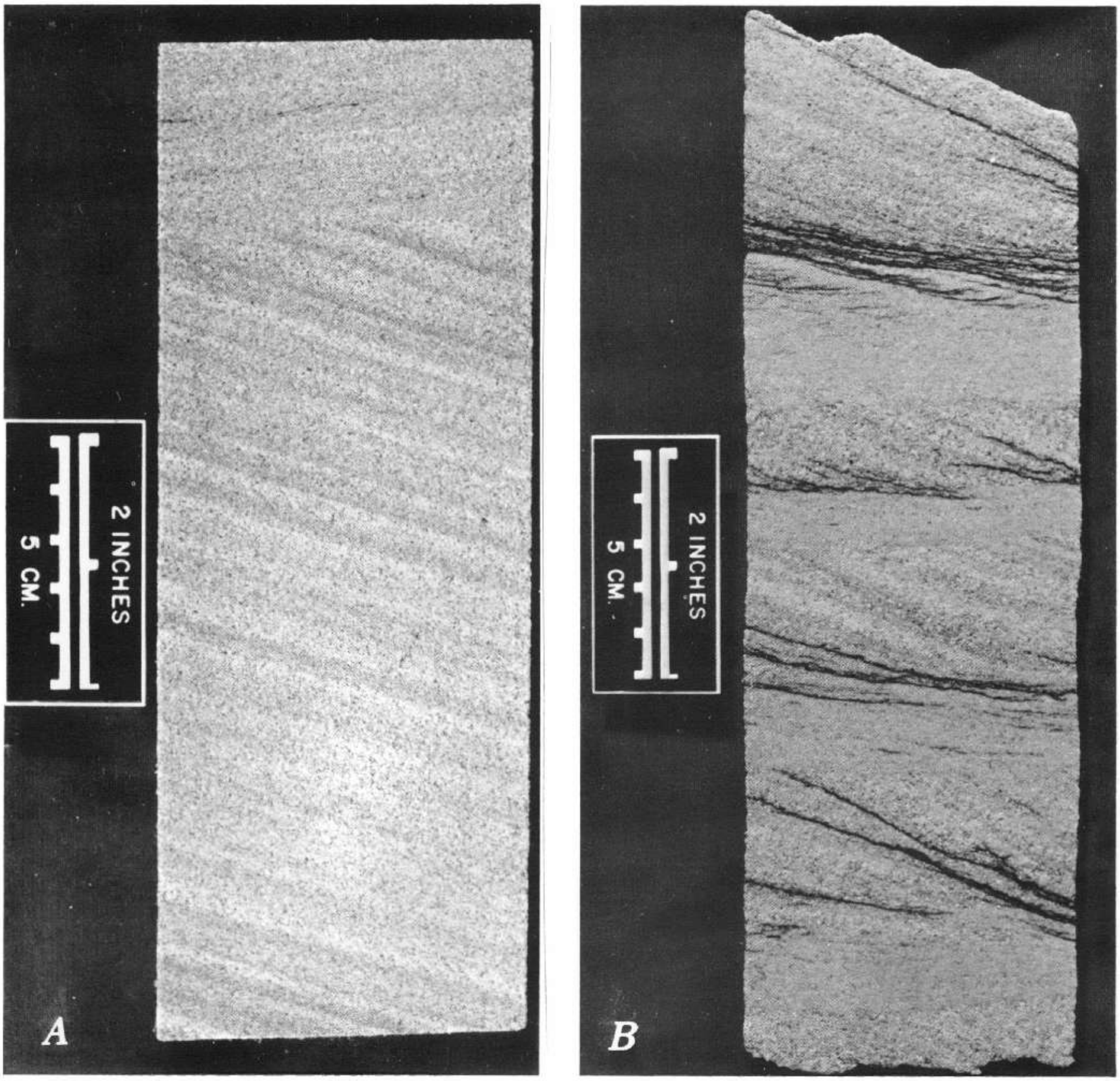


Figure 6. Trough- and planar tabular crossbedded sandstone facies. *A*, Foresets in trough-crossbedded fine-grained sandstone. This facies is common in fluvial deposits (facies assemblage III). *B*, Four planar tabular beds. Each bed has fine-grained toesets with countercurrent ripples that grade upward to medium-grained foresets with double mud drapes (gray). These facies are interpreted as small dunes in a subtidal environment (facies assemblage II). *A* is from 444.3 ft (135.4 m) in SMP-1-91; *B* is from 157.5 ft (48.0 m) in SMP-1-91.

containing these rocks are 4.6–27.0 m thick. Swaley-bedded sandstones are fine to medium grained and generally well sorted, although some beds contain scattered extraformational pebbles (fig. 7*C*) and flat mudclasts. Inoceramid and oyster shell fragments are common (fig. 7*C*, *D*). Bone fragments, shark teeth, and *Ophiomorpha* burrow traces (fig. 9*A*) are less common. Swaley cross-stratified bedsets commonly have basal lags deposited over erosion surfaces of low relief. The lag deposits are composed of extraformational pebbles, mudclasts, or shell debris.

Interpretation.—Rocks of facies assemblage I are interpreted as shoreface deposits (fig. 14) based on the dominance of swaley bedding and marine fossils. Swaley crossbedding is interpreted to have formed above fair-weather wave base by storm-generated waves (Leckie and Walker, 1982). The near absence of trough crossbedding

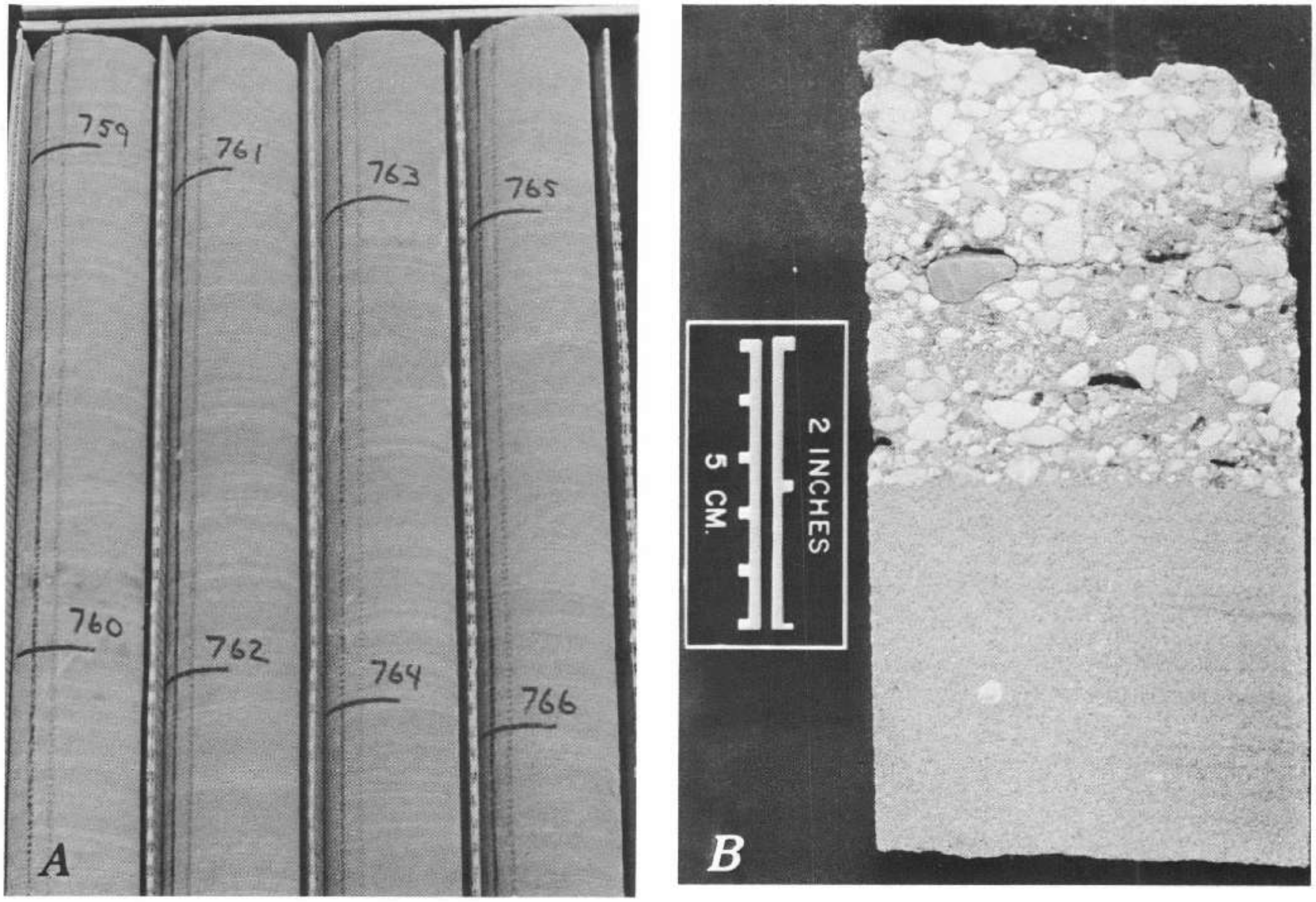
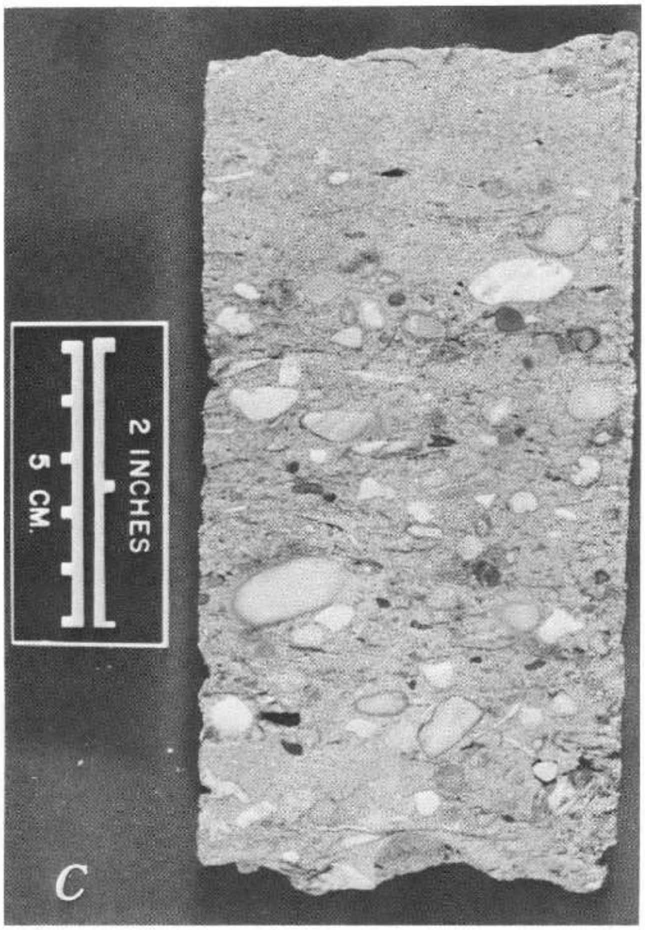


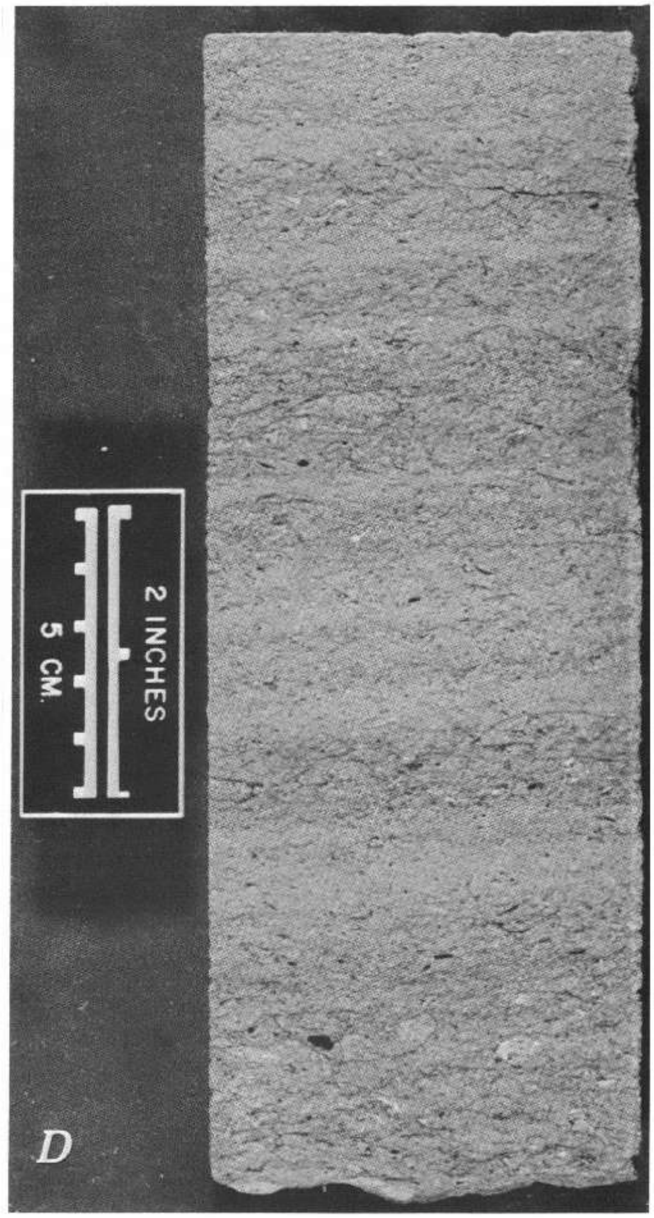
Figure 7 (above and facing page). Common facies in shoreface deposits (facies assemblage I). *A*, Swaley bedding in very fine grained to fine-grained sandstone. Swaley cross-stratification is interpreted from thick units of subhorizontal bedding associated with marine fossils. Shoreface deposits commonly contain beds of conglomerate (*B*) and conglomeratic sandstone (*C*) that contain subangular to subrounded extraformational pebbles. Oyster and inoceramid shell fragments are common in shoreface deposits (*C* and *D*). *A* is from 758.7 to 766.4 ft (231.2 to 233.6 m) in CT-1-91; *B* is from 893.2 ft (272.3 m) in CT-1-91; *C* is from 805.0 ft (245.4 m) in CT-1-91; *D* is from 912.0 ft (277.9 m) in CT-1-91.

and mud within facies assemblage I suggests that the deposits were probably within the upper shoreface. Similar interpretations have been made from swaley-bedded sandstones in the John Henry Member in Left Hand Collet Canyon (Shanley and McCabe, 1991; Shanley and others, 1992). Extraformational pebbles, mudclasts, and shell debris at the base of swaley cross-stratified bedsets are interpreted as transgressive lags deposited over ravinement surfaces. Similar interpretations were made for lags deposited on the flooding surfaces of shoreface parasequences in Upper Valley (location, fig. 1) (Hettinger and others, 1994).

FACIES ASSEMBLAGE II—TIDAL

Description.—Facies assemblage II comprises heterolithic strata (fig. 11). Heterolithic strata consist of interbedded sandstone and mudrock stacked in intervals that are 0.3–40.5 m thick. Facies include mudclast conglomerate; trough- and planar tabular crossbedded (fig. 6*B*), cross-laminated, horizontally laminated, and massive sandstone; bioturbated sandstone and mudrock (fig. 9*B*); mudrock (fig. 10*A*); convoluted bedding (fig. 12*B*); and flaser, wavy, lenticular, and streaky bedding (figs. 9*B*; 11*A*, *B*, *C*). Bedding may be inclined as much as 20° from horizontal. Sandstone is generally very fine grained to fine grained, less commonly medium grained, and rarely coarse grained, granular, or pebbly. Mud drapes and drape couplets (double mud drapes) commonly overlie bounding surfaces and foresets of trough- and planar tabular crossbedded and cross-laminated sandstone (fig. 6*B*). Fossils typically include bivalve shell fragments of oyster (figs. 10*A*; 12*B*), inoceramid, *Corbula*, and *Brachidontes*; gastropod shells; *Ophiomorpha* (fig. 9*A*) and *Thalassinoides* burrow traces; *Teredolites* borings (fig. 13); wood and abundant





amounts of finely disseminated plant debris (fig. 13). Less common are bone fragments, resin blebs, ammonite casts, and burrow traces of *Cylindrichnus*, *Palaeophycus*, *Planolites*, *Scoyenia*, *Skolithos*, *Teichichnus*, and *Terebellina*.

Heterolithic intervals are either sandstone dominated or sandstone-mudrock dominated. Sandstone-dominated intervals are 0.7–8.7 m thick and generally consist of trough- and planar crossbedded or cross-laminated sandstone with thin mud drapes and double mud drapes. Some sandstone-dominated intervals are completely bioturbated. Sandstone-mudrock-dominated intervals are 0.2–9.2 m thick and contain about 30–95 percent mudrock (fig. 11). Beds of sandstone are about 1 cm to 1 m thick, although some bioturbated intervals are as much as 4 m thick. Interbeds of mudrock are generally 1–4 cm thick but may be as much as 2.3 m thick. Sandstone-mudrock-dominated intervals are typically flaser, wavy, lenticular, or streaky bedded (fig. 11*A*, *B*, *C*), or bioturbated (fig. 9*B*). Streaky, lenticular, wavy, and flaser bedding is commonly formed in upward-coarsening intervals that may contain siderite concretions or synaeresis cracks (fig. 11*B*).

Interpretation.—Heterolithic strata contain many features that are suggestive of deposition in a subaqueous environment under the influence of tidal currents. Environments within the tidal zone (fig. 14) include lagoons, tidal creeks, and estuaries. Brackish-water conditions are indicated by oysters, *Corbula*, and *Brachidontes*. Trace fossils of *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Skolithos*, and *Thalassinoides* are abundant in Cretaceous brackish-water, marginal marine deposits described by Kamola (1984). The abundance of *Teredolites*, inoceramids, ammonites, wood fragments, bone, and finely disseminated and comminuted plant material indicates both open marine and terrestrial sources. Flaser, wavy, lenticular, and streaky bedding all are products of mixed energy environments such as the alternating slack and turbulent water episodes associated with both subtidal and intertidal processes (Reineck and Singh, 1980). Mud drapes are commonly deposited over dunes during

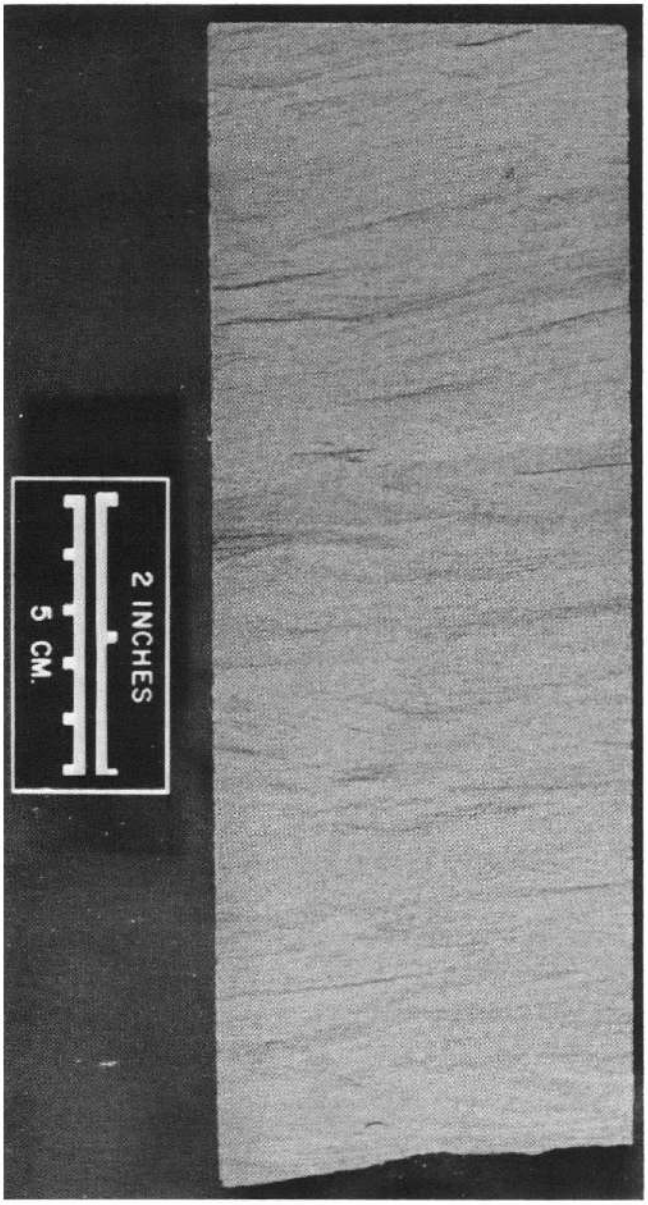


Figure 8. Cross-laminated sandstone facies. Figure shows ripple cross-lamination in very fine grained sandstone. Absence of mud drapes in this cross-laminated sandstone suggests that these deposits are fluvial rather than tidal in origin. Sample is from 356.0 ft (108.5 m) in SMP-1-91.

slack water conditions of high tide. Double mud drapes result from deposition of mud during slack water of both low and high tides; they are a characteristic feature of subtidal deposits (Visser, 1980). Alternating beds of sandstone and mudrock (fig. 11*D*) are indicative of rhythmic sedimentation and may represent tidal bundles similar to those described by Boersma and Terwindt (1981a, b). Inclined bedding is a prominent feature of complex compound cross-stratified sandstones. Shanley and others (1992) interpreted complex compound crossbeds in the Straight Cliffs Formation as sandwaves that contain large-scale reactivation and erosion surfaces within tidally influenced rivers. Similar bedding has also been attributed to the migration of large tidal bedforms such as those described in the Bay of Fundy by Dalrymple (1984). Inclined beds of sandstone and mudrock are interpreted as inclined heterolithic strata. Inclined heterolithic strata with rhythmic and persistent mud drapes have been described in modern lateral accretion deposits of point-bars in tidally influenced rivers (Smith, 1987; 1988), and have been used as a criterion to distinguish ancient tidally influenced point-bars (Thomas and others, 1987).

FACIES ASSEMBLAGE III—FLUVIAL CHANNELS AND TIDALLY INFLUENCED FLUVIAL CHANNELS

Description.—Facies assemblage III is dominated by single and multistoried sandstones that are 3–32 m thick. Sandstone is very fine grained to very coarse grained and locally granular or pebbly. Stories are defined by basal erosion surfaces that may be overlain by mudclast conglomerate lags. Stories are 0.3–9.7 m thick and average about 3 m thick. Stories typically either fine upwards or are of uniform grain size, and they consist of trough- and planar crossbedded sandstone (fig. 6*A*). The upper parts of some stories contain cross-laminated (fig. 8), horizontally laminated, convolute bedded, or massive sandstone, and rare thin beds of mudrock. Fossils include rare scattered wood fragments, isolated burrow traces, and roots. Some beds have sparse *Teredolites* borings, bivalve shell fragments, or mud drapes.

Interpretation.—Strata of facies assemblage III are interpreted as fluvial channel deposits based on erosion surfaces, mudclast conglomerate lags, an upward-fining grain size, and an upward transition from trough and planar tabular crossbedding to horizontal- and cross-lamination, and mudrock. Similar features have been described in numerous fluvial models that are summarized by Collinson (1986). Fluvial channels (facies assemblage III) are distinguished from tidal deposits (facies assemblage II) by a general lack of mud, bivalves, and trace fossils. The fluvial channels are interpreted to have been deposited in a coastal plain setting and landward of the tidal zone (fig. 14), after models of McCabe and Shanley (1992). Sandstones containing sparse *Teredolites* borings, mud drapes, or bivalve shell fragments are interpreted as tidally influenced fluvial deposits that accreted in the transition between the tidal zone and fluvial channels. Similar interpretations were made from channel sandstones with sparse tidal features in Left Hand Collet and Tibbet Canyons (Shanley and others, 1992). Coarser grained fluvial rocks that are correlative with the Calico sandstone and Drip Tank Member are interpreted as braided river deposits, after regional studies by Peterson (1969a, b) and Shanley and McCabe (1991). The braided river deposits are

Figure 9. Bioturbated sandstone and mudrock facies. *A*, Fine-grained bioturbated sandstone containing mud-lined and pelleted burrows. The burrows are interpreted as *Ophiomorpha* and are common in both shoreface and tidally influenced deposits. *B*, Disturbed wavy and lenticular laminae in burrowed mudrock overlain by intensely bioturbated sandstone and mudrock. These facies are common in tidally influenced deposits. *A* is from 790.5 ft (240.9 m) in CT-1-91; *B* is from 329.5 ft (100.3 m) in SMP-1-91.

interpreted to have accumulated landward of the coastal plain.

FACIES ASSEMBLAGE IV—FLOODPLAINS AND MIRES

Description.—Facies assemblage IV is dominated by mudrock, coal, carbonaceous shale, and minor sandstone. Intervals containing some or all of these lithologies range from 0.2 to 15.1 m in thickness. Fossils include roots, burrows, leaf imprints, and fragments of wood, coalified plants, and bone. Resin blebs are also common. Sandstone is 0.1–1.5 m thick, very fine grained to fine grained, typically crossbedded, but less commonly trough or planar tabular crossbedded, horizontally laminated, convoluted, or bioturbated. Mudrock is 0.2–10.0 m thick and commonly has a mottled texture, convoluted bedding, randomly oriented slickensides, roots (fig. 10*B*), and rare septarian concretions. Intervals of mixed sandstone and mudrock are as much as 5.1 m thick and display convoluted bedding (fig. 12*A*). Coal is 0.1–4.4 m thick and carbonaceous shale is 0.2–1.4 m thick. Coal and carbonaceous shale are interbedded in intervals as much as 9.7 m thick. Preliminary analyses of coal facies by Pierce and others (1992) indicate that thin coal beds and the

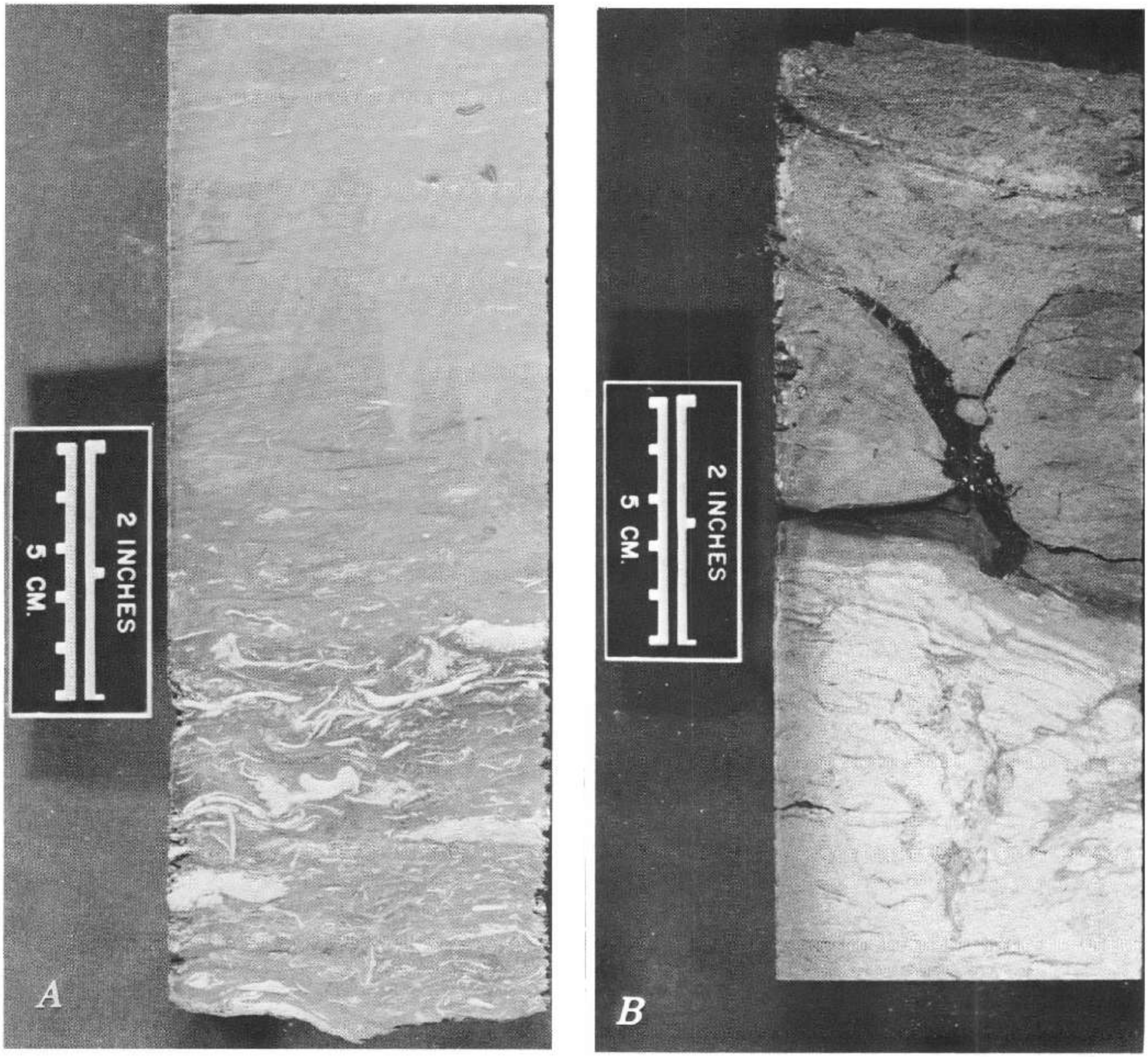


Figure 10. Mudrock facies. *A*, Horizontally laminated mudrock containing abundant oyster shell fragments. These rocks commonly contain *Corbula* bivalves (not shown) and are interpreted as tidally influenced brackish-water deposits. *B*, Rooting in mudrock. Root in upper half of photograph is coalified. Thick units of rooted mudrock containing coalified plant debris are common in floodplain deposits (facies assemblage IV). *A* is from 629.5 ft (191.9 m) in SMP-1-91; *B* is from 376.5 ft (114.7 m) in SMP-1-91.

lower half of thick coal beds have relatively thin subunits with high ash contents. By contrast, the upper halves of thick coal beds have relatively thick and clean subunits. Furthermore, thin coals have sharp upper contacts, whereas thick coals are transitional into the overlying strata.

Interpretation.—Strata of facies assemblage IV are interpreted as vegetated floodplain deposits. These rocks are interpreted to have been deposited on the coastal plain, adjacent to the tidal zone and lateral to fluvial channels (fig. 14), after models of McCabe and Shanley (1992). Sandstone and mudrock are interpreted as overbank splay and floodbasin deposits derived from fluvial channels. The deformation in thick units of convolute bedded sandstone and mudrock is interpreted as liquefaction. Liquefaction in lagoonal sediments of the Cardium Formation in Alberta has been attributed to abrupt expulsion of gas or water (Plint and Walker, 1987). Deformation by liquefaction may also have been produced by large animals that walked along shorelines of lakes or estuaries. Convoluted bedding produced by animal tracks has been recorded in the sediment of modern ponds located along the Nueces Bay, Texas (McGowen, 1971). Randomly oriented slickensides are indicative of expandable clays and are common in paleosols (Mack and others, 1993). Beds of coal and carbonaceous shale, wood and coalified plant fragments, leaf imprints, resin blebs, and roots indicate that the floodplain was vegetated. The relatively thick and clean subunits of the thicker coals suggest that thick peat deposits were isolated from clastic sources for long periods of time and may have accumulated in domed mires (Pierce and others, 1992). This supports interpretations by McCabe and Shanley (1992), who have suggested that thick coals of the Straight Cliffs Formation developed from raised mires.

SEQUENCE STRATIGRAPHIC INTERPRETATION OF THE CORE

The sequence stratigraphic interpretation of the core is based on vertical relationships of depositional facies. The recognition of such depositional relationships is basic to the identification of sequences and associated systems tracts defined in Van Wagoner and others (1990). For example, deepening-upward successions are interpreted to reflect faster rates of increase in accommodation space. Conversely, shallowing-upward successions are interpreted to reflect slower rates of increase in accommodation space. Unconformities cut during falls in base-level are recognized from significant basinward shifts of depositional facies. Depositional successions in the core closely match those described from regional outcrop studies of coeval rocks by Shanley and McCabe (1991), Shanley and others (1992), and Hettinger and others (1994), and the sequence stratigraphic interpretation of the core is therefore supported by these regional studies. The sequence stratigraphic interpretation of the core is shown in figure 15, and the core is correlated to the regional sequence stratigraphic studies in Left Hand Collet Canyon and Tibbet Canyon on plate 2.

SEQUENCE BOUNDARIES

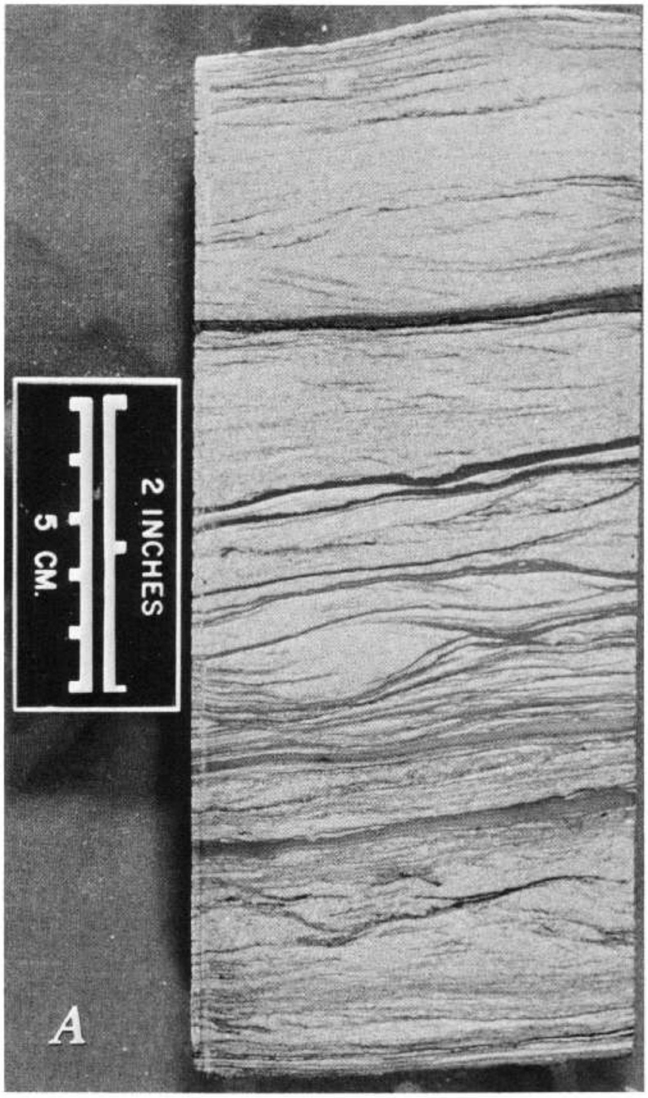
Three sequence boundary unconformities are recognized in the core. Each unconformity is interpreted at a significant basinward facies dislocation and correlates to a sequence boundary unconformity identified in Left Hand Collet Canyon and Tibbet Canyon. Two extreme basinward facies shifts are recognized in the core where coarse-grained, granular, and locally pebbly braided river deposits are juxtaposed over finer grained coastal plain strata. The lower facies shift is located at 1,041.1 ft (317.3 m) in CT-1-91 and 944.1 ft (287.8 m) in SMP-1-91 (fig. 15; pl. 1) and correlates to the Calico sequence boundary in Left Hand Collet Canyon and Tibbet Canyon (pl. 2). The upper facies shift is located at 206.0 ft (62.8 m) in CT-1-91 and 143.1 ft (43.6 m) in SMP-1-91 (fig. 15; pl. 1) and correlates to the Drip Tank sequence boundary in Left Hand Collet Canyon and Tibbet Canyon (pl. 2). The braided river deposits overlying each sequence boundary correlate to the Calico sandstone and Drip Tank Member, respectively. Evidence of prolonged subaerial exposure below each unconformity is indicated in the core by the development of thick paleosols interpreted from mudrock containing roots and randomly oriented slickensides (see intervals from 206.0 to 219.9 ft (62.8 to 67.0 m) and 1,041.1 to 1,046.5 ft (317.3 to 318.9 m) in CT-1-91, and 944.1 to 956.2 ft (287.8 to 291.5 m) in SMP-1-91 (pl. 1)).

The third sequence boundary is interpreted at a less extreme basinward facies dislocation that juxtaposes coarser grained tidally influenced deposits (facies assemblages II and III) over finer grained shoreface and mire deposits (facies assemblages I and IV, respectively). This facies dislocation is located at 890.0 ft (271.2 m) in CT-1-91 and 758.9 ft (231.3 m) in SMP-1-91 (fig. 15; pl. 1) and correlates to the A- sequence boundary identified in Left Hand Collet Canyon and Tibbet Canyon (pl. 2).

TRANSGRESSIVE SYSTEMS TRACTS

Two transgressive systems tracts are identified within the core. Each overlies a sequence boundary unconformity and is characterized by an overall deepening-upward (retrogradational) succession of strata. The percent of depositional facies and total coal in each transgressive systems tract is shown in table 4.

The lower transgressive systems tract overlies the Calico sequence boundary and is 19 m thick at CT-1-91 and 25 m thick in SMP-1-91. The systems tract comprises fine-grained to very coarse grained, pebbly sandstone (fluvial channel deposits) and rooted mudrock (floodplain deposits) that pass upward to very fine grained and medium-grained heterolithic strata (tidally influenced deposits) with thin interbeds of carbonaceous shale and coal (mires). Fluvial channel and mudrock deposits in the lower part of the systems tract correlate to braided river strata of the Calico sandstone. Heterolithic strata in the upper part of the systems tract are about 12 m thick at SMP-1-91 and thin to 2.5 m at CT-1-91. Interbeds of coal in the upper part of the systems tract are 0.1–0.2 m thick, and rarely as much as 0.9 m thick. Thin interbeds of terrestrial strata in the upper part of the systems tract may reflect infilling of estuaries or lagoons during minor progradational episodes within the overall transgression. The lower transgressive systems tract in the core correlates with a similar deepening-upward progression of valley-fill deposits in the Calico transgressive systems tract at Left Hand Collet Canyon and Tibbet Canyon (Shanley and others, 1992) (pl. 2). In Left Hand Collet Canyon, the Calico transgressive systems tract is capped by a maximum flooding surface that converges landward with a



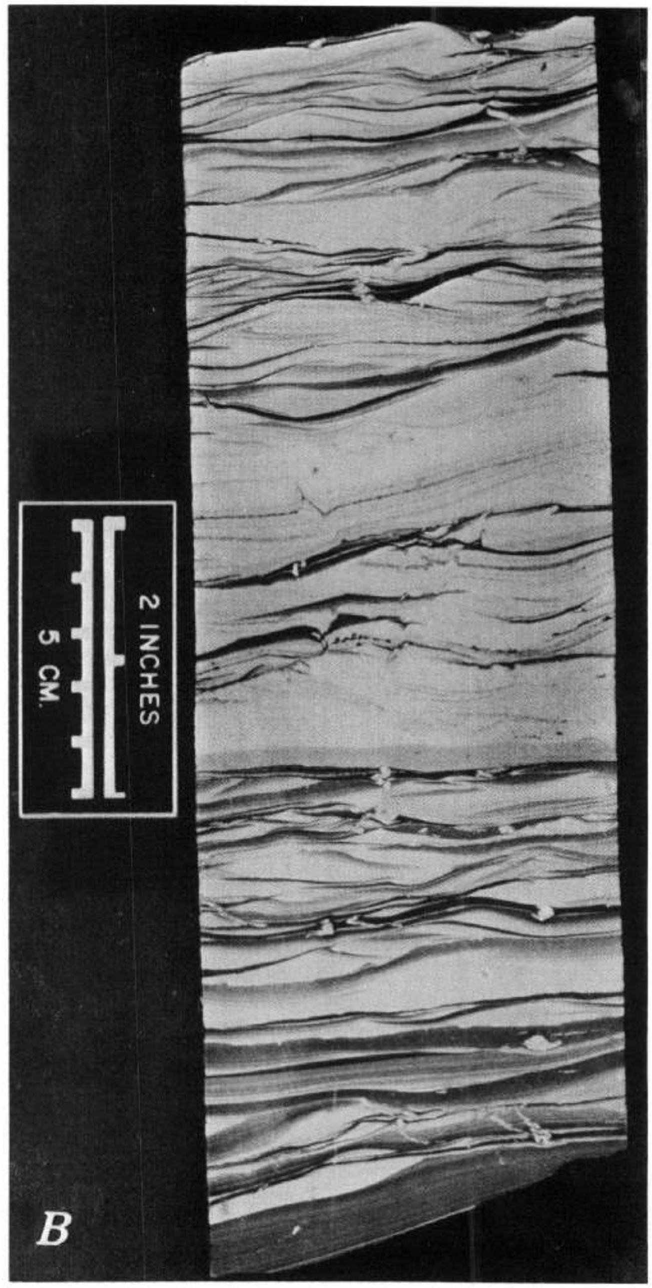
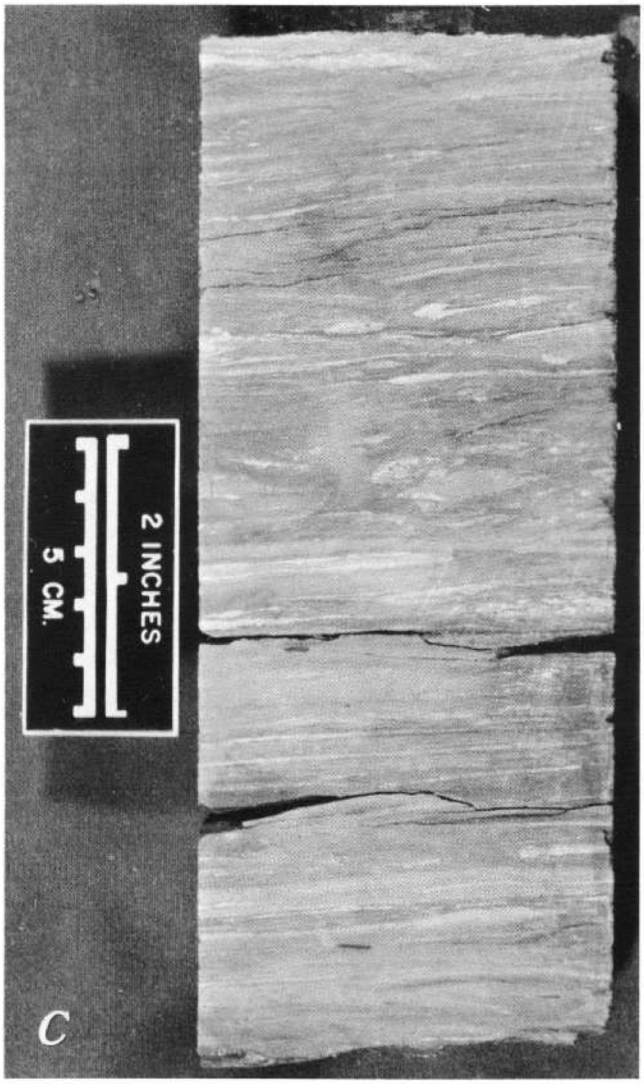
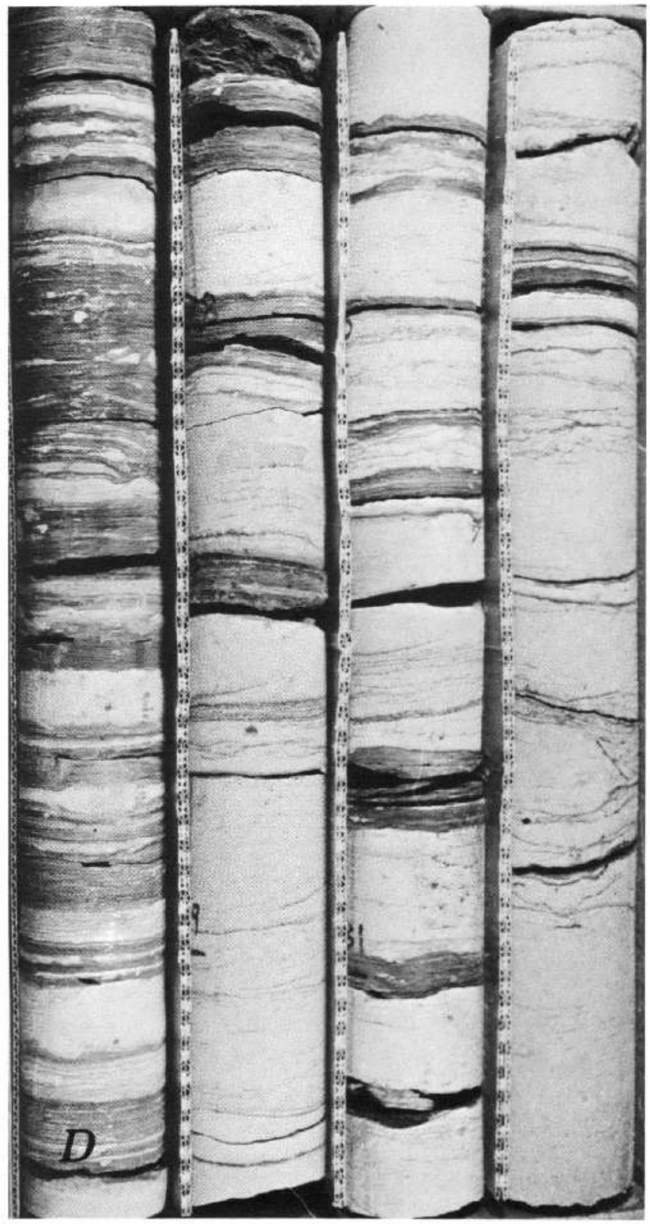


Figure 11 (above and facing page). Heterolithic strata in tidally influenced deposits (facies assemblage II). Heterolithic strata comprise thinly interbedded sandstone and mudrock. *A* and *B*, Flaser, wavy, and lenticular bedding. Small synaeresis cracks in *B* indicate periods of salinity fluctuation. *C*, Streaky laminae of very fine grained sandstone in mudrock. Rocks in *A*, *B*, and *C* are interpreted as tidally influenced deposits (facies assemblage II). *D*, Rhythmically interbedded sandstone and mudrock. Sandstone is trough crossbedded and cross-laminated and commonly contains wood with *Teredolites* borings (not shown). Mudrock contains abundant plant debris, lenticular sandstone laminae, and burrows. Rocks in *D* are interpreted as tidal bundles that accumulated in the subtidal zone. *A* is from 433.4 ft (132.1 m) in CT-1-91; *B* is from 899.0 ft (274 m) in SMP-1-91; *C* is from 833.0 ft (253.9 m) in SMP-1-91; *D* is from 325.5 to 333.4 ft (99.2 to 101.6 m) in CT-1-91.

transgressive ravinement lag composed of extraformational pebbles (Shanley and McCabe, 1991; Shanley and others, 1992; this report, pl. 2). The transgressive lag has been mapped as the base of the John Henry Member by Zeller (1978), and Zeller and Vaninetti (1990). At CT-1-91, a conglomerate underlying the A- sandstone is interpreted to be correlative with the transgressive lag and maximum flooding surface. The conglomerate is between the depths of 977.7 and 979.6 ft (298.0 and 298.6 m) in CT-1-91, and its top marks the top of the systems tract in that core (fig. 15; pl. 1). At SMP-1-91, the conglomerate is absent and the maximum flooding surface is inferred at a depth of 861.8 ft (262.7 m), at the base of shoreface deposits that correlate to the A- sandstone (fig. 15; pl. 1).





The upper transgressive systems tract overlies the A-sequence boundary. At CT-1-91 the systems tract is 25 m thick and dominated by tidally influenced heterolithic strata. The upper part of the systems tract is sandstone-mudrock dominated and contains a few interbeds of coal less than 0.8 m thick. At SMP-1-91, coeval rocks are 9 m thick and consist entirely of very fine grained to fine-grained tidally influenced fluvial deposits. Similar stratigraphic relationships were described from correlative estuarine deposits that overlie the A- sequence boundary by Shanley and others (1992). In Left Hand Collet Canyon, the estuarine deposits are capped by a transgressive pebble lag located at the base of a shoreface stack (pl. 2). The lag is interpreted as the maximum flooding surface and top of the systems tract (Shanley and others, 1992). No lag is present in either core, however, and the maximum flooding surface is inferred at the base of correlative shoreface strata, located at 810.6 ft (247.1 m) in CT-1-91, and laterally equivalent floodplain (coastal plain) strata located at 730.8 ft (222.7 m) in SMP-1-91 (fig. 15; pl. 1).

HIGHSTAND SYSTEMS TRACTS

Three highstand systems tracts are recognized in the core. The upper two overlie transgressive systems tracts and all three are capped by sequence boundary unconformities. The highstand systems tracts in the core correlate to the Tibbet, Calico, and A- highstand systems tracts and are truncated by the Calico, A-, and Drip Tank sequence boundaries, respectively. The Calico and A- highstand systems tracts in the core contain all of the facies listed in table 3. The percentages of depositional facies, and total coal in each highstand deposit are shown in table 4. Sandstones are generally very fine grained to medium grained and rarely coarse grained or pebbly. Between 8 and 20 m of total coal is contained in each highstand systems

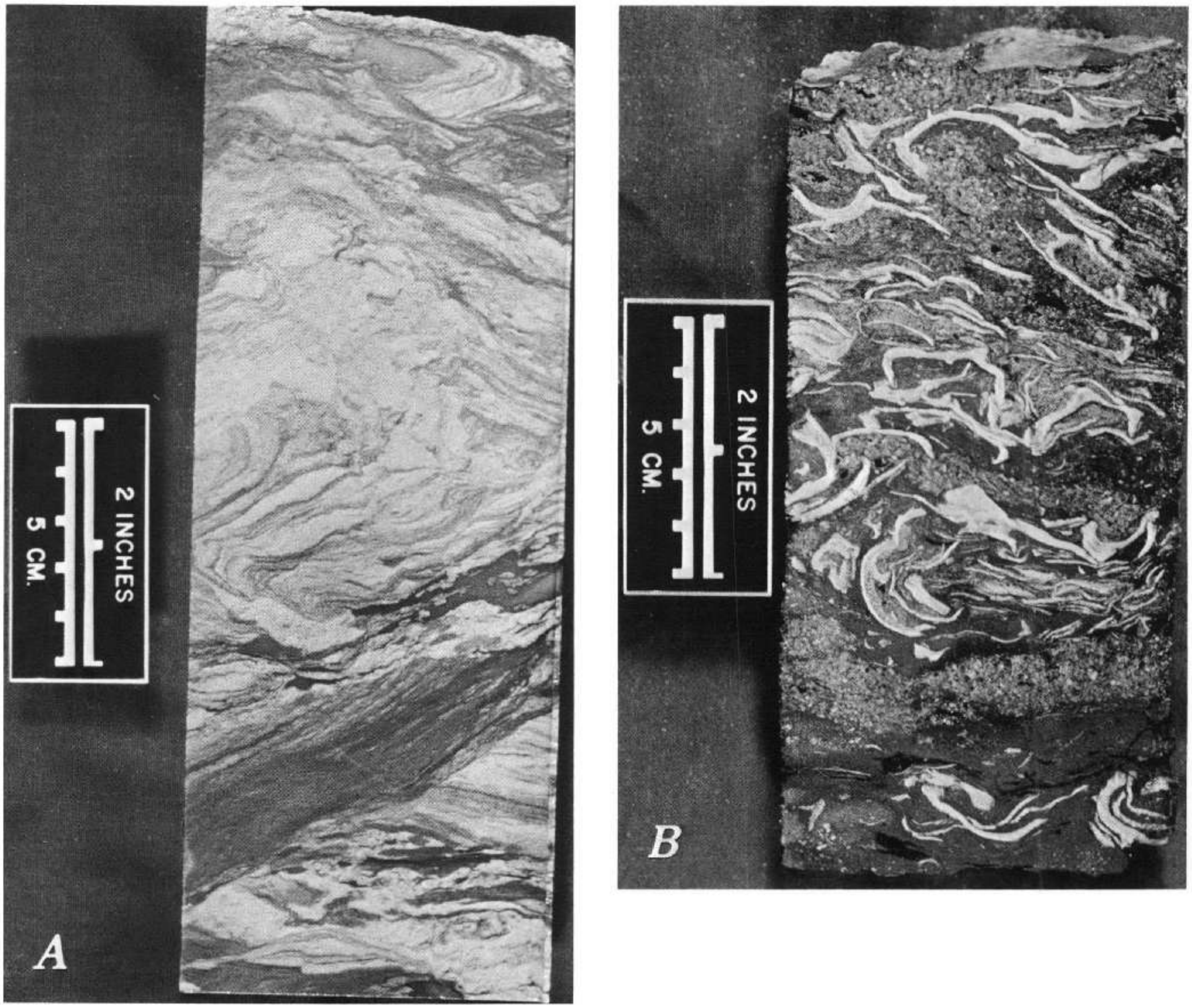


Figure 12. Convoluted bedding. *A*, Mixed sandstone and mudrock. Absence of burrows suggests that these deposits were mixed by liquefaction rather than bioturbation. Thick intervals mixed by liquefaction are associated with floodplain deposits (facies assemblage IV). ***B***, Slightly convoluted sandstone and mudrock with abundant transported oyster shell fragments. These rocks are associated with tidally influenced deposits (facies assemblage II). *A* is from 261.5 ft (79.7 m) in SMP-1-91; *B* is from 477.0 ft (145.4 m) in CT-1-91.

tract, and the coal beds are as much as 4.4 m thick. The upper part of the Tibbet highstand systems tract consists of coastal plain strata; only several meters of these rocks were retrieved in the core, and the highstand interpretation is based solely on regional studies of Shanley and McCabe (1991). The Calico highstand systems tract is 27–32 m thick in the core and is dominated by shoreface, tidal, and coal-bearing coastal plain deposits at SMP-1-91, and by shoreface deposits at CT-1-91 (fig. 15). The A- highstand systems tract is 180–184 m thick in the core and is dominated by coastal plain and tidally influenced strata at SMP-1-91, and tidally influenced strata with minor shoreface and coal-bearing coastal plain deposits at CT-1-91 (fig. 15).

Deposition patterns within the highstand systems tracts of the Calico and A- sequences are interpreted to be progradational based on overall shallowing-upwards successions and basinward shifts of strata. For example, within the Calico highstand systems tract, shallowing-upwards succession of shoreface, tidal, and coastal plain strata at SMP-1-91 shows a basinward transition to shoreface strata in CT-1-91 (fig. 15). Depositional patterns in the A- highstand systems tract have similar characteristics as the systems tract demonstrates an overall basinward shift from predominantly coastal plain strata at SMP-1-91 to predominantly tidally influenced and shoreface strata at CT-1-91 (fig. 15). Furthermore, the A- highstand systems tract at CT-1-91 consists of three superposed intervals that have

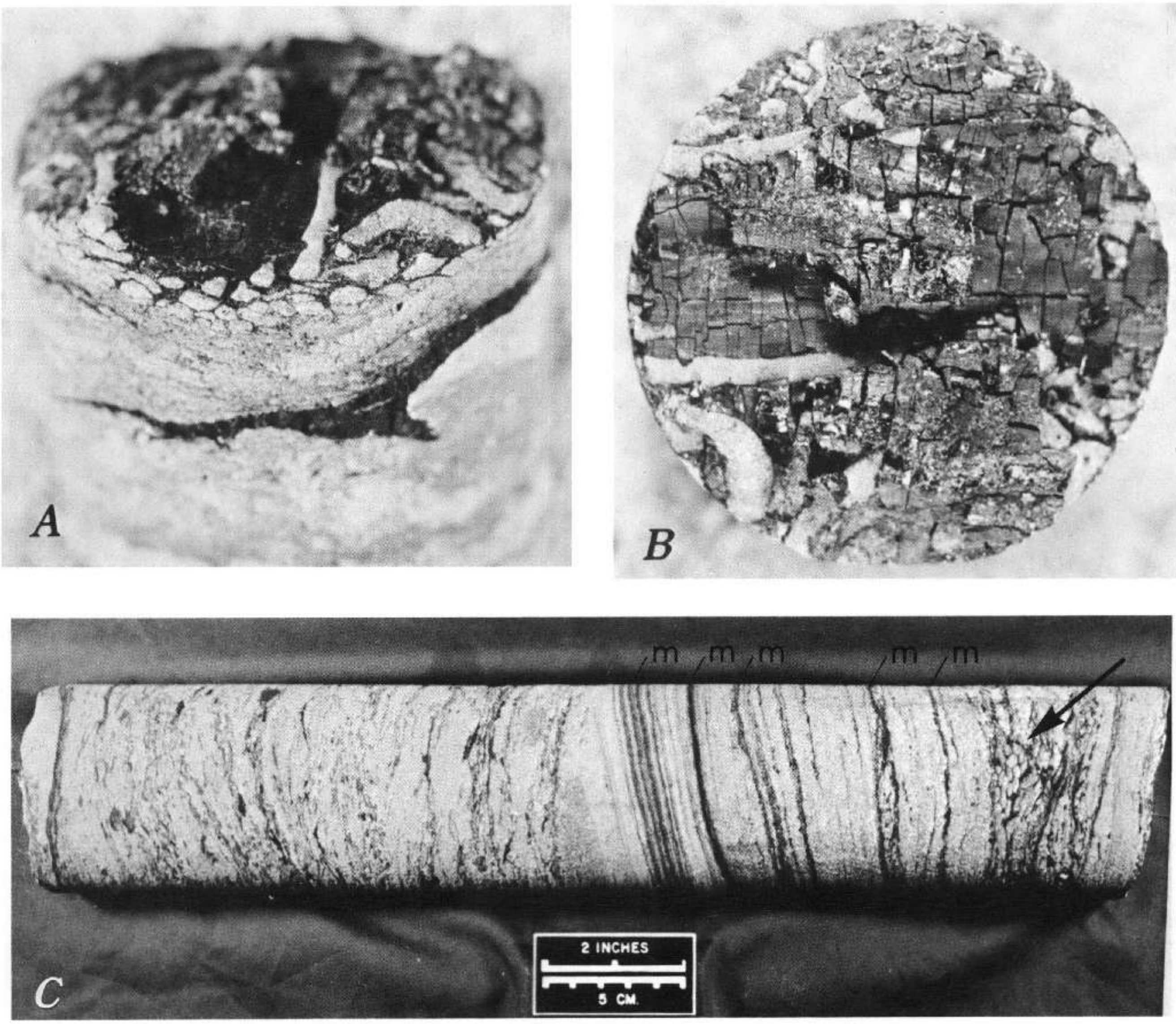


Figure 13. *Teredolites* borings. *A* and *B*, Club-shaped sand-filled *Teredolites* borings in coalified wood fragment. Borings about 0.3–0.5 cm across. *C*, *Teredolites* borings (arrow) in fine- to medium-grained, cross-laminated sandstone with abundant plant fragments (irregular black lines and specks) and mud drapes (m). *Teredolites* borings, mud drapes, and abundant plant debris are common components of tidally influenced deposits (facies assemblage II). *A* and *B* from 205.9 ft (62.8 m) in CT-1-91; *C* from 706.0 ft (215.2 m) in CT-1-91.

overall shallowing-upward successions. The intervals are 55–70 m thick and located between the depths of 810.6 and 602.7 ft (247.1 and 183.7 m), 602.7 and 438.3 ft (183.7 and 133.6 m), and 438.3 and 206.0 ft (133.6 and 62.8 m), respectively (pl. 1). The lowest interval passes upward through shoreface, tidal, and coastal plain strata. The upper two intervals pass upward from predominantly tidally influenced strata to predominantly coastal plain strata. Each shallowing-upward interval overlies a flooding surface and may represent the landward equivalent of a progradational shoreface parasequence set located in Left Hand Collet Canyon (pl. 2).

The core also contains numerous thin shallowing-upward units that may be equivalent to parasequences as defined by Van Wagoner and others (1990). The thick shoreface intervals in the Calico and A- highstand systems tracts are interpreted to consist of stacked parasequences. The swaley-bedded sandstones are divided by conglomerate and shell debris lags that are spaced at 1 to 4 m intervals. The lags are interpreted as transgressive deposits, and strata within each interval may comprise a parasequence. Similar transgressive lags were traced along flooding surfaces that cap shoreface parasequences in Upper Valley (Hettinger and others, 1994). Although the parasequences in the core are thinner than those in Upper Valley, the differences may be accounted for by erosional thinning at the more proximal locality of the core. Examples of shallowing-upward

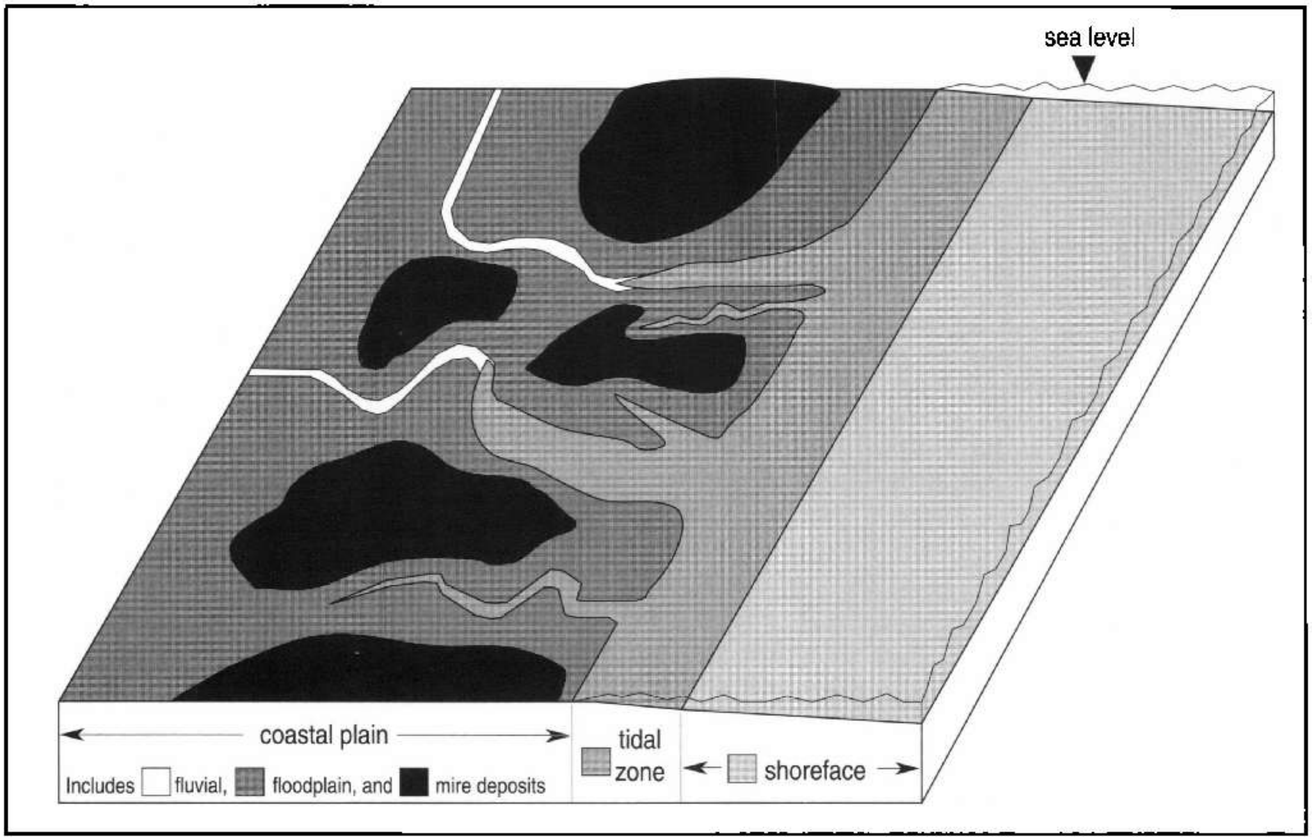


Figure 14. Coeval relationships of shoreface, tidal, and coastal plain environments described in facies assemblages I–IV.

successions at the parasequence scale are also found in nonmarine rocks. For example, the interval between 626.5 and 556.1 ft (190.1 and 169.5 m) in CT-1-91 contains several superposed units that grade upward from tidally influenced to coal-bearing strata (pl. 1). The units are 2.5–6.3 m thick each, but are as much as 11–19 m thick when decompacted using ratios of 1:1 for sandstone, 2.1:1 for mudrock and 11.1:1 for coal, after Ryer and Langer (1980). The decompacted thicknesses approximate that of shoreface parasequences in Left Hand Collet Canyon described by McCabe and Shanley (1992). Flooding surfaces that cap each shallowing-upward succession may be correlative with marine flooding surfaces that cap shoreface parasequences. Some of the shallowing-upward succession in the core may therefore be the nonmarine equivalent of a parasequence.

Forward-stepping stacking patterns within the Calico and A- highstand systems tracts are most apparent when the core is compared with coeval rocks at Left Hand Collet Canyon and Tibbet Canyon (pl. 2). Near the mouth of Left Hand Collet Canyon, the highstand systems tracts consist entirely of stacked shoreface parasequences (Shanley and McCabe, 1991). In exposures 2 km to the southwest, several shoreface parasequences in the A- highstand systems tract grade laterally into coastal plain strata that contain about 9 m of cumulative coal. Five kilometers inland from the shoreface stack, the combined highstand systems tracts at CT-1-91 are 55 percent tidally influenced, 25 percent coastal plain, and 20 percent shoreface in origin and contain 19 m of coal. Shoreface strata remain only in the Calico and lower part of the A- highstand systems tracts. Fifteen kilometers inland from the shoreface stack, coeval rocks at SMP-1-91 are 71 percent coastal plain, 27 percent tidally influenced, and 2 percent shoreface in origin and contain about 28 m of coal. Here, shoreface deposits remain only in the lower part of the Calico highstand systems tract. Thirty-five kilometers inland, at Tibbet Canyon, both highstand systems tracts are primarily alluvial in origin and lack significant coal deposits (Shanley and McCabe, 1991; Shanley and others, 1992).

CONCLUSIONS

Detailed sedimentological analyses show that core from Upper Cretaceous rocks in the central regions of the Kaiparowits Plateau, southern Utah, consists of interbedded shoreface, tidal, and coastal plain (fluvial, floodplain, and mire) deposits and contains thick beds of coal. The distribution of depositional facies varies considerably between the

Table 4. Percent of facies assemblages (depositional facies) and total coal within the Calico and A- sequences in cores CT-1-91 and SMP-1-91.

Sequence	Systems tract	Core (systems tract thickness in meters)	shoreface	tidal	tidally influenced fluvial channels	fluvial channels	floodplains and mires	coastal plain (fluvial channels, floodplains, and mires)	Total meters coal
			Percent depositional facies in systems tract						
A- sequence	A- highstand systems tract	SMP-1-91 (180 m)	---------	17	9	21	53	74	20
A- sequence	A- highstand systems tract	CT-1-91 (184 m)	10	56	6	---------	28	34	19
A- sequence	A- transgressive systems tract	SMP-1-91 (9 m)	---------	6	94	---------	---------	---------	---------
A- sequence	A- transgressive systems tract	CT-1-91 (24 m)	---------	91	---------	---------	9	9	0.7
Calico sequence	Calico highstand systems tract	SMP-1-91 (32 m)	15	36	---------	---------	49	49	8
Calico sequence	Calico highstand systems tract	CT-1-91 (27 m)	100	---------	---------	---------	---------	---------	---------
Calico sequence	Calico transgressive systems tract	SMP-1-91 (25 m)	---------	47	---------	31	22	---------	1.4
Calico sequence	Calico transgressive systems tract	CT-1-91 (19 m)	3	13	---------	53	31	---------	0.3

[The distribution of depositional facies is shown for each systems tract and core. Fluvial, flooplain, and mire deposits in the highstand systems tracts and A- transgressive systems tract are interpreted to have accumulated in a coastal plain setting after models by Shanley and McCabe (1991), Shanley and others (1992), and McCabe and Shanley (1992). Leaders (- - - -) indicate that depositional facies is not present in systems tract within core.]

core and coeval outcrops located along the plateau margins. However, predictive sequence stratigraphic models by Shanley and McCabe (1991), and Shanley and others (1992) allow for precise correlations between core and outcrop. Unconformities in the core are interpreted from significant basinward facies shifts and are correlative with sequence boundary unconformities recognized on outcrop. Progradational intervals in the core are recognized by shallowing-upward successions and are correlative with highstand systems tracts identified on outcrop. Retrogradational intervals in the core are recognized by deepening-upward successions and are correlative with transgressive systems tracts identified on outcrop. These results support the models of Shanley and McCabe (1991), and Shanley and others (1992). The combined studies detail stratigraphic relationships between nearshore marine and coastal plain deposits and demonstrate the value of sequence stratigraphy as a correlative tool between marine and nonmarine strata. Furthermore, these results demonstrate the utility of detailed sedimentological analyses and show that reliable sequence stratigraphic interpretations can be made from isolated cores. The studies may provide a model that allows for sequence stratigraphic interpretations in areas lacking outcrop data.

Depositional facies relationships in the core also demonstrate that thick peat deposits persisted for long periods of time with limited input from either fluvial or marine realms. Thick coal beds are located between 5 and 15 km landward of stacked shoreface parasequences and are interstratified with tidal deposits. These associations suggest that thick deposits of peat accumulated on a coastal plain dissected by tidal creeks and estuaries and are in close proximity to the strand plain. However, preliminary coal bed analyses by Pierce and others (1992) show that the thicker coals are relatively clean in spite of their close association to clastic sources. These relationships suggest, therefore, that the thicker peat deposits accumulated in raised mires similar to those described elsewhere in the Straight Cliffs Formation by McCabe and Shanley (1992). By contrast, low-lying swamps and marshes adjacent to modern coastlines do not produce coals, due to the significant amount of clastic material received from marine waters (Breyer and McCabe, 1986).

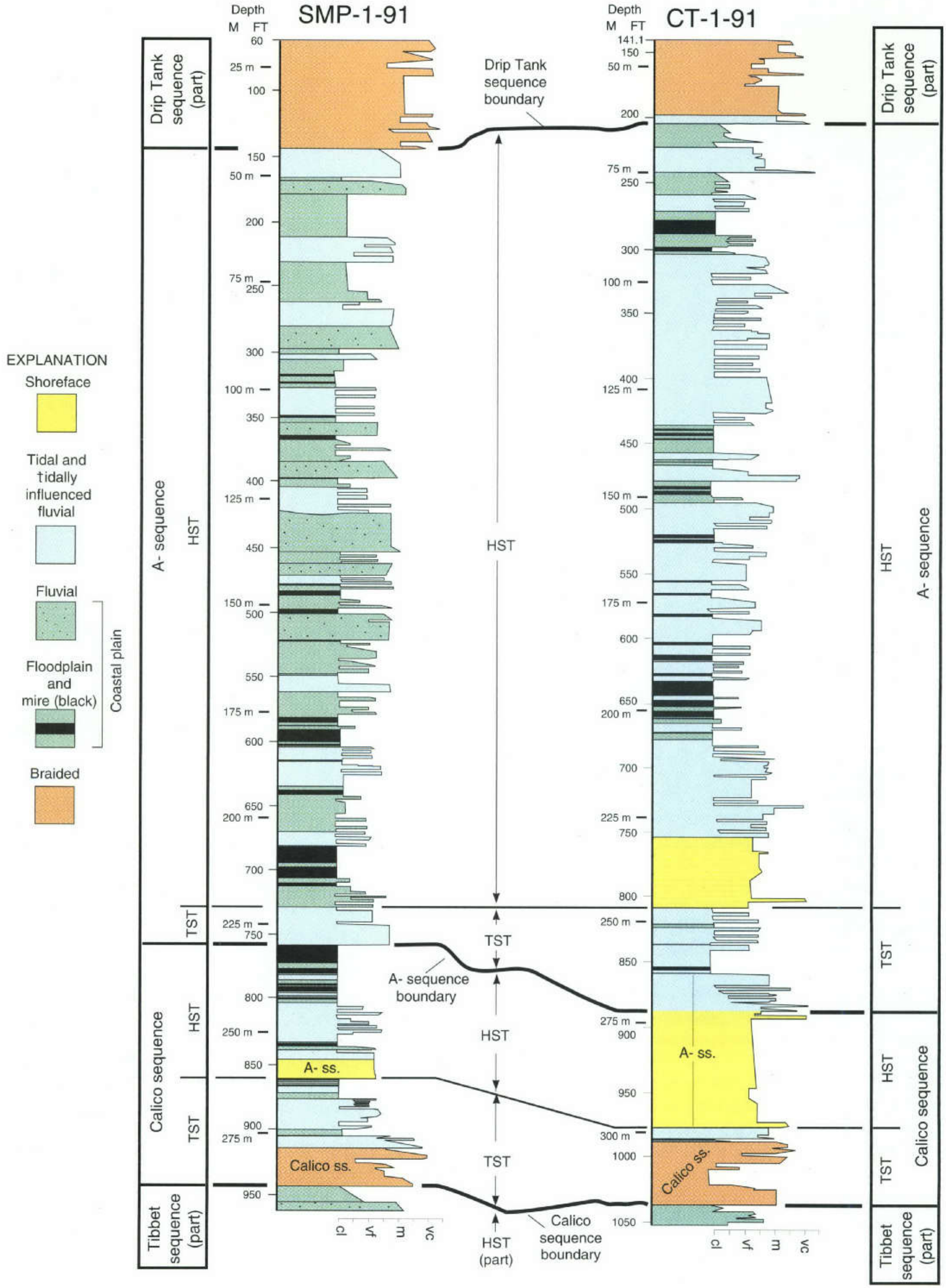

EXPLANATION
Shoreface
Tidal and tidally influenced fluvial
Fluvial
Floodplain and mire (black)
Coastal plain
Braided
SMP-1-91
CT-1-91
Depth M FT
Drip Tank sequence (part)
Drip Tank sequence boundary
A- sequence
HST
TST
A- sequence boundary
A- ss.
Calico sequence
Calico ss.
Calico sequence boundary
HST (part)
Tibbet sequence (part)
cl vf m vc

Figure 15 (facing page). Distribution of facies assemblages and correlation of sequences and associated highstand (HST) and transgressive (TST) systems tracts in cores CT-1-91 and SMP-1-91. Grain size is shown by rake scale at bottom of cores: clay (cl), very fine sand (vf), medium sand (m), and very coarse sand (vc).

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APPENDIX. GEOPHYSICAL LOGS RECORDED FROM CORE HOLES CT-1-91 and SMP-1-91

EXPLANATION

Trough or planar tabular cross-stratification

Swaley cross-stratification

Ripple cross-lamination

Wavy bedding

Lenticular or streaky bedding

Convoluted bedding

Double mud drapes or carbonaceous drapes

Coal

Carbonaceous shale

Extraformational pebbles

Roots

Burrows

Bivalve shell debris

x x x Volcanic ash

Dashed symbols indicate very faint features

S.P., spontaneous potential, in megavolts (MV)

Gamma Ray in American Petroleum Institute (API) Units

Bulk density in grams per cubic centimeter (GR/CC)

GRAIN SIZE:

cl clay

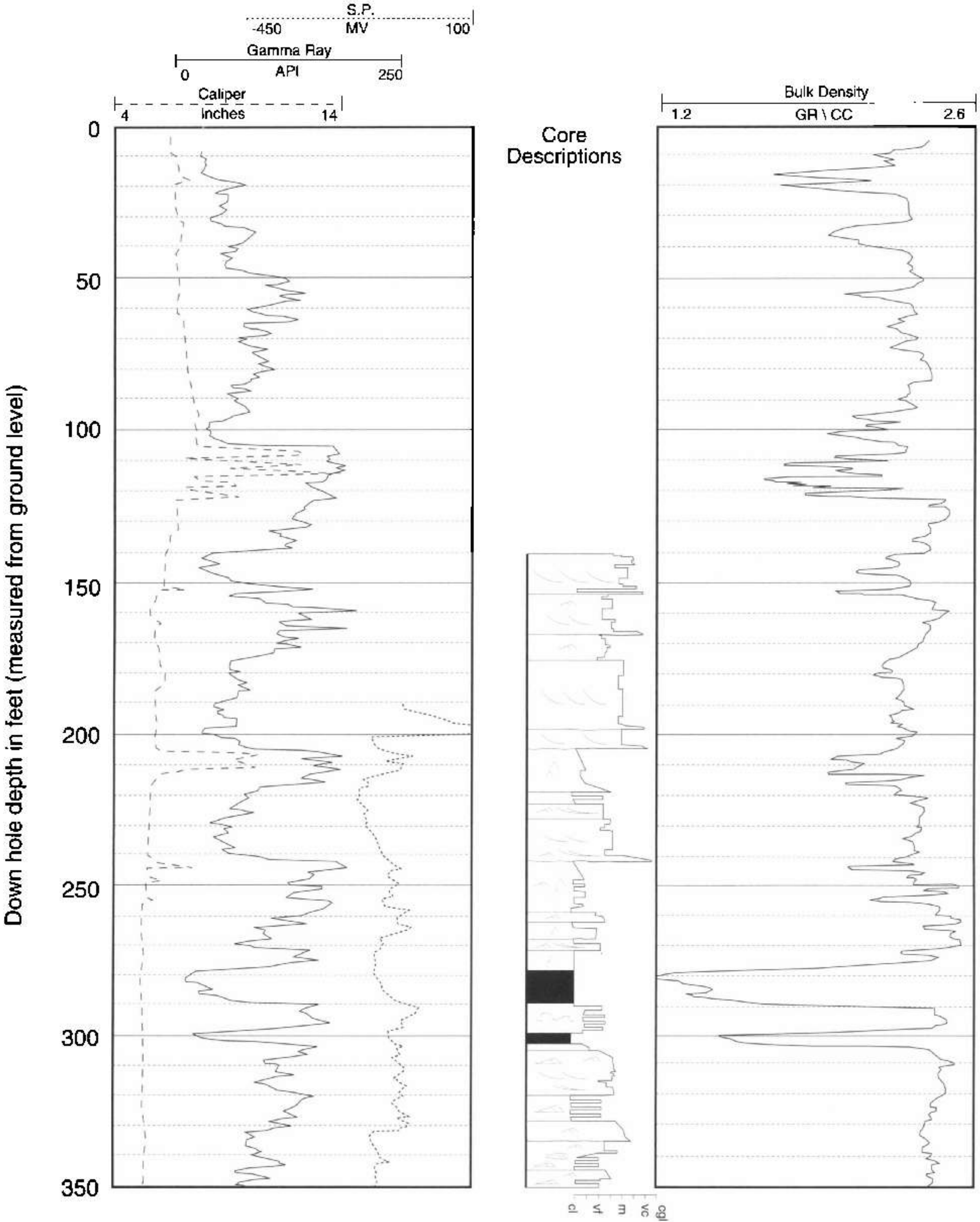
vf very fine sand

m medium sand

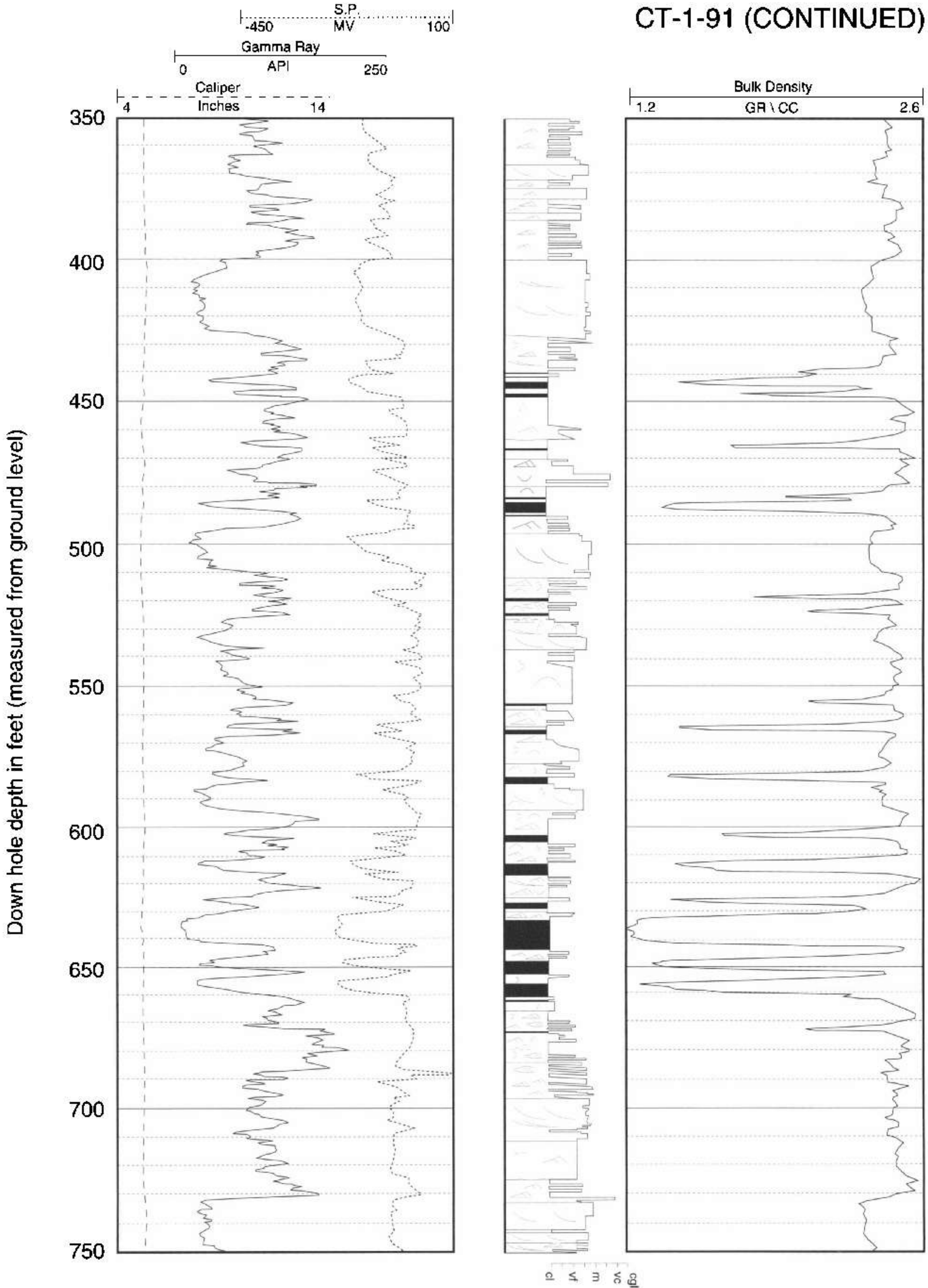
vc very coarse sand

cgl conglomerate

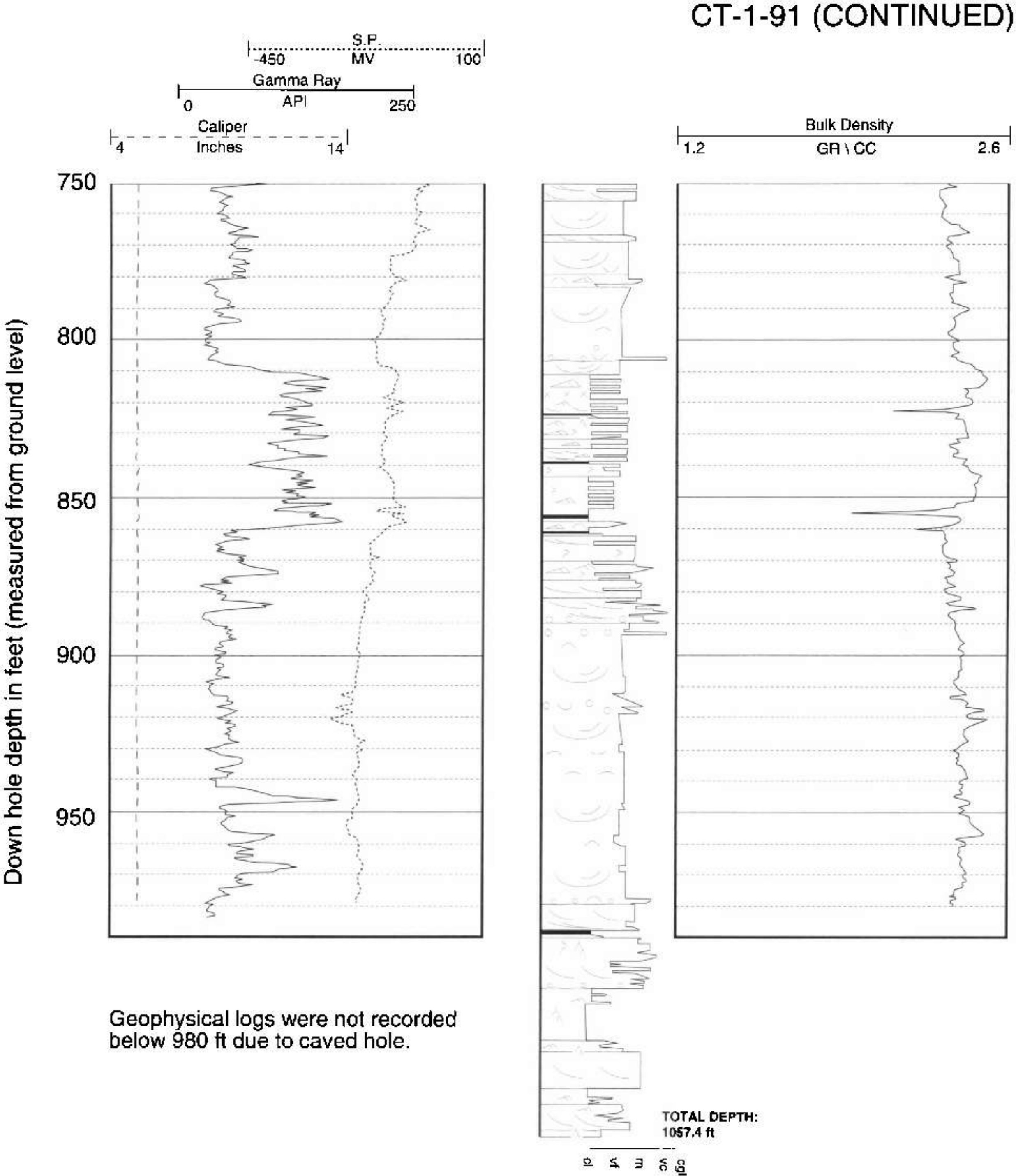
GEOPHYSICAL LOGS AND GENERALIZED DESCRIPTIONS FOR CORE CT-1-91



CT-1-91 (CONTINUED)



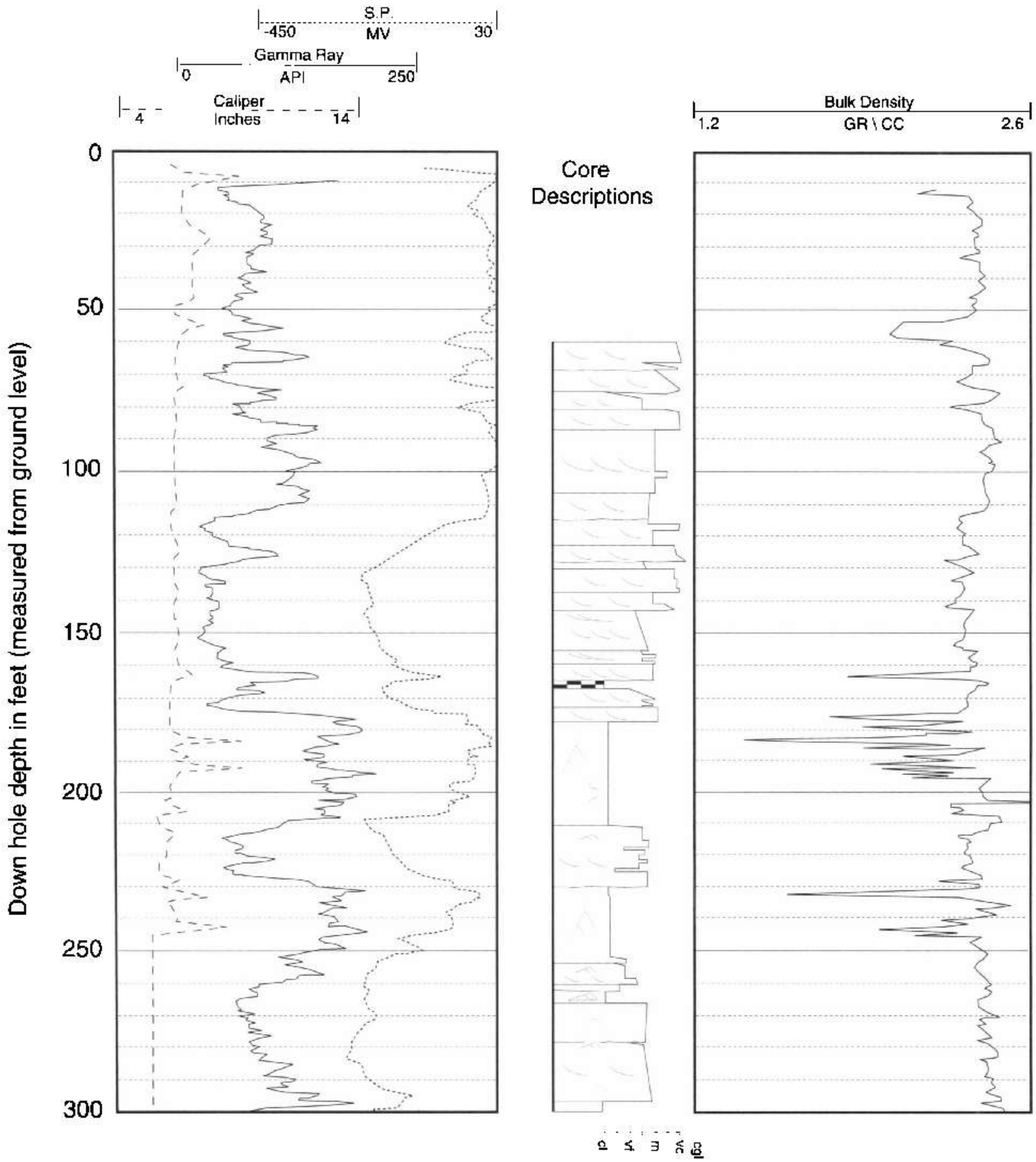
CT-1-91 (CONTINUED)



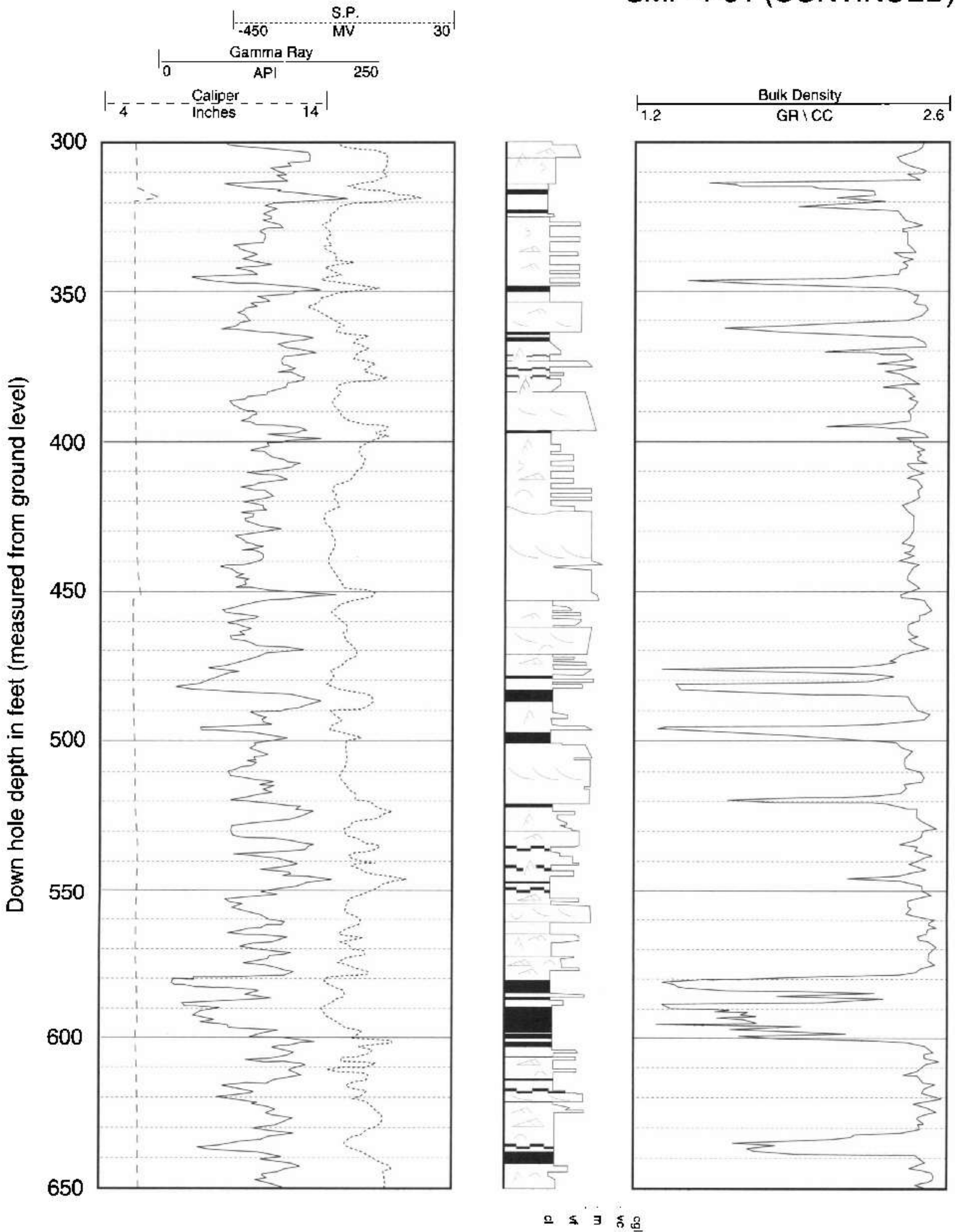
Geophysical logs were not recorded below 980 ft due to caved hole.

GEOPHYSICAL LOGS AND GENERALIZED DESCRIPTIONS FOR CORE SMP-1-91

(Note: Geophysical logs from SMP-1-91 record lithologies at depths approximately 2 ft higher than core descriptions)



SMP-1-91 (CONTINUED)



SMP-1-91 (CONTINUED)

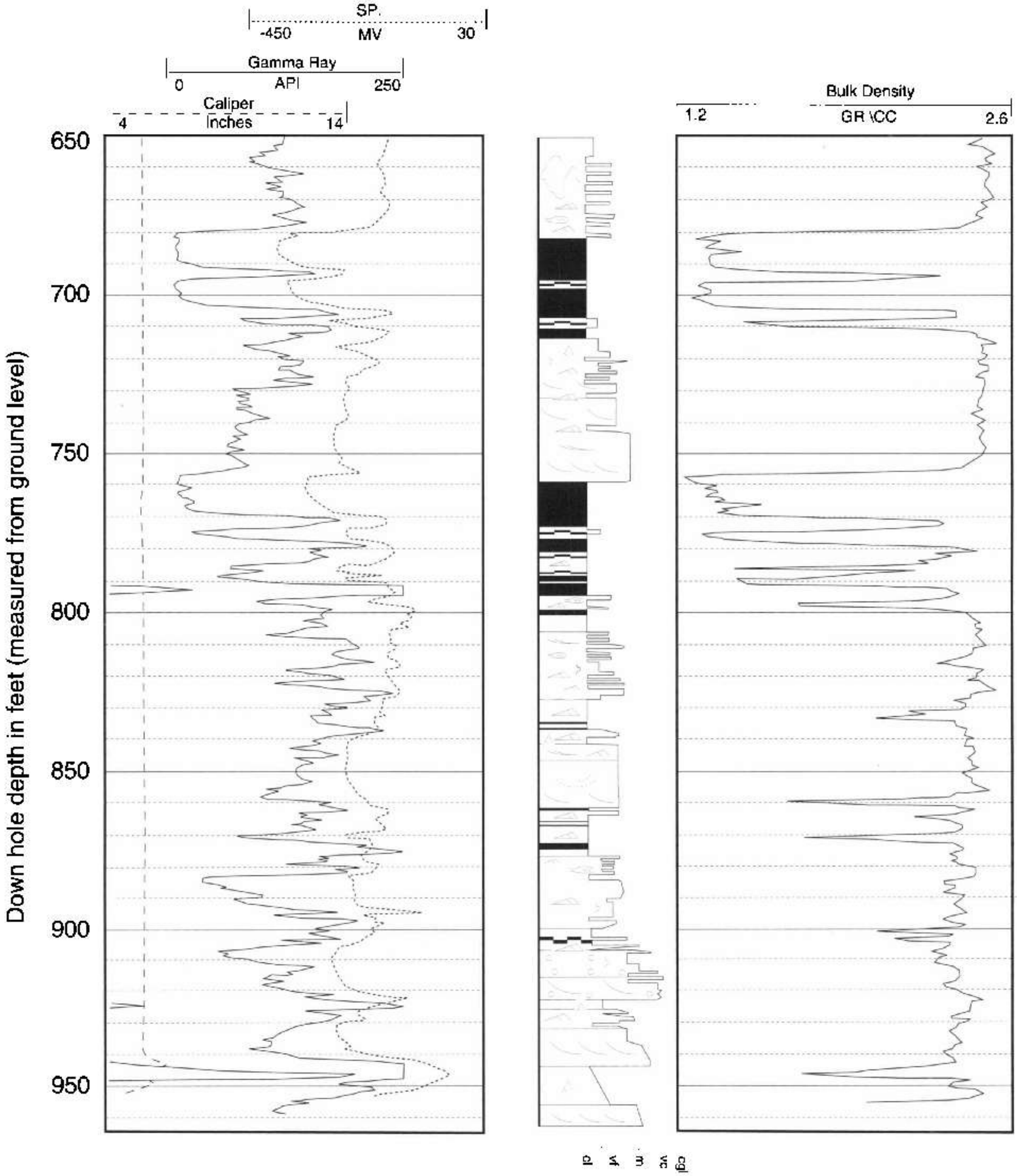


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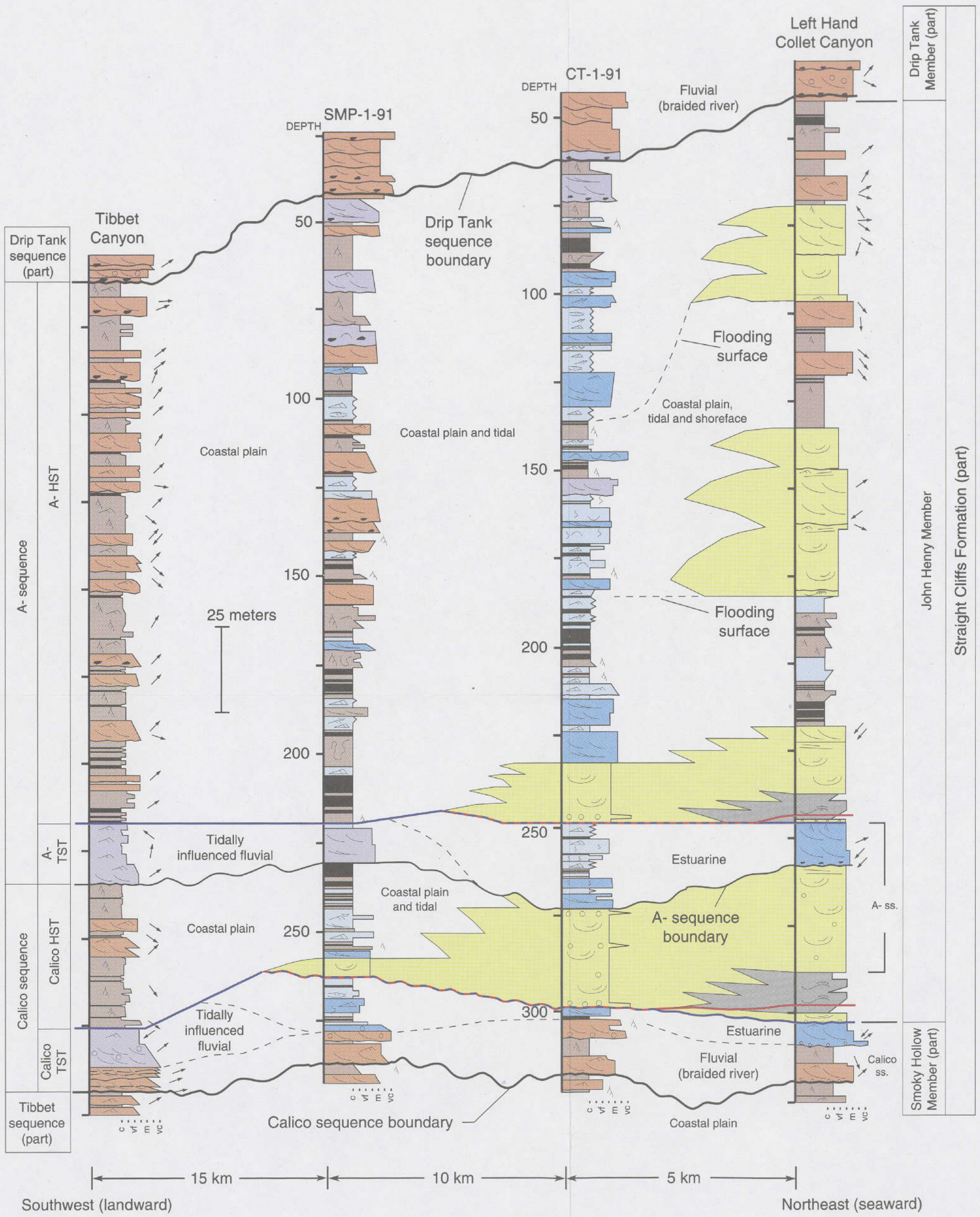
CHART SHOWING SEDIMENTOLOGICAL FEATURES AND DEPOSITIONAL INTERPRETATIONS FOR CORES SMP-1-91 AND CT-1-91, KAIPAROWITS PLATEAU, UTAH

By
Robert D. Hettinger
1995



Distance shown between measured sections and core holes indicate distance inland from the vertical shoreface stack located at mouth of Left Hand Collet Canyon

EXPLANATION

FACIES ASSOCIATIONS

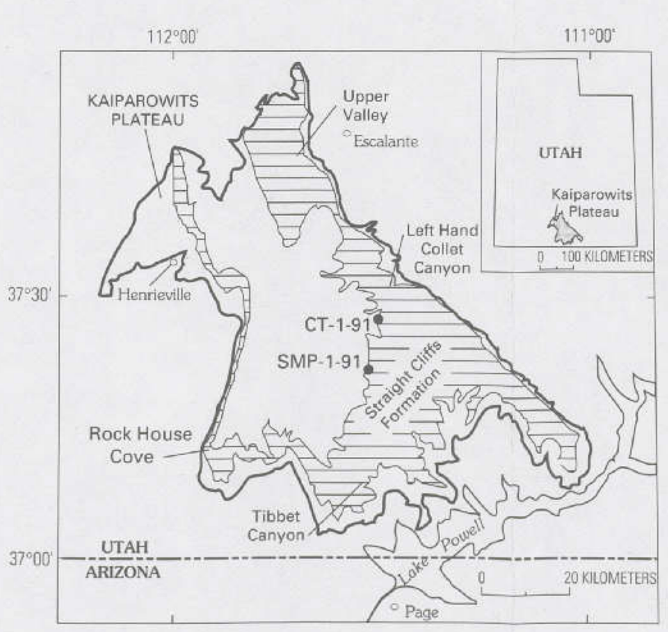
- Upper shoreface
- Lower shoreface (not described in text)
- Tidally influenced (sandstone dominated)
- Tidally influenced (sandstone-mudrock-dominated)
- Tidally influenced fluvial channels
- Fluvial channels
- Floodplains and mires (mire deposits (coals) are shown in black)

Maximum flooding surface — Condensed section — Ravinement surface

- Trough or planar tabular cross-stratification
- Swaley cross-stratification
- Hummocky cross-stratification
- Ripple cross-lamination
- Flaser bedding
- Wavy bedding
- Lenticular or streaky bedding
- Horizontal or subhorizontal bedding
- Convoluted bedding
- Double mud or carbonaceous drapes
- Erosional contact
- Sharp contact
- Coal
- Mud clasts
- Extraformational pebbles
- Roots
- Bioturbated
- Bivalve shell fragments
- Paleocurrent direction

Grain Size:

c l — clay
vf — very fine sand
m — medium sand
vc — very coarse sand



LOCATION MAP

Measured sections and sequence stratigraphic interpretations in Left Hand Collet Canyon and Tibbet Canyon are modified from Shanley (1991) and Shanley and others(1992). The John Henry Member consists almost entirely of stacked shoreface parasequences 2 km farther northeast of the section shown in Left Hand Collet Canyon (Shanley and McCabe, 1991)

CHART SHOWING SEQUENCE STRATIGRAPHIC CORRELATIONS FROM CORES SMP-1-91 AND CT-1-91 TO OUTCROPS IN LEFT HAND COLLET CANYON AND TIBBET CANYON, KAIPAROWITS PLATEAU, UTAH

By
Robert D. Hettinger
1995