Facies Analysis and Sequence Stratigraphic Framework of Upper Campanian Strata (Neslen and Mount Garfield Formations, Bluecastle Tongue of the Castlegate Sandstone, and Mancos Shale), Eastern Book Cliffs, Colorado and Utah

By Mark A. Kirschbaum and Robert D. Hettinger

U.S. Geological Survey Digital Data Series DDS–69–G

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Version 1.0 2004

For sale by U.S. Geological Survey, Information Services
Box 25286, Denver Federal Center
Denver, CO 80225

This publication is also available online at:
http://geology.cr.usgs.gov/pub/dds/dds-069-g/

Published in the Central Region, Denver, Colorado
Manuscript approved for publication 09/21/04

ISBN=0-607-90854-5

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Abstract

Facies and sequence-stratigraphic analysis identifies six high-resolution sequences within upper Campanian strata across about 120 miles of the Book Cliffs in western Colorado and eastern Utah. The six sequences are named after prominent sandstone units and include, in ascending order, upper Sego sequence, Neslen sequence, Corcoran sequence, Buck Canyon/lower Cozzette sequence, upper Cozzette sequence, and Cozzette/Rollins sequence. A seventh sequence, the Bluecastle sequence, is present in the extreme western part of the study area. Facies analysis documents deepening- and shallowing-upward successions, parasequence stacking patterns, downlap in subsurface cross sections, facies dislocations, basinward shifts in facies, and truncation of strata.

All six sequences display major incision into shoreface deposits of the Sego Sandstone and sandstones of the Corcoran and Cozzette Members of the Mount Garfield Formation. The incised surfaces represent sequence-boundary unconformities that allowed bypass of sediment to lowstand shorelines that are either attached to the older highstand shorelines or are detached from the older highstand shorelines and located southeast of the main study area. The sequence boundary unconformities represent valley incisions that were cut during successive lowstands of relative sea level. The overlying valley-fill deposits generally consist of tidally influenced strata deposited during an overall base level rise. Transgressive surfaces can be traced or projected over, or locally into, estuarine deposits above and landward of their associated shoreface deposits. Maximum flooding surfaces can be traced or projected landward from offshore strata into, or above, coastal-plain deposits. With the exception of the Cozzette/Rollins sequence, the majority of coal-bearing coastal-plain strata was deposited before maximum flooding and is therefore within the transgressive systems tracts. Maximum flooding was followed by strong progradation of parasequences and low preservation potential of coastal-plain strata within the highstand systems tract. The large incised valleys, lack of transgressive retrogradational parasequences, strong progradational nature of highstand parasequences, and low preservation of coastal-plain strata in the highstand systems tracts argue for relatively low accommodation space during deposition of the Sego, Corcoran, and Cozzette sequences.

The Buck Canyon/Cozzette and Cozzette/Rollins sequences contrast with other sequences in that the preservation of retrogradational parasequences and the development of large estuaries coincident with maximum flooding indicate a relative increase in accommodation space during deposition of these strata. Following maximum flooding, the Buck Canyon/Cozzette sequence follows the pattern of the other sequences, but the Cozzette/Rollins sequence exhibits a contrasting offlapping pattern with development of offshore clinoforms that downlap and eventually parallel its maximum flooding surface. This highstand systems tract preserves a thick coal-bearing section where the Rollins Sandstone Member of the Mount Garfield Formation parasequences prograde out of the study area, stepping up as much as 800 ft stratigraphically over a distance of about 90 miles. This progradational stacking pattern indicates a higher accommodation space and increased sedimentation rate compared to the previous sequences.

Introduction

This study develops a sequence stratigraphic framework for about 600 ft of Upper Cretaceous strata that are exposed in the Book Cliffs and traceable into the adjacent subsurface areas, between Grand Junction, Colorado, and Green River, Utah, a distance of about 100 mi (fig. 1). The project was designed initially to better understand the origin and paleogeography of Cretaceous Western Interior coal deposits but was completed as part of the National Oil and Gas Assessment project of the U.S. Geological Survey.

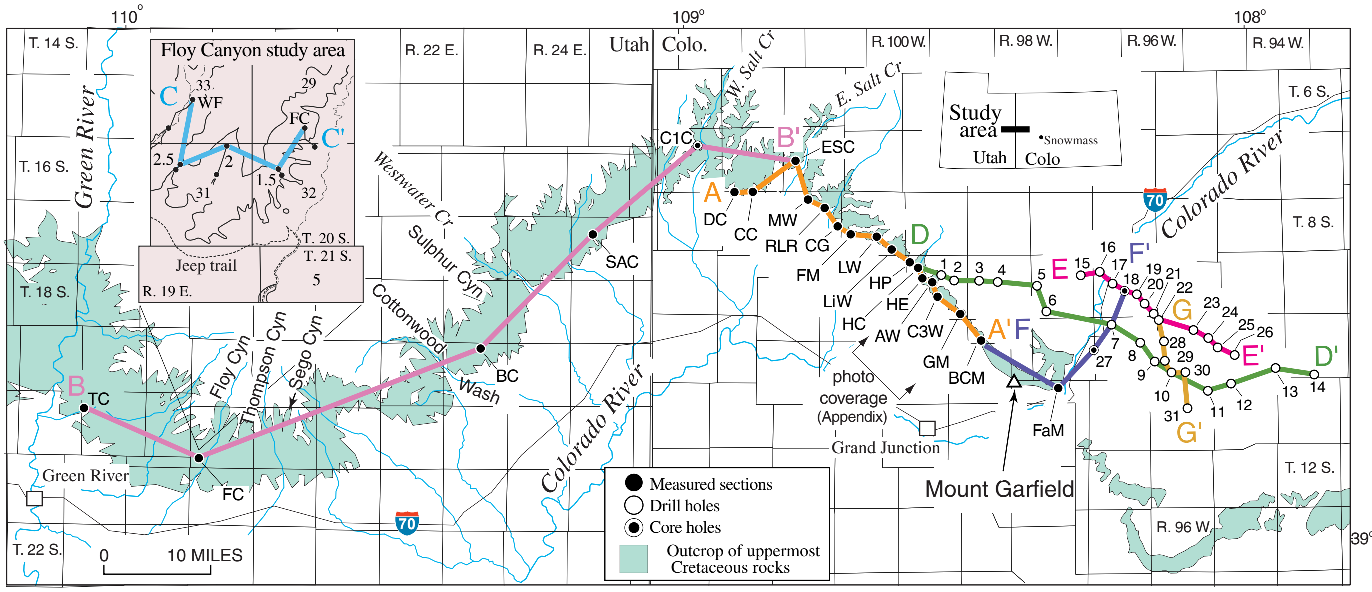


Figure 1. Index map showing locations of cross sections, measured sections, and drill holes. Cross section A–A′ (pl. 1) represents a detailed study based on measured sections along the Colorado portion of the Book Cliffs. Cross section B–B′ (pl. 2) is based on measured sections, a core hole, and observations along the length of the Utah portion of the Book Cliffs. Cross section C–C′, figure 6 (see inset for location), was based on closely spaced, detailed, measured sections in the Floy Canyon area near the depositional landward terminus of coal deposits in the Neslen Formation. Cross sections D–D′ (pl. 3), E–E′ (pl. 4), and G–G′ (pl. 6) were constructed from geophysical logs. Cross section F–F′(pl. 5) was constructed from a measured section and core holes to tie NW/SE cross sections together. Interpretive diagrams (fig. 20; plate 7) were constructed from sections along A–D–D′. Location of photo mosaic is also shown. Abbreviations: BC, Buck Canyon; C1C, USGS Carbonera core hole #1; FC, Floy Canyon; SAC, San Arroyo Canyon; TC, Tusher Canyon; DC, Dry Canyon; CC, Camp Creek; ESC, East Salt Creek; MW, Mack Wash; RLR, Ruby Lee Reservoir; CG, Coal Gulch; FM, Fruita Mine; LW, Layton Wash; LiW, Lipan Wash; HP, Hunter Point; HC, Hunter Canyon; HE, Hunter east; AW, Adobe Wash; C3W, Corcoran 3 west; GM, Grasso Mine; BCM, Book Cliffs Mine; FaM, Farmers Mine; WF, West Fork. Descriptions of localities are in table 1.

The Corcoran and Cozzette sandstones within the Mount Garfield Formation are important reservoirs for gas in the Piceance Basin, and this study supported an assessment of undiscovered gas resources in these sandstones (Kirschbaum, 2003). Coals in the Neslen and Mount Garfield Formations were intensely mined in the last century, but there is slightly less interest in these coals today and no mines are active in the study area (as of 2004). However, there is considerable interest in the coals from a coal-bed methane development standpoint.

The stratigraphic interval consists of part of the Sego Sandstone and the Neslen Formation in Utah, equivalent strata of the Mancos Shale and Mount Garfield Formation in Colorado, and part of the Bluecastle Tongue of the Castlegate Sandstone (figs. 2 and 3). The age of the Neslen Formation and equivalent strata of the Mount Garfield Formation is constrained within the Campanian Stage of the Late Cretaceous by the presence of *Baculites scotti* within the upper part of the Sego Sandstone in the eastern Book Cliffs (Gill and Hail, 1975), *Didymoceras nebrascense* just above the Corcoran Member of the Mount Garfield (Gill and Hail, 1975), *Didymoceras stevensoni* within distal sands of the Cozzette Member of the Mount Garfield, and *Didymoceras cheyennense* in strata well above the Rollins (Trout Creek equivalent) Sandstone Member of the Mount Garfield in the Grand Hogback area (Madden, 1989).

Stratigraphic Nomenclature

The main focus of the present study is on the upper part of the Sego Sandstone, the Corcoran, Cozzette, and Rollins Sandstone Members of the Mount Garfield Formation (pl. 1), and the equivalent coal-bearing strata of the Neslen Formation (pl. 2). The name Neslen Formation is replaced at the Utah/Colorado State line by the name Mount Garfield Formation. The coal-bearing facies of the Neslen can be traced into the Grand Junction area where it pinches out between nearshore marine sandstones of the Sego Sandstone and Mount Garfield Formation. Nearshore marine sandstones in the Mount Garfield are assigned to the Corcoran, Cozzette, and Rollins Sandstone Members, and offshore marine deposits are assigned to the Mancos Shale. The main coal zones are, in ascending stratigraphic order: Anchor, Palisade, Chesterfield, and Cameo (pl. 2). Summaries of the stratigraphic nomenclature are discussed by Young (1955, 1983), Franczyk (1989), Johnson (1989), and Hettinger and Kirschbaum (2002). Information regarding downhole depths of formations, members, and lithologies (sandstone, shale, and coal) in the Mesaverde Group are provided in a database by Hettinger and others (2000). That database includes preliminary interpretations made from geophysical logs recorded in about 500 drill holes distributed throughout the southern part of the Piceance Basin.

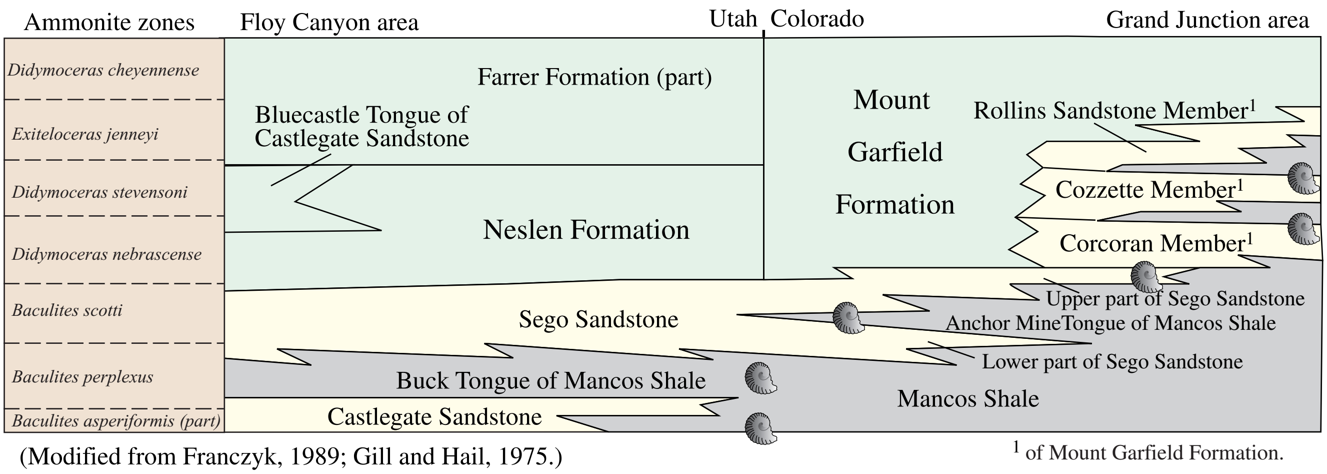


Figure 2. Generalized stratigraphic chart for the study area in eastern Utah and western Colorado. Ammonite zonation for part of the Campanian is shown with ammonite symbols indicating the location of a collected specimen from Gill and Hail (1975).

Methods

About 25 stratigraphic sections were measured with varying degrees of detail during this study. Sections were concentrated in the Floy Canyon area of Utah and in the Colorado portion of the Book Cliffs (fig. 1; locations in table 1). In Floy Canyon there are three complete sections and two partial sections (see fig. 1), and lithofacies were walked out between sections. In the eastern part of the study area, complete sections were measured in detail through the Sego to Rollins interval at the Book Cliffs Mine, the Grasso Mine, Hunter Canyon, Coal Gulch, and East Salt Wash (fig. 1). Numerous partial sections were also measured in areas of complexity, and three complete but less detailed sections were measured at Mack Wash, Layton Wash, and Ruby Lee Reservoir. Between the two main study areas, we measured detailed sections at San Arroyo Canyon and Buck Canyon and sketched numerous sections across the Book Cliffs, visiting most of the easily accessible canyons. Facies interpretations and paleocurrent measurements were made along two preexisting measured sections at Tusher Canyon by Lawton (1983) and near Palisade, Colorado, by Gill and Hail (1975, Farmers Mine section) (fig. 1). Correlations were made on oblique aerial photographs where available (fig. 4; photos 3–1 to 3–20 in Appendix) or from photos taken on the ground, and many key beds were walked out from canyon to canyon (fig. 5). In addition, four subsurface cross sections were constructed from oil and gas drill holes (pls. 3–6) in the Colorado part of the study area, and three cores were described to interpret facies and to calibrate the geophysical logs to the rock record (fig. 1; pl. figs. 2.1, 5.1, and 5.2).

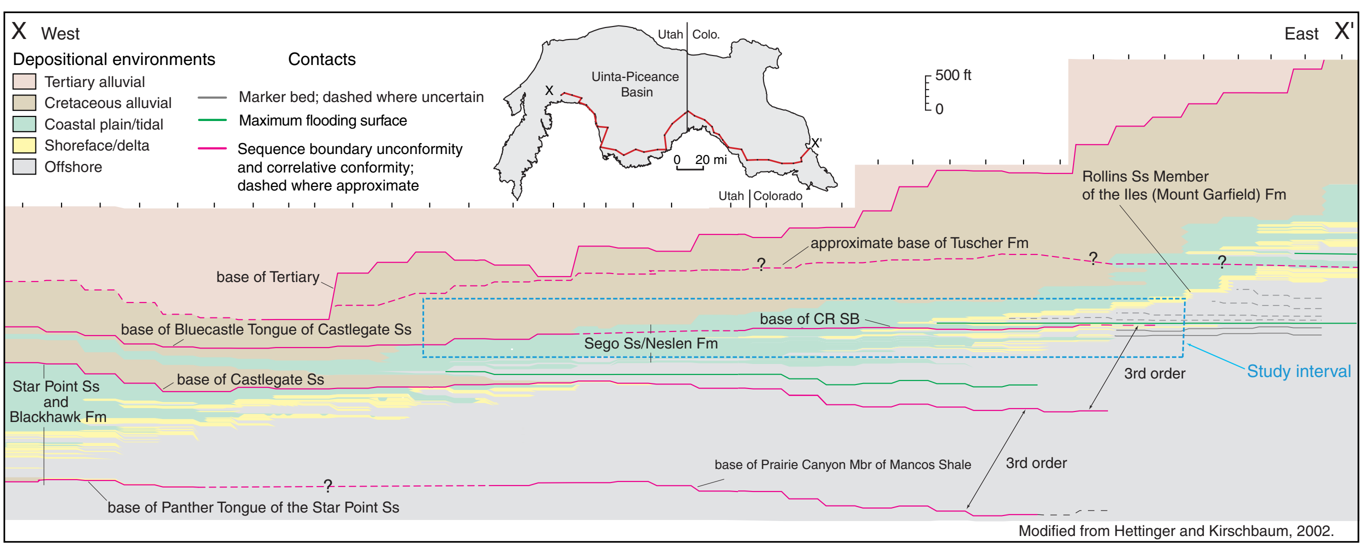


Figure 3. Regional cross section of Upper Cretaceous and undivided lower Tertiary strata across the Uinta and Piceance Basins. The study area is shown by the box outlined in blue. Major sequence boundaries (red) are shown and named by the strata directly overlying the surface.

Table 1. Locations of measured sections and drill holes: TC, modified from Lawton (1983); ESC, measured along dirt road; CG, measured on promontory south of Coal Gulch (see Erdmann, 1934); upper part of section was offset to the north into Coal Gulch; L2W, measured two promontories west of Lipan Wash (not shown in fig. 1); LW, measured on east side of drainage out toward promontory; HC, lower and upper parts measured in steep cliffs to east of drainage, and middle part measured in drainage; C3W, measured three drainages west of Corcoran Point; GM, measured up drainage; FM, sedimentary structures, paleocurrents, and grain size added to thicknesses measured by Gill and Hail (1975). Detailed locations of Floy Canyon section are shown in inset in figure 1, and three short sections measured in the Buck Canyon area are shown in figure 16.

Measured section	ID	Section	Township	Range
Tusher Canyon	TC	13	20 S.	19 E.
Floy Canyon composite	FC	29	20 S.	19 E.
Buck Canyon	BC	3	19 S.	23 E.
San Arroyo Canyon	SAC	9	17 S.	25 E.
Dry Canyon	DC	5	8 S.	103 W.
Camp Creek	CC	3	8 S.	103 W.
East Salt Creek	ESC	20	7 S.	102 W.
Mack Wash	MW	4	8 S.	102 W.
Ruby Lee Reservoir	RLR	11	8 S.	102 W.
Coal Gulch (lower part)	CG	24	8 S.	102 W.
Coal Gulch (upper part)	CG	18	8 S.	101 W.
Fruita Mine	FM	30	8 S.	101 W.
Layton Wash	LW	27	8 S.	101 W.
Lipan 2 -W	L2W	35	8 S.	101 W.
Lipan Wash	LiW	35	8 S.	101 W.
Hunter Point	HP	6	9 S.	100 W.
Hunter Canyon	HC	5 & 8	9 S.	100 W.
Hunter East	HE	17	9 S.	100 W.
Adobe Wash	AW	16	9 S.	100 W.
Corcoran 3-W	C3W	22	9 S.	100 W.
Grasso Mine	GM	36	9 S.	100 W.
Book Cliffs Mine	BCM	8	10 S.	99 W.
Farmers Mine	FM	3	11 S.	98 W.

Operator	Lease name	ID no.	Section	Township	Range
Koch Exploration	Winter Flat 1-10-100	1	10	9 S.	100 W.
Koch Exploration	Winter Flat 1-14	2	14	9 S.	100 W.
Koch Exploration	Winter Flat 1-18	3	18	9 S.	99 W.
Koch Exploration	Winter Flat 1-16	4	16	9 S.	99 W.
Coors Energy	USA 1-18 Jackson Canyon	5	18	9 S.	98 W.
Dome Petroleum	Dome Alberson 1-32	6	32	9 S.	98 W.
Texaco	Roberts Canyon	7	5	10 S.	97 W.
Coors Energy	Nichols 1-14	8	14	10 S.	97 W.
Coors Energy	Harvey 2-25	9	25	10 S.	97 W.
Coors Energy	Wood 4-12	10	32	10 S.	96 W.
Teton Energy	Bull Basin 1-3	11	1	11 S.	96 W.
Coors Energy	Swetland 1-5	12	5	11 S.	95 W.
Exxon	Old Man Mountain # 2	13	36	10 S.	95 W.
Exxon	Old Man Mountain # 1	14	33	10 S.	94 W.
Dekalb Energy	Wagon Trail 44-11	15	11	9 S.	98 W.
Coors Energy	De Beque 1-8	16	8	9 S.	97 W.
Koch Exploration	Horseshoe Canyon 1-17	17	17	9 S.	97 W.
Koch Exploration	Horseshoe Canyon 1-21	18	21	9 S.	97 W.
Alta Energy	Alta #23-1	19	23	9 S.	97 W.
Norris Oil	Federal 26-1	20	26	9 S.	97 W.
Norris Oil	Federal 36-2	21	36	9 S.	97 W.
Compass Exploration	Shire Gulch #1	22	6	10 S.	96 W.
Flying Diamond	Federal 10-1	23	10	10 S.	96 W.
Norris Oil	Currier 14-2	24	14	10 S.	96 W.
Flying Diamond	Nichols 13-1	25	13	10 S.	96 W.
Bow Valley Petroleum	Reed 20-3	26	20	10 S.	95 W.
U.S. Geological Survey	CA-77-2	27	13	10 S.	98 W.
Coors Energy	Nystrom 3-18	28	18	10 S.	96 W.
Coors Energy	Bevan 1-30	29	30	10 S.	96 W.
Bow Valley Petroleum	Federal 33-2	30	33	10 S.	96 W.
Kenai Oil and Gas	Bull Basin 15-3	31	15	11 S.	96 W.
U.S. Geological Survey	Carbonera Core Hole	C1C	10	7 S.	104 W.

Figure 4. Part of an oblique aerial photo mosaic (Appendix, photo 3–20) of an area east of Hunter Canyon. View is to northeast, showing stratigraphic units and interpreted sequence boundaries. Location of Hunter East measured section shown. Full photographic coverage (Appendix) extended from Hunter Canyon on the west to near the Book Cliffs Mine section on the east. Photo 3–20 was digitally enhanced to hide joins and to interpolate missing areas of scenery at top of outcrop exposures, but stratigraphic accuracy is retained. The red coloration is the result of the burning of the Cameo coal zone and baking of the adjacent rocks. Abbreviations for sequence boundaries: Nes, Neslen; Cn1, Corcoran; BC, Buck Canyon/lower Cozzette; Cz, upper Cozzette; CR, Cozzette/Rollins.

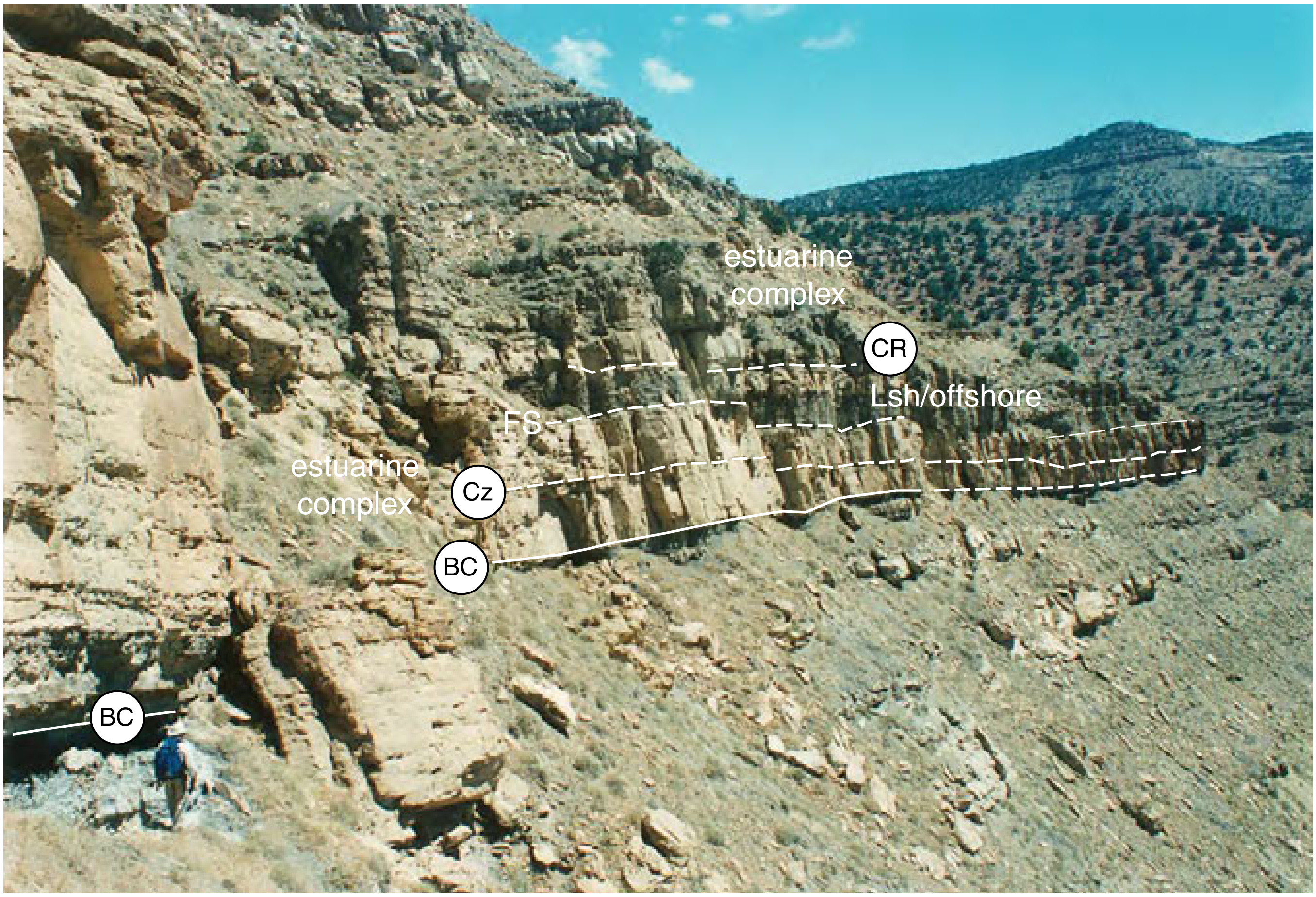


Figure 5. View of geologist (left foreground) walking out estuarine complexes of the Cozzette Member east of the Layton Wash section (see fig. 1). Abbreviations: BC – Buck Canyon/lower Cozzette sequence boundary; Cz, upper Cozzette sequence boundary; CR, Cozzette/Rollins; FS, flooding surface; Lsh, lower shoreface.

Facies Analysis

Eighteen lithofacies, identified on outcrop and in core, are described for the Neslen Formation and equivalent strata in the Mount Garfield Formation and Bluecastle Tongue of the Castlegate Sandstone (tables 2 and 3). The lithofacies can be recognized in nine facies assemblages (table 4), which in turn are interpreted to have been deposited in five general depositional environments: alluvial plain, coastal plain, estuarine complex, shoreface/delta front, and offshore marine (for example, see pl. 1). The relative abundance of the facies assemblages was calculated from three complete measured sections: Coal Gulch and Grasso Mine (pl. 1) and Floy Canyon (figs. 1 and 6). Depositional environments are identified by color patterns on cross sections. Because of complex interfingering between the facies assemblages, it was convenient to map some facies assemblages within more than one depositional environment (for example, organic-rich facies is found in both estuarine complexes and coastal-plain deposits).

Alluvial plain deposits as defined in this report include strata deposited within and adjacent to river systems located landward of any brackish-water influence; they are present only in the western part of the study area (pl. 2; fig. 6). Coastal-plain deposits are defined as rocks that accumulated dominantly in freshwater environments adjacent to a paleoshoreline; such deposits are dominated by organic-rich rocks, lenticular to tabular sandstones, and inclined heterolithic strata but can have some minor tidal influence. The estuarine complexes are dominated by brackish-water and both tidal and wave influences consisting of compound cross-stratification, flaser, wavy and lenticular-bedded sandstone, wave-rippled sandstone, and mudrock.

On cross sections, the coastal-plain deposits are mapped with a light green background color and estuarine complexes are mapped with an orange color. Relative salinity shown in the columns of measured section (for example, pl. 1) is a subjective estimate of whether the rocks were deposited in fresh, brackish, or marine conditions based on lithology, sedimentary structures, and fossils; freshwater deposits are indicated by a green color, brackish-water deposits are indicated by an orange color, and normal marine deposits are indicated by a yellow or gray color.

In the following discussions, facies assemblage headings are identified by number and depositional interpretation.

Table 2. Lithofacies interpreted to have been deposited in lower and upper shoreface environments. Facies are defined on the basis of grain size and sedimentary and biogenic structures. Data from detailed descriptions made at Dry Canyon, East Salt Creek, Grasso Mine, and Hunter Canyon sections include information recorded from the upper part of the Sego Sandstone, and Corcoran, Cozzette, and Rollins Sandstone Members of the Mount Garfield Formation. [<, less than; ft, feet; cm, centimeters]

Facies	Description of sedimentary structures	Grain size	Facies thickness	Comments
Subhorizontal laminated sandstone	Low-angle, subhorizontal, parallel lamination with some isolated cross stratification.	Upper fine to lower medium sand.	5.6–16.4 ft (170–500 cm)	Minor component (<5 percent) of preserved shoreface deposits.
Crossbedded sandstone	Trough and planar-tabular cross stratification; beds generally are 0.5–0.7 ft (15–20 cm) thick.	Upper fine to lower medium sand.	5.4–14.3 ft (165–435 cm)	Minor component of preserved shoreface; for example, makes up only 3.5 percent of total section at Grasso Mine.
Swaley-bedded sandstone	Swaley cross stratification.	Upper fine to lower medium sand.	3.1–36 ft (95–1100 cm)	*Ophiomorpha* burrows are common; represents up to 30 percent of total section (Grasso Mine).
Hummocky cross-stratification beds	Hummocky cross stratification is the dominant stratification. Beds are 0.15–1.6 ft (5–50 cm) thick and commonly include horizontal lamination, wave ripples, and some silt interbeds.	Very fine to lower fine sand; rarely lower medium sand.	1–12 ft (30–366 cm)	*Ophiomorpha* and *Thalassinoides* burrows and gutter casts are common. Hummocky cross stratification makes up to 8 percent of total section.
Bioturbated sandstone	Original stratification is completely destroyed by burrowing organisms.	Very fine to lower medium sand.	1.9–16.7 ft (58–510 cm)	Mostly *Ophiomorpha* and *Thalassinoides* burrows.
Interbedded sandstone and mudrock	Horizontal and cross-laminated sandstone in beds <0.7 ft (1–20 cm) thick; hummocky cross stratification a minor component. Laminated silt and clay in beds <1.3 ft (1–40 cm) thick; burrows are common.	Very fine sand. Silt and clay.	1.5–29.5 ft (45–900 cm)	May contain shark teeth, baculites, or bivalves, including *Inoceramus*.

Table 3. Lithofacies interpreted to have been deposited in tidal and coastal-plain environments. Facies are defined on the basis of grain size and sedimentary and biogenic structures. Data from detailed descriptions made in Floy Canyon area (including one unpublished section), Buck Canyon, San Arroyo Canyon, Dry Canyon, East Salt Creek, Coal Gulch, Hunter Canyon, and Grasso Mine. [<, less than; ft, feet; cm, centimeters]

Facies	Description of sedimentary structures	Grain size	Facies thickness	Comments
Intraformational conglomerate	Crude stratification and imbrication of mud clasts, shells, and logs.	Granule to cobble size material in a sand matrix.	0.5–6.6 ft (15–200 cm)	Logs with *Teredolites* especially common; bivalves including oysters common in lower part of Neslen; bone fairly common; rare gastropods; turtle carapace.
Crossbedded sandstone	Trough/planar tabular cross stratification in beds 0.1–3.3 ft (3–100 cm) thick; mostly 0.5–0.7 ft (15–20 cm) thick.	Very fine to medium sand.	0.3–13.5 ft (10–410 cm)	Mud clasts are common. Troughs are up to 6.6 ft (200 cm) wide.
	Some crossbeds have bounding surfaces separated by cross lamination; beds 0.2–1.1 ft (5–35 cm) thick; some symmetrical ripples and ripples with carbonaceous or mud drapes.	Fine to medium sand.	2.0–12.1 ft (60–370 cm)	Reactivation surfaces and clay/silt rip-ups common; trough 1.6-6.6 ft (50-200 cm) wide; mud drapes are common on foresets (some double) and bounding surfaces; some syneresis cracks; burrows, especially horizontal, and *Teredolites* common; some *Ophiomorpha*.

Table 3. Lithofacies interpreted to have been deposited in tidal and coastal-plain environments.—Continued

Facies	Description of sedimentary structures	Grain size	Facies thickness	Comments
Ripple laminated sandstone	Undulatory-based asymmetrical and symmetrical ripples; some with offshoots. Ripple indexes measured include 4, 5, 6, 6, 6, 6.5, 8, 8.5, and 13.	Upper very fine to lower fine sand.	0.2–8.8 ft (5–300 cm)	Horizontal/vertical burrows are common; paleocurrents can be bidirectional; bed tops may have straight-crested symmetrical or flattened ripples; often single or double carbonaceous or mud drapes, clay rip-ups, or syneresis cracks.
	Erosionally based (planar) climbing ripples; angle of climb <1 to 17 degrees; <0.05 ft (1–2 cm) heights.	Upper very fine to lower fine sand.	0.2–15.1 ft (5–460 cm)	Unidirectional paleocurrents; rare plant fragments or burrows on bedding planes.
Streaky, lenticular, wavy, and flaser bedded sandstone	Alternating beds of cross laminated sandstone and mudrock; ss in beds 0.1–1.2 ft (3–38 cm) consisting of undulatory based ripples; silt in beds <0.05–0.2 ft (0.5–7 cm).	Upper very fine to lower fine sand.	0.3–9.3 ft (10–284 cm)	Comprises as much as 18 percent of a stratigraphic section (Coal Gulch); burrows and plant fragments are common. Burrow include *Thalassinoides*, *Arenicolites*, *Teichichnus*, *Scolithus*, *Planolites*. Oysters and *Teredolites* are rare.
Inclined heterolithic strata	Alternating sandstone/mudrock; sandstone beds 0.1–1.3 ft (3–40cm) thick with ripples, horizontal lamination, wavy bedding, some crossbeds; tops of beds can have straight crested symmetrical ripples. Laminated silt beds are <0.3 ft (1–10 cm) thick; sandstone makes up 20–90 percent.	Very fine to lower fine sand.	3.4–25.6 ft (104–780 cm)	Plant fragments and burrows are abundant. Includes *Rhizocorallium*, *Chevronensis*, *Teichichnus*. Lags commonly contain *Teredolites*, bone, and granule to pebble-size clay rip-ups. Surfaces are inclined from 3 to 19 degrees (averaging 9; N=16). Some surfaces are overlain by continuous mud drapes.
Horizontal laminated sandstone		Very fine to fine sand.	0.3–8.8 ft (10–300 cm)	Burrows are rare.
Convoluted sandstone		Very fine to lower medium sand.	2.2–9 ft (67–275 cm)	
Bioturbated sandstone	Primary sedimentary structures have been destroyed by roots or burrowing organisms.	Very fine to upper fine sand.	0.75–3.9 ft (23–120 cm) 2.1–6.2 ft (16–189 cm)	Roots. Horizontal and vertical sand-filled burrows.
Mudrock	Gray laminated mud.		0.05–5.4 ft (2–166 cm)	Plant fragments and roots are common; gastropods, bivalves and leaves are rare. Includes altered volcanic ash beds <0.3 ft (0.5–10 cm) thick.
	Gray mud with original bedding destroyed by burrowing organisms or roots.		<9.0 ft (1–275 cm)	Slickensides, roots, or plant fragments are common; also contains gastropods, concretions, and burrows; rare *Teredolites*.
Carbonaceous shale	Organic material is very abundant and is interlaminated with silt, clay, or sand.		0.1–9.3 ft (3–285 cm)	Roots, slickensides, and coaly streaks are common; bone, gar scales, and conifer pinnules are rare.
Coal	Greater than 50 percent organic material as determined by visual inspection.		0.05–4.8 ft (2–145 cm)	Contains alternating bright (vitrain) and dull (durain) bands; bright bands are up to 1.5 ft (47 cm) and thick, dull bands are up to 0.03 ft (10 cm) thick. Resin blebs are abundant.
Limey siltstone or sandstone	None.	Silt to very fine sand.	0.3–2.2 ft (10–66 cm)	Pods are rare, display conchoidal fracture, and can contain gastropods, bivalves, or leaves; pods are located at edges of channels.

Table 4. List of facies assemblages (facies) identified in the stratigraphic interval studied.

Facies	Description	Interpretation
1	Organic rich	Mire/marsh/flood plain
2	Lenticular/tabular sandstone and inclined heterolithic strata	Fluvial, tidally influenced, and tidal channel and bayhead delta
3	Symmetrical and flaser/wavy/lenticular cross-laminated sandstone	Wave dominated sand flat/estuarine shoreface or spit
4	Compound cross stratification	Tide-dominated sand flat/tidal delta, and flood/ebb channel
5	Mudrock	Open estuarine
6	Cross-stratified and planar laminated sandstone	Upper shoreface
7	Interbedded sandstone and mudrock	Lower shoreface/offshore
8	Medium- to coarse-grained cross-stratified sandstone	Fluvial channel
9	Inclined graded beds/horizontal laminated sandstone and siltstone	Delta front, distributary mouth bar, distal bar, and prodelta

Facies Assemblage 1: Organic-rich rocks (mire/marsh/flood plain)

Description

Facies 1 consists of coal, carbonaceous shale, and organic-rich mudrock (fig. 7). Coal makes up about 1–4 percent of the stratigraphic section, is dull to bright with a banded appearance, and is highly resinous. Carbonaceous shale in our usage is highly fissile, brown to black, and organic rich and composes as much as 13 percent of the stratigraphic section, for example at Floy Canyon (fig. 6). Organic rich mudrock is light to dark gray, contains disseminated plant material and (or)roots, and constitutes as much as 12 percent of the total section at Floy Canyon. About two-thirds of the organic-rich mudrock in the study interval is not laminated. Post-depositional structures include roots, burrows, slickensides, and deformed bedding. The organic-rich mudrock, and in a few cases carbonaceous shale, contains fossils of gastropods and bivalves, leaves, *Teredolites*, and dinosaur bones.

Interpretation

Coal, carbonaceous shale, and organic-rich mudrock are interpreted to represent the deposits of wetlands: freshwater mires and marshes, salt marshes, and flood plains. Bivalves, gastropods, and *Teredolites* within some mudrock units indicate a transition from freshwater to brackish-water conditions. This is supported by Fisher and others (1960), who found both freshwater and brackish-water fossils within the Neslen Formation in Utah. Randomly oriented slickensides are attributable to expanding clays, and roots indicate the presence of paleosols (Mack and others, 1993). Deformed bedding can be attributed to compaction and dewatering of the sediments. This facies assemblage makes up a large proportion of the original sediment deposited in the study interval, considering the high compaction ratio of organic matter following burial.

Facies Assemblage 2: Lenticular cross-stratified sandstone, tabular ripple-laminated sandstones, and inclined heterolithic strata (fluvial channel, tidally influenced channel, tidal channels, and bayhead delta)

Description

Facies assemblage 2 consists of cross-stratified sandstone, ripple-laminated sandstone, and inclined heterolithic strata (IHS). This complex facies assemblage is found within laterally extensive successions that grade from lenticular deposits to tabular sandstones (figs. 6 and 7). The facies assemblage forms isolated to amalgamated (fig. 7) deposits and is commonly interbedded with mire, marsh, and flood plain deposits (facies assemblage 1; fig. 6) or open-estuarine deposits (facies assemblage 5).

Lenticular deposits have an overall fining-upward grain size or are heterolithic and consist of cross-stratified sandstone or inclined heterolithic strata. Units are as much as 24 ft thick, but thicknesses typically average 9–12 ft (fig. 6), and individual lenticular deposits are typically less than 300 ft wide. Cross-stratified sandstones contain trough and planar-tabular cross stratification, abundant mud clasts, bone fragments, and bored logs; burrows are locally common. Sigmoidal beds with reactivation surfaces of facies assemblage 4 have also been observed within some deposits. Inclined heterolithic strata (table 3) constitute as much as 11 percent of a stratigraphic section and consist of couplets of sandstone and mudstone (fig. 8) that are commonly separated by straight-crested symmetrical ripples. The sandstone part of the couplets is ripple-laminated, wavy/lenticular bedded, or bioturbated. Some inclined sandstone beds in IHS units can be traced downdip to where they pinch out into mudstone and locally can be traced into a single wavy-bedded bedset. Inclined surfaces dip from 3 to 19 degrees.

Lenticular deposits in the vicinity of the Hunter Canyon/

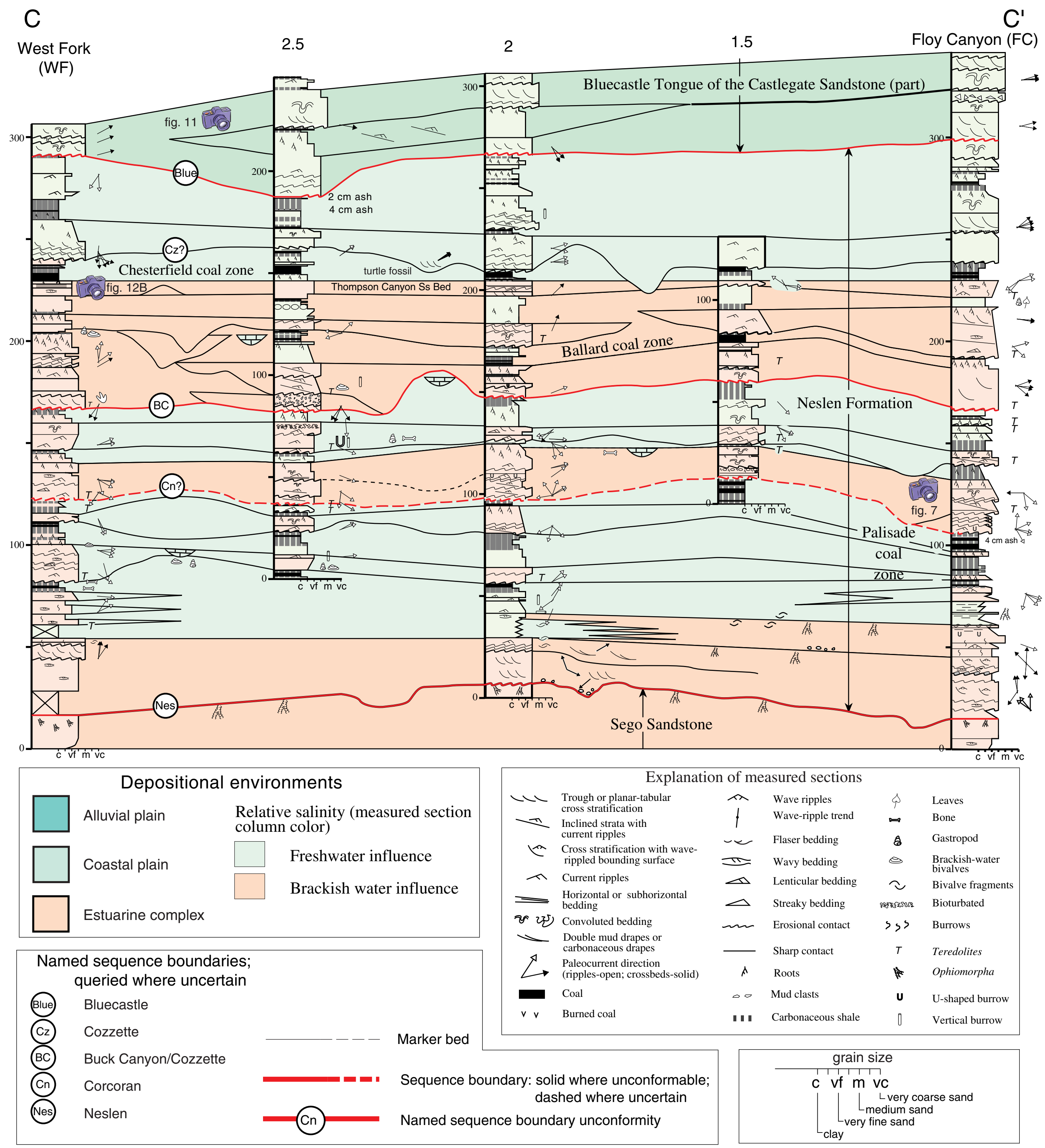


Figure 6. Detailed cross section C–C′ constructed from measured sections in the Floy Canyon area, showing the uppermost Sego Sandstone, Neslen Formation, and lowermost Bluecastle Tongue of the Castlegate Sandstone. See inset in figure 1 for location of sections. Solid correlation lines were walked out between sections; sequence boundaries and other dashed lines are inferred correlations. Relative salinity shown in columns is a subjective determination of whether the rocks were deposited in fresh, brackish, or marine conditions based on lithology, sedimentary structures, and fossils.

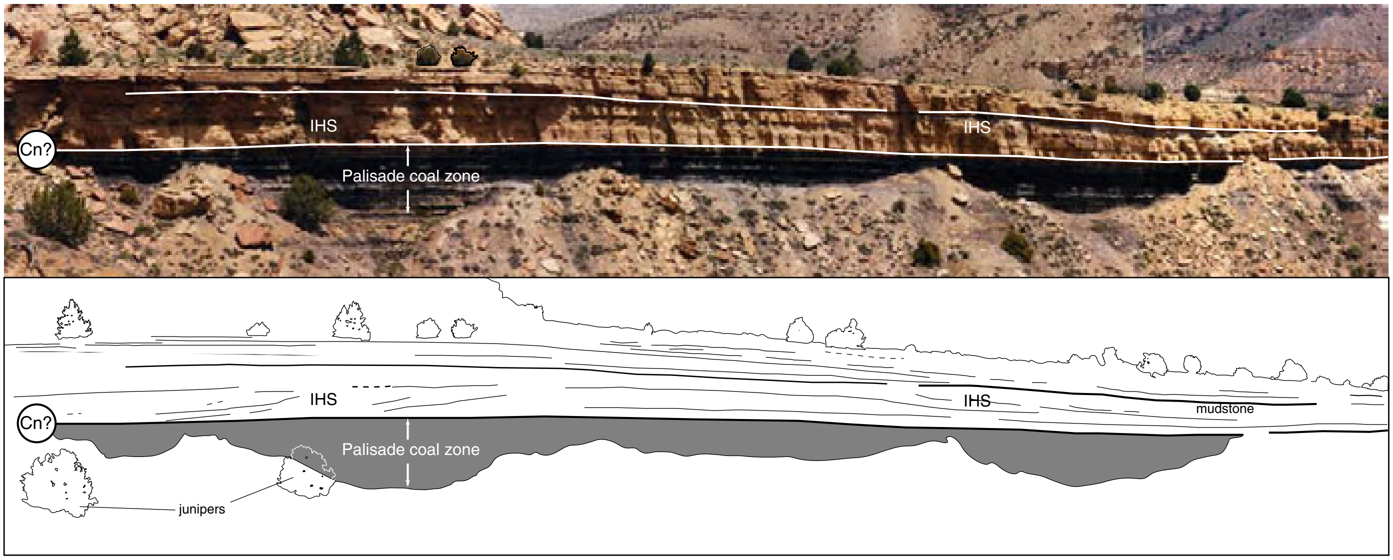


Figure 7. Photo mosaic and line drawing of Floy Canyon exposures showing coal (facies assemblage 1), tabular sandstones, and lenticular inclined heterolithic strata (IHS) (facies assemblage 2) in the lower Neslen Formation at the location of the Floy Canyon measured section. The sandstone is interpreted to be a bayhead deltaic complex that prograded into a peat mire as represented by the Palisade coal zone. Abbreviation: Cn?, uncertain position of Corcoran sequence boundary.

Lipan Wash area are composed mainly of sandstone, but locally they contain inclined heterolithic bedding; the lenses are 1 to 25 ft thick and about 10 to 100 ft wide (fig. 9A and B). Primary sedimentary structures are trough cross stratification and ripples, but many units are completely convoluted. There is evidence of differential compaction of the coal around the lenticular units (fig. 9).

Tabular sandstones are predominantly sharp based and ripple laminated and can have slightly inclined bounding surfaces that separate bedsets. They frequently form the tops of coarsening-upward successions that grade upward from mudrock (facies assemblage 5) or carbonaceous shale (facies assemblage 1)(fig. 7). The coarsening-upward successions are as thick as 15 ft. Other sedimentary structures include symmetrical ripples, horizontal laminations, and graded beds that are composed of ripple-laminated sandstone fining upward to siltstone. Lamination is commonly disrupted by burrows or locally by root traces. Tabular sandstones also grade laterally into low-energy units dominated by mudstones and burrows (facies assemblage 5).

Interpretation

The lenticular deposits in this facies assemblage are interpreted as deposits of fluvial or tidally influenced channels. The tabular sandstones represent overbank, crevasse-splay, and bayhead-delta deposits depending on their size and facies associations. Both the lenticular deposits and tabular sandstones have abundant *Teredolites* and locally an assemblage of trace fossils that includes *Rhizocorallium*, *Teichichnus*, *Bergaueria*, and *Pelecypodichnus* (table 5), indicating brackish-water or even marine salinities.

The tabular nature of the ripple-bedded sandstones indicates deposition by unconfined flows or flow expansion. Coarsening-upward successions capped by the tabular sandstones are interpreted as prograding crevasse splays and bayhead deltas. Low-angle bounding surfaces between the tabular sandstones were created during pauses in sedimentation based on the presence of silt drapes or wave-rippled tops between bedsets.

The lenticular channels show variations in amount of cross stratification, ripple lamination, ratios of sand to mud, and degree of burrowing, depending on their location within the depositional system (fig. 10). High-energy fluvial channels contain abundant cross-stratified sandstone, lag deposits, low amounts of interlaminated mudrock, and sparse burrows. Middle-energy tidally influenced or tidal channels are dominated by ripple-laminated sandstone, inclined heterolithic strata (IHS) (fig. 8), and common burrows. Low-energy tidal channels are heavily burrowed (table 5), but some beds still retain relict IHS and wavy/lenticular bedding.

At some localities, multiple channels are present at the same stratigraphic level and are particularly well exposed within the Anchor coal zone in the Hunter Canyon and Lipan Wash area (fig. 9). There, the channels have variations both in size and types of fill similar to anastomosed river systems described by Kirschbaum and McCabe (1992), some of which were reinterpreted to have a tidal influence (Uličný, 1999).

Inclined heterolithic strata represent lateral accretion of bars within meandering or anastomosed channels. Paleocurrent indicators from current ripples were observed oriented perpendicular, oblique, and rarely parallel (both up and down) to the dip of the IHS. The presence of low-energy bedforms in the bottom of some barforms and mud drapes that extend all

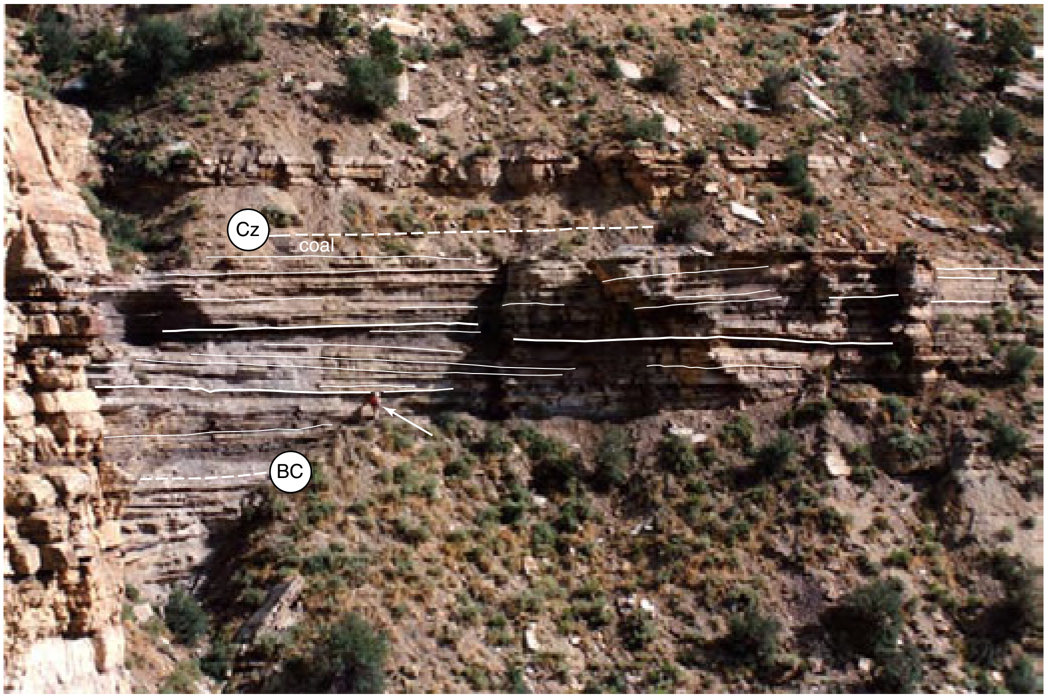
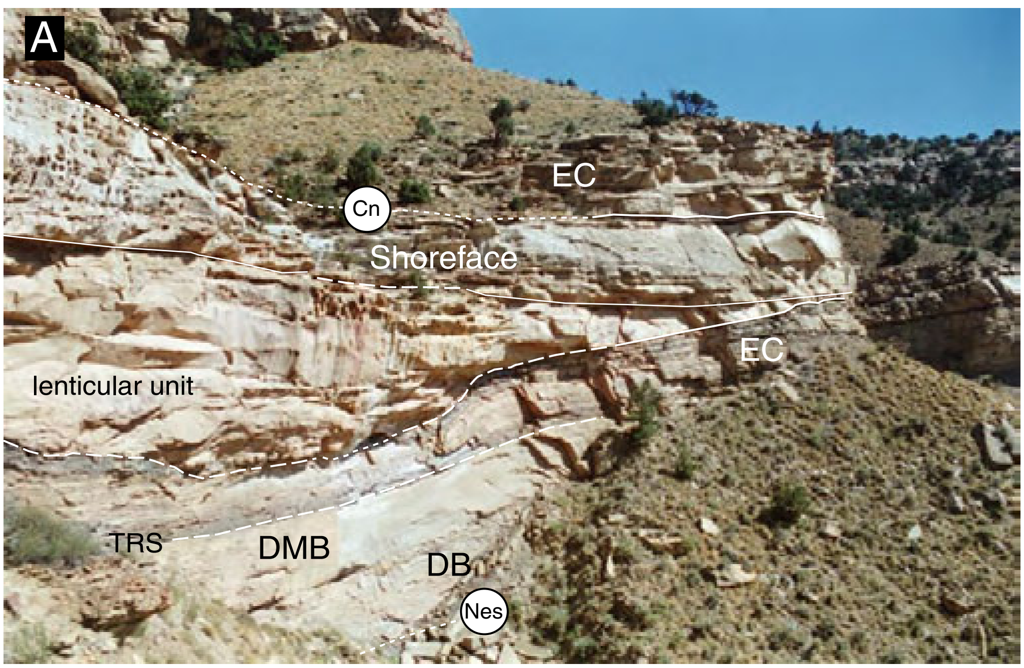


Figure 8. Inclined to planar bedded heterolithic strata at Dry Canyon. The Buck Canyon/lower Cozzette (BC) and upper Cozzette (Cz) sequence boundaries bracket the interval between 185 and 220 ft in the Dry Canyon measured section (pl. 1). Arrow points to person for scale. Inclined heterolithic strata above the person's head dips 8 degrees due west; ripple foresets within the inclined heterolithic strata indicate paleoflow to the southwest.



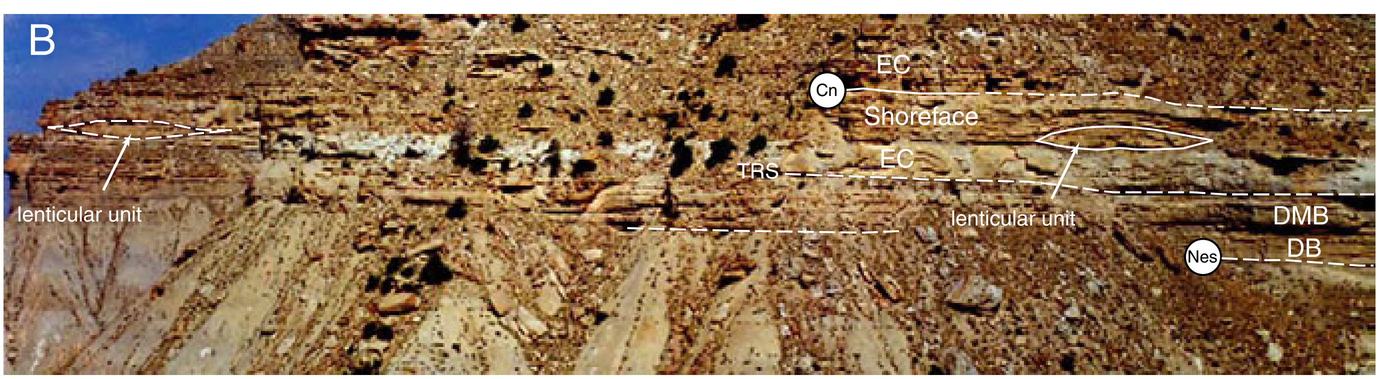


Figure 9. (A) Lenticular units in the Neslen sequence at Lipan Wash (east wall of canyon, halfway between the head and mouth). Lenticular unit is about 25 feet thick. (B) Small lenticular units (about 10 ft thick) in the Neslen sequence near Hunter Point. Abbreviations: DB, distal bar; DMB, distributary-mouth bar; EC, estuarine complex; TRS, tidal ravinement surface; Nes, Neslen sequence boundary; Cn, Corcoran sequence boundary.

the way down the inclined strata indicates migration of sand along the barform at relatively constant flow velocities and deposition of mud during slack water periods, which is consistent with tidal conditions. Some heterolithic deposits also represent abandonment fills (fig. 11) or secondary channels that receive mixed fluvial and tidal influence. Another possibility for interpretation of the IHS deposits is a bayhead delta origin. However, the erosional bases with lags, steep angles to the accretion surfaces (as much 19 degrees), lenticular shape, and fining-upward grain size of most of these deposits favors a channel interpretation over deltaic origin. Amalgamated complexes of this facies assemblage in Floy Canyon (fig. 6) and in the Coal Gulch area (pl. 1, 320- to 420-ft level) are dominated by channels. This is expected because as the fluvial system progrades into an estuary it would cannibalize previously deposited deltaic deposits.

Facies Assemblage 3: Symmetrical and flaser/wavy/lenticular, and ripple-laminated sandstone (wave-dominated sand flat/estuarine shoreface or spit)

Description

This facies assemblage consists of laterally continuous sandstone units (fig. 12A) that can be traced over tens of miles (Fisher, 1936). The sandstones are in the upper part of overall coarsening-upward successions that grade upward from mudrock (fig. 12B). The primary sedimentary structures are symmetrical ripple lamination (fig. 12C) and wavy/lenticular lamination. Trace fossils are common and the sandstones are locally bioturbated. Cross stratification, horizontal lamination, or small-scale hummocky cross stratification is present but rare. The most striking features of the sandstones are the clean well-sorted sand grains; the high quartz percentage (greater than 90 percent) imparts an overall white appearance. The sandstones change facies laterally into carbonaceous mudrock or mudrock and are commonly capped by a thin coal.

Interpretation

The presence of abundant *Teredolites* and burrows, such as *Diplocriterian* and *Arenicolites* (see table 5) indicates brackish-water or marine salinities during deposition of these sandstones. The abundance of wave-generated ripples indicates more wave influence than tidal influence, and this is further supported by the clean, winnowed nature of the sands. Finally, the continuous nature of the sandstones, their association with marsh and bayhead deltaic mudrock, and dominance of wave-generated ripple lamination indicates a low-energy, wave-dominated sand flat, estuarine shoreface, spit, or perhaps reworked bayhead deltas as the depositional environment of these beds (see fig. 10).

Facies Assemblage 4: Compound cross-stratified sandstone (tide-dominated sand flat, tidal delta, and flood and ebb channel)

Description

This facies assemblage consists primarily of stacked sets of cross-stratified sandstone. Cross stratification set boundaries commonly are separated from each other by ripple-laminated sandstone and siltstone or carbonaceous drapes. In some places, ripple-laminated sandstone is separated from the cross-stratified sandstone by paired mud drapes. Also included in this facies assemblage are ripple-laminated and bioturbated sandstone and lenticular and flaser-bedded sandstone. Units are erosionally based, with as much as 15 ft of relief, and their geometries are lenticular or tabular. Trace and invertebrate fossils are common, as are mud chips and intraformational lags.

Table 5. Trace fossils from tidally influenced strata based on observations made in the Floy Canyon area (includes field identifications by George Pemberton and Jason Lavigne).
[IHS, inclined heterolithic strata]

Laminated IHS (facies assemblage 2)	Heavily burrowed IHS (facies assemblage 2)	Laminated continuous sandstone (facies assemblage 3)
Chevronensis	*Chondrites*	*Arenicolites*
Chondrites	*Palaeophycus*	*Diplocriterian*
Horizontal feeding traces	*Planolites*	Horizontal feeding traces
Horizontal U-shaped (pencil- point size)	*Rhizocorallium* (?)	Horizontal U-shaped
Pelecypodichnus	*Teichichnus*	*Skolithos*
Planolites	*Bergaueria*	Syneresis cracks
Syneresis cracks		*Teichichnus (?)*
Teredolites clavatus		

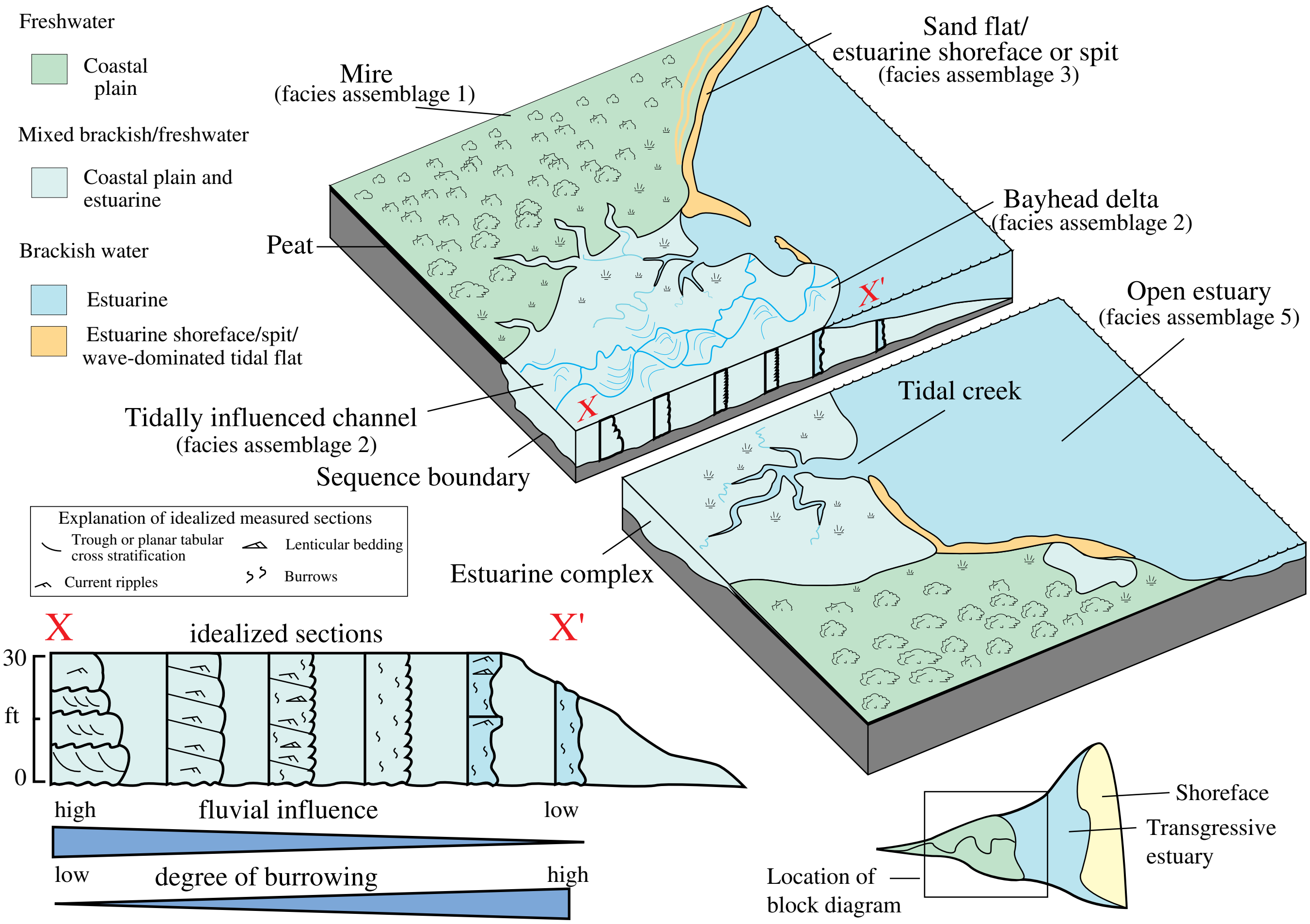


Figure 10. Interpretive block diagram showing facies assemblages related to development of large estuaries formed during maximum flooding of the Buck Canyon/lower Cozzette and Cozzette/Rollins sequences (see pl. 2). Idealized sections are shown along the edge of the block diagram and in detail in inset. See explanation of sedimentary structures and table 5 for typical trace fossils.

Figure 11. Basal Bluecastle Tongue of the Castlegate Sandstone between the West Fork and Canyon 2.5 sections in the Floy Canyon area; strata are dominantly amalgamated trough cross-stratified and convoluted sandstone. Inclined heterolithic strata at right of photograph represent abandoned channel deposits (AC). Most workers interpret a major sequence boundary at the base of this unit (Olsen and others, 1995; Yoshida and others, 1996; and McLaurin and Steel, 2000). Blue, Bluecastle sequence boundary.

Figure 12. (A) Three continuous sandstones of the Thompson Canyon Sandstone Bed of the Neslen Formation (TCSB-bracketed by dashed line) in the Strychnine Wash area (view toward northwest to exposure in NE1/4, SW1/4, sec. 36, T. 19 S., R. 21 E.). Sandstones are each about 5 feet thick. (B) Coarsening upward succession with capping planar bedded sandstone (facies assemblage 3) of Thompson Canyon Sandstone Bed in the West Fork section, Floy Canyon study area. Hammer circled for scale. (C) Tilted block of Thompson Canyon Sandstone Bed in the vicinity of the West Fork section showing the symmetrical wave-generated ripples on the right of the bedding plane; ripples (less than 1 inch in height) are draped by a covering of silt and plant fragments on the left. The Thompson Canyon Sandstone Bed is interpreted as a shoreface, spit, or sand flat within an estuary.

Interpretation

The presence of *Teredolites* and oysters (*Ostrea glabra*, see Fisher and others, 1960) indicates a brackish-water environment for this facies assemblage. *Ophiomorpha* burrows in the lower Neslen Formation and upper Sego Sandstone also indicate some marine influence. This facies is usually found proximal to shoreface deposits and therefore is likely to have been deposited close to open-marine water. Cross-laminated units that separate the cross-stratified sets, reactivation surfaces within the crossbeds, and mud preserved within cross-laminated sets all indicate fluctuating flow velocities that are consistent with tidal currents. Lenticular rippled beds that cap cross-stratified beds and rare double mud drapes within cross stratification indicate a subtidal environment for deposition. Flattened symmetrical wave ripples are indicative of emergence related to deposition within an intertidal zone. Facies assemblage 4 is interpreted to represent ebb and flood channels, tidal bar, and sand flats of open estuaries similar to deposits described for the Rock Springs Formation in Wyoming by Kirschbaum (1989). This facies near the Farmer Mine section may include tidal inlet channels and flood-tidal delta deposits.

Facies Assemblage 5: Mudrock (open estuarine)

Description

This facies assemblage consists of laminated or burrowed mudrock and streaky to lenticular-bedded shale. The facies is gradational with the bayhead delta, tidal channel, and wave-dominated sand-flat facies assemblages (2, 3, and 4), specifically streaky to flaser-bedded sandstones. Plant fragments are common. Rare bivalves including *Corbula* sp. and oysters and abundant, mostly unidentified trace fossils are present, and one limpet was found. This facies is relatively rare in the stratigraphic interval studied, but it is most common in the Cozzette sandstone interval (pl. 1). *Ophiomorpha* is commonly found in the base of sandstones at Farmers Mine.

Interpretation

The locally abundant trace fossils and rarely preserved brackish-water bivalves indicate a brackish-water to marine environment for deposition of this facies assemblage. The predominance of mud indicates quiet water deposition, and the association of the facies with tidal flat and estuarine shoreface/spit indicates an estuarine or lagoonal origin for deposition.

Facies Assemblage 6: Cross-stratified and planar-laminated sandstone (upper shoreface)

Description

This facies assemblage consists of coarsening-upward successions of very fine to medium-grained, well-sorted sandstone (fig. 13). Sedimentary structures include hummocky cross stratification (HCS), swaley cross stratification (SCS), trough or planar tabular cross stratification, or subhorizontal lamination. Gutter casts are common at the bases of many bedsets. Some beds are burrowed or can be completely bioturbated. Swaley cross stratification is volumetrically the most common sedimentary structure, while trough and planar-tabular cross stratification and subhorizontal lamination are minor components. Swaley beds are commonly eroded into, and overlain by, the tidal facies assemblage. This facies has a close association with facies assemblage 7.

Interpretation

This facies succession is interpreted to be upper shoreface deposits based on: (1) its coarsening-upward grain size, (2) an upward increase in flow strength indicated by the sedimentary structures, and (3) the presence of SCS and HCS bedding, which is indicative of storm-generated wave structures typically found in nearshore marine settings (Dott and Bourgeois, 1982; Leckie and Walker, 1982). Trace fossils include *Ophiomorpha* and *Thalassinoides*. Well-sorted trough and planar tabular crossbedded sandstones are interpreted as deposits of the surf zone, possibly longshore bars, and horizontal-laminated sandstones capping the upward-coarsening successions are interpreted as swash-zone deposits.

Facies Assemblage 7: Interbedded sandstones and mudrock (lower shoreface to offshore-marine transition)

Description

Facies assemblage 7 consists of interbedded sandstone and mudrock (fig. 13). Sedimentary structures in the sandstone include symmetrical ripple lamination, wavy, lenticular, and streaky bedding, horizontal lamination, and isolated hummocky cross stratification. These deposits are juxtaposed against, or are laterally gradational into, amalgamated sandstones that have hummocky or swaley cross stratification. Burrows and bioturbation are common within this facies, as are marine ammonites (Gill and Hail, 1975). Not well exposed on outcrop, the best place to observe this facies is in core CA–77–2 (pl. fig. 5.1).

Interpretation

This facies assemblage represents deposition in an area of transition from shoreface to offshore conditions on the presence of marine fossils and trace fossils including *Terebellina*, and its association with hummocky and swaley cross-stratified sandstone interpreted as shoreface deposits. The hummocky cross-stratified beds were deposited between fair weather and storm wave base, and mudrock was mostly deposited out of suspension below storm wave base.

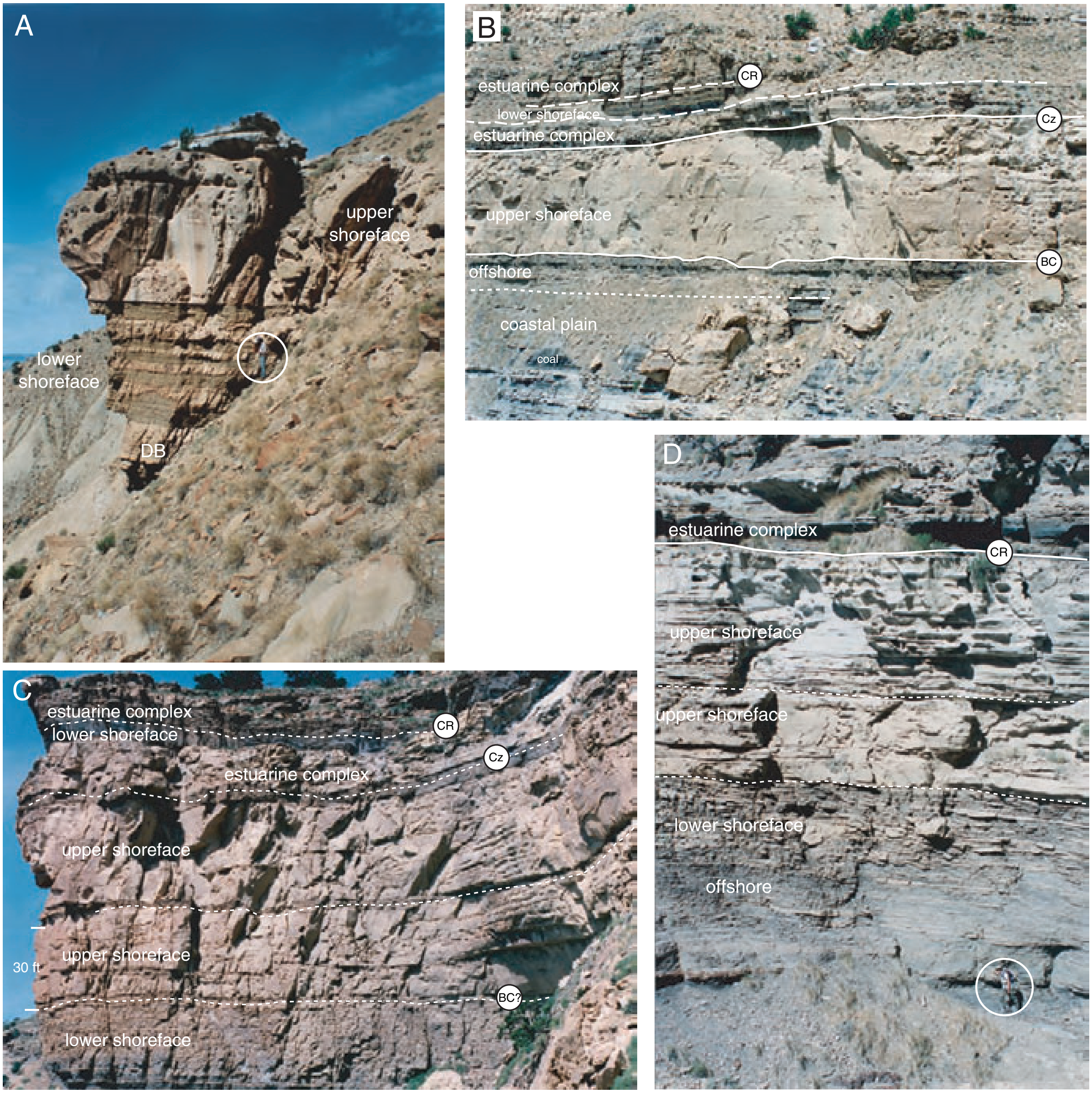


Figure 13. Selected shoreface deposits. Abbreviations: BC, Buck Canyon/lower Cozzette; Cz, upper Cozzette; CR, Cozzette/Rollins. (A) Shoreface parasequence of the Sego Sandstone at the Corcoran 3–W measured section (pl. 1). DB designates distal bar deposits of the Sego Sandstone. Note the isolated gutter casts and thin, hummocky cross-stratified (HCS) sandstones within the lower shoreface unit, and the sharp base to the main, swaley cross-stratified sandstone (SCS; labeled upper shoreface). The uppermost HCS bed was traced to the west where it grades into a sharp-based SCS bed that amalgamates together with the overlying SCS sandstone of this photo. Person circled for scale. (B) Lower sandstone (55 feet thick) of the Cozzette Member of Mount Garfield Formation on the wall opposite where the section was measured at Hunter East (see fig. 4). Note the sharp base and large gutter cast at the base of the sandstone and compare this contact with that of the BC sequence boundary in figure 5. The uppermost Cozzette sandstone is eroded out at this locality and is replaced by estuarine complex strata. (C) Lower Cozzette sandstone just west of the Grasso Mine measured section. Note the gradational lower contact of the unit at the probable BC sequence boundary. (D) Upper Cozzette sandstone at Book Cliffs Mine measured section showing a relatively sharp base to first upper shoreface unit and isolated gutter casts within lower shoreface deposits. Person circled for scale. These lower shoreface deposits are the same as those below the CR sequence boundary in figures 13B and C.

Facies Assemblage 8: Medium- to coarse-grained cross-stratified sandstone (fluvial channel)

Description

This facies assemblage consists of primarily trough and planar-tabular cross-stratified sandstone and minor amounts of ripple-laminated to convoluted sandstone. The deposits generally are present in fining-upward successions, are erosionally based, contain abundant intraformational clasts, and show an upward decrease in the scale of sedimentary structures. The deposits are laterally and vertically amalgamated into a mappable unit, the Bluecastle Tongue of the Castlegate Sandstone (fig. 11). The sandstone is distinctive because it contains the first coarse-grained deposits above the Buck Tongue of the Mancos Shale and is restricted to the western part of the study area.

Interpretation

These strata are interpreted as channel deposits on the basis of their vertical facies pattern, overall upward reduction in flow strength, and multiple erosion surfaces. The absence of burrowing, the lack of *Teredolites* (which is extremely abundant in the Neslen), the coarse-grained nature, and the high-energy, unidirectional flow indicate that these deposits were produced by fluvial rather than tidally influenced processes.

Facies Assemblage 9: Inclined graded beds–horizontally laminated sandstone to siltstone (delta front, distributary mouth bar, distal bar, and prodelta)

Description

This facies assemblage is dominated by low-angle stratified and horizontally laminated, very fine to fine-grained sandstone beds (figs. 14 and 15); it is restricted to Hunter Canyon and adjacent areas. Sandstone beds are generally less than 2 ft thick, have inclinations of less than a few degrees, and can be traced laterally for hundreds of feet in both depositional strike and downdip directions before they pass into burrowed sandstone and shale. The inclined beds are truncated in the updip direction by an overlying erosional surface. Beds are sharp based to erosive, have gutter casts, and may have clay rip-up clasts. Internally, they contain abundant plant fragments or mica on lamina. Laminated sandstones grade upward into symmetrical ripples with interval unidirectional foresets and ultimately grade into siltstone that contains streaky to lenticular sand beds. Varieties of sedimentary structures include trough cross stratification, convoluted bedding, escape structures of organisms, and varying degrees of burrowing from discrete traces to complete bioturbation. Sandstone bedsets are arranged in coarsening- and thickening-upward successions about 10–15 ft thick (fig. 15) that are similar in arrangement to shoreface deposits. Tops of these successions may have hummocky cross stratification.

Interpretation

The coarsening- and thickening-upward nature of the successions indicates an overall upward increase in flow velocities. High flow velocities of the upper flow regime are indicated by the horizontal lamination. Rapid deposition is also indicated by the absence of burrowing in the thicker beds and the presence of escape structures and convoluted bedding. The vertical transition into symmetrical ripples indicates wave reworking of the tops of beds with decreasing flow velocities as indicated by streaky and lenticular sands, and siltstone deposited from suspension. The sharp or erosional base of individual beds, upward decrease in flow velocities, and grading indicate deposition from discrete events, probably storm events. The inclined nature of the beds and decreasing flow strengths both along strike and down depositional dip indicate deposition from a point source in the updip direction. These relationships are consistent with deposition associated with a delta-front environment. The presence of *Ophiomorpha* indicates marine conditions. Coarser and higher energy sandy parts of these deposits are interpreted as distributary mouth bars, heterolithic burrowed parts as distal bars, and siltstone parts as prodelta (fig. 15). Note that in our limited study of the deltaic deposits in Hunter Canyon, no distributary deposits were found associated with this facies because they were removed by erosion associated with a subsequent event.

Lithostratigraphy

The main study interval includes the Neslen Formation and the lower part of the Mount Garfield Formation, which are time-equivalent units that change names at the Utah-Colorado State line. The coal-bearing Neslen Formation and the western part of the Mount Garfield Formation change facies eastward into shoreface sandstones of the Mount Garfield, including the Corcoran, Cozzette, and Rollins Sandstone Members, and marine deposits of the Mancos Shale (fig. 2). The relationship of the Neslen and Mount Garfield with the underlying Sego Sandstone is complex and has been the cause of some confusion and the subject of numerous studies. This section discusses stratigraphic problems of units in the study interval.

Sego Sandstone

The Sego Sandstone is divided into a lower and an upper part, separated by the Anchor Mine Tongue of the Mancos

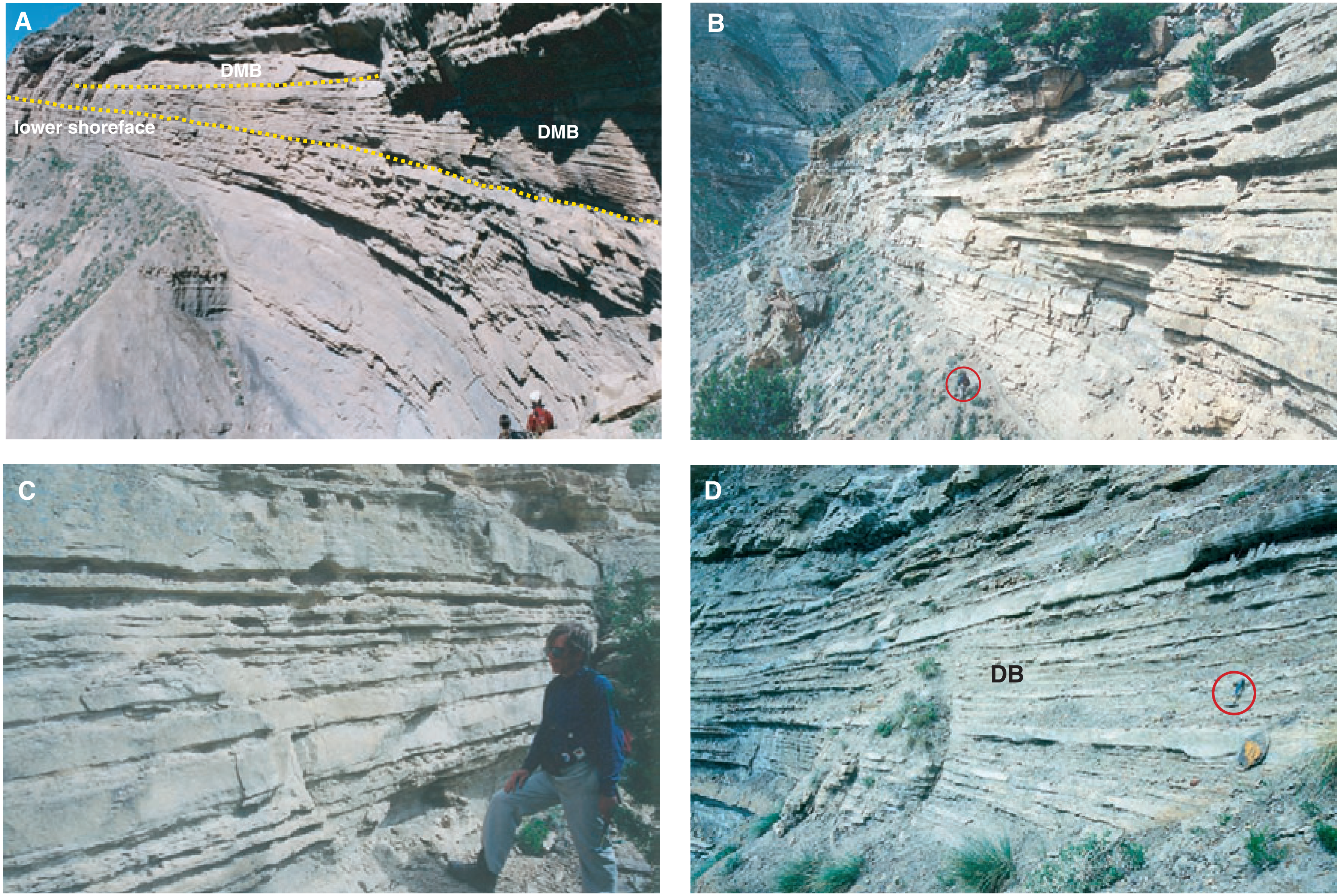


Figure 14. (A) Sego Sandstone at the Hunter Canyon section; located on west wall above the drainage. Sharp contact at lower dashed line records contact between delta front and burrowed hummocky cross-stratified beds interpreted as the Neslen sequence boundary. Persons at lower right for scale. (B) Planar bedded unit on east wall of the first canyon west of Hunter Canyon (just left of photograph A). Person at base of cliff (circled) for scale. (C) A more detailed view of photograph B showing graded beds with horizontal laminated sandstone at base grading up into rippled sands to silt. (D) Closeup view of bedding a few hundred yard northwest of photograph B within distal bar showing increased mud content above sharp-based horizontal-laminated sands. Hammer is circled for scale. Figure abbreviations: DMB, distributary-mouth bar; DB, distal bar.

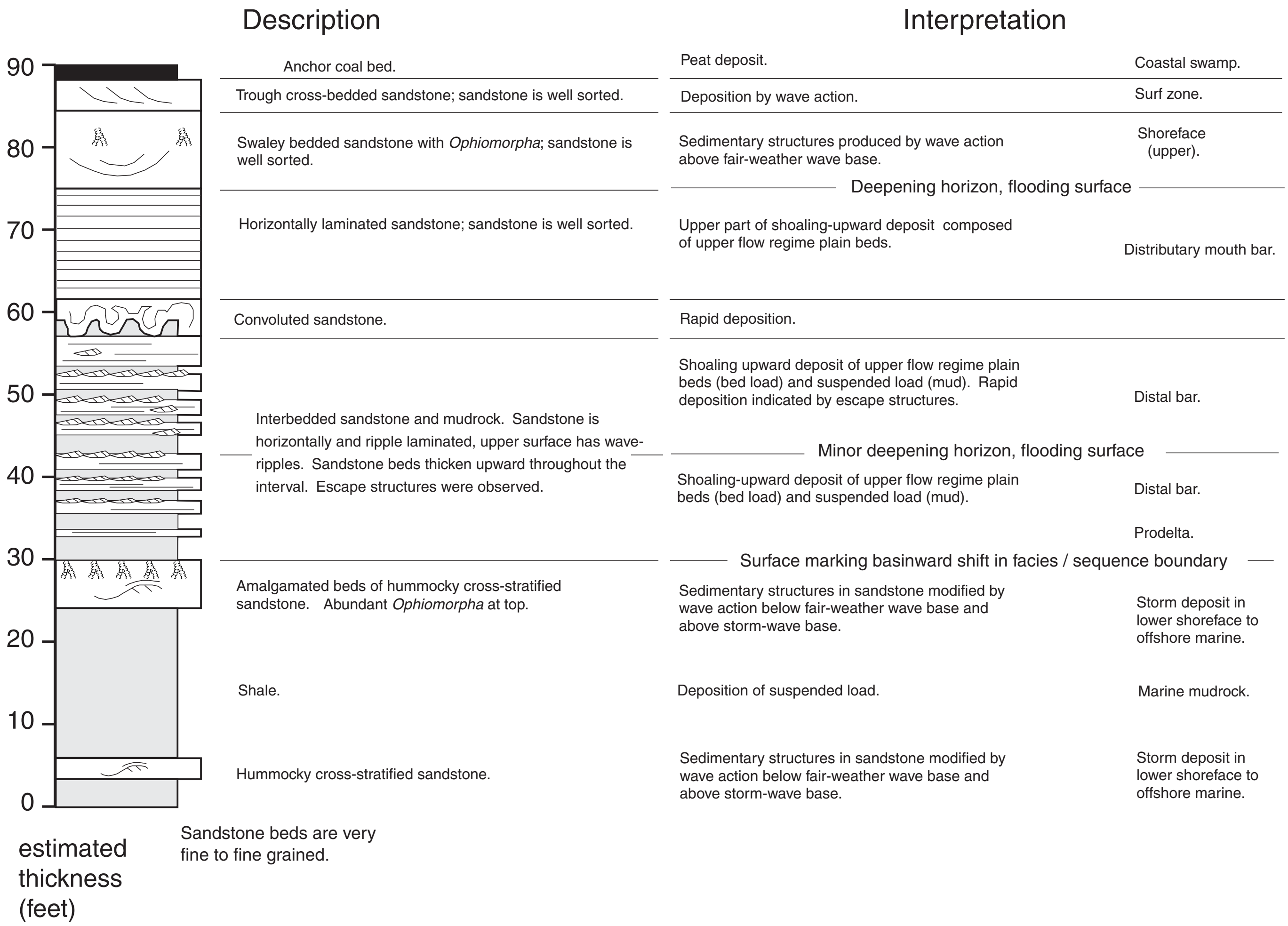


Figure 15. Sketch section of Sego Sandstone 100 yards west of Hunter Canyon measured section (see pl. 1) showing details of deltaic facies (facies assemblage 9).

Shale; the lower and upper parts each contain lower shoreface and nearshore marine strata (Erdmann, 1934; Young, 1955; Gill and Hail, 1975). More recent studies have concluded that the lower and upper parts of the Sego Sandstone also contain multiple high-frequency sequences that include estuarine strata (Van Wagoner and others, 1990; Van Wagoner, 1991) or deposits of tidally dominated deltas (Willis and Gabel, 2001).

There is still some confusion about the maximum seaward (eastward) extent of the upper Sego Sandstone. Erdmann (1934) and Fisher and others (1960) showed the unit extending south of the Colorado River whereas Young (1955, 1983) and Gill and Hail (1975) showed it pinching out near Mount Garfield, a few miles west of the Farmers Mine section (fig. 1). Van Wagoner (1991) considered the upper Sego to be mostly estuarine sandstone and described the estuarine facies as changing eastward into coastal-plain deposits between East Salt Creek to near Coal Gulch. Our study also documents a similar arrangement for an estuarine unit (50-ft level, East Salt Wash section, pl. 1) that pinches out between East Salt Creek and Mack Wash (pl. 1), but it was not physically traced out.

The complex arrangement of shoreface and estuarine deposits at the top of the Mancos Shale in this area makes it difficult (perhaps impossible) to distinguish Sego shoreface sandstones from overlying Corcoran sandstones of the Mount Garfield Formation, especially in the subsurface. Furthermore, the sandstones mapped as Sego by previous workers in exposures north of Fruita and Grand Junction, Colorado, consist of wholly different facies than is described for the Sego in Utah (see delta-front facies assemblage) and perhaps should not be included in the Sego.

Neslen Formation

The Neslen Formation was named for coal-bearing strata above the Sego Sandstone, and where present, below the Bluecastle Tongue of the Castlegate Sandstone (Fisher and others, 1960). Based on our correlations, the Neslen is approximately equivalent to strata of the Mount Garfield Formation that extend upward to at least as high as the lower part of the Cameo coal zone (pl. 2). Based on a review of the work of Fisher (1936), it is apparent that the contact with the Sego Sandstone was placed at the break in slope between cliff-forming sandstone of the Sego and slope-forming sandstone and mudrock of coal-bearing strata of the Neslen. Unfortunately, this is not a good criterion because, unlike other Cretaceous nearshore marine sandstones that show good coarsening upward successions, the Sego consists primarily of estuarine sandstones and heterolithic strata. Tidal deposits of the Neslen can cut many feet into tidal deposits of the Sego (Van Wagoner, 1991) making this contact difficult to determine without detailed studies over the whole of the central Book Cliffs.

Palisade Coal Zone

The Palisade coal zone is the lowest coal zone in the Neslen Formation and was mapped with confidence from the Colorado/Utah State line into the Floy Canyon area by Fisher (1936) but does not correlate to the Palisade coal zone of Erdmann (1934). Rather, the Palisade of Fisher is equivalent to the Anchor coal zone of Erdmann, as pointed out by Young (1955). The Palisade coal zone in the Neslen splits into numerous seams and attains a maximum thickness of about 5 ft (Fisher, 1936).

Ballard Coal Zone

Fisher (1936) named the Ballard coal zone for a persistent zone of coal just below the Thompson Canyon Sandstone Bed. Fisher (1936) originally mapped the Ballard coal zone over a distance of about 15 mi from Floy Canyon to Buck Canyon, and Gualtieri (1991a, 1991b) extended the coal zone an additional 7.5 mi eastward to near the Utah/Colorado State line. The Ballard coal zone is at the same approximate stratigraphic position as the Palisade coal zone of Erdmann (1934) in Colorado but, based on our studies (pl. 1 A–A′; pl. 2, B–B′; see also Hettinger and Kirschbaum, 2002), may be mostly younger than the zone of Erdmann.

Thompson Canyon Sandstone and Sulphur Canyon Sandstone Beds

The Thompson Canyon Sandstone (fig. 12A–C) and Sulphur Canyon Sandstone Beds were named by Fisher (1936) for relatively continuous sandstone beds that can be traced for miles on outcrop and share some distinctive features described in facies assemblage 3. In addition to their continuity, the sandstones are dominated by wavy/lenticular bedding and symmetrical wave ripples (fig. 12C), locally are burrowed to bioturbated including *Ophiomorpha* (see Franczyk, 1989, her pl. 2, Sego Canyon section), and contain hummocky cross stratification at some localities. The most striking feature of the sandstones is the clean, well-sorted quartz sand that makes up the beds. We traced the beds into tidally influenced channel sandstones (Buck Canyon) and carbonaceous shale (fig. 6, between West Fork section and Canyon 2.5 section). We interpret the sandstones as sand-flat and estuarine shoreface deposits that formed marginal to bayhead deltas and channels.

There has been some debate about the continuity and correlation of the Thompson Canyon and Sulphur Canyon Sandstone Beds. Fisher (1936, p. 18) thought that they were two continuous beds equivalent to the Rollins Sandstone Member. Others thought they were the same bed (Gualtieri, 1991a), which would make them continuous for almost 30 mi. Erdmann (1934), however, did not mention the beds. In this study, we were able to correlate the Sulphur Canyon Bed into the Cozzette Member between Dry Canyon and East Salt Creek (pl. 1 A–A′). We did not trace the bed the entire way, so some uncertainty still exists as to the true correlation. It is also apparent that at any one locality, there are several beds that are candidates for the Thompson Canyon Bed; for example, at Strychnine Wash there are three continuous beds that could be candidates (fig. 12A). At Buck Canyon, Fisher (1936) showed the Thompson Canyon Bed pinching out to the east and the Sulphur Canyon Bed pinching out to the west. In our detailed examination of the strata at Buck Canyon (Fisher, 1936, his pl. 7, section 232), we interpreted the Thompson Canyon Bed to be replaced laterally by a 25-ft-thick tidal-channel complex, which we believe represents an estuarine deposit on the basis of its complex fill and continuous nature (fig. 16). The Sulphur Canyon Bed consists of at least four thin, coarsening-upward successions that are capped by a coal. In tracing out the top bed, we also recognized a fifth coarsening-upward succession above the coal, indicating a shingling of the sandstones to the east. The lowest coarsening-upward succession tends to be enclosed in mudrock, indicating a landward shift in facies, whereas the upper several successions appear to be small-scale progradational successions (figs. 16 and 17A). We interpret the successions to be retrogradational and progradational estuarine shoreface/spit or sand flats. Thus, the Thompson Canyon and Sulphur Canyon Beds are probably not the same sandstone—the overall geometry is complex. A detailed study from Cottonwood Wash into Buck Canyon and on to Sulphur Canyon would probably be the best place to develop a better understanding of the internal geometry of these sandstones.

Chesterfield Coal Zone

The Chesterfield coal zone is one of the most extensive coal zones in the Neslen Formation, being traceable for about 75 mi along the Book Cliffs from a few miles east of Tusher Canyon (Fisher, 1936) to near East Salt Creek in Colorado (fig. 1 and pl. 2, B–B′). The zone maintains a fairly consistent thickness of about 9 ft with one or two seams on top of the Thompson Canyon Sandstone Bed in the western part of the study area (fig. 6). However, the Chesterfield becomes a highly diffuse zone with numerous seams in an interval as much as 80 ft thick near Buck Canyon (fig. 1; Fisher, 1936, his pl. 7, sections 232–234).

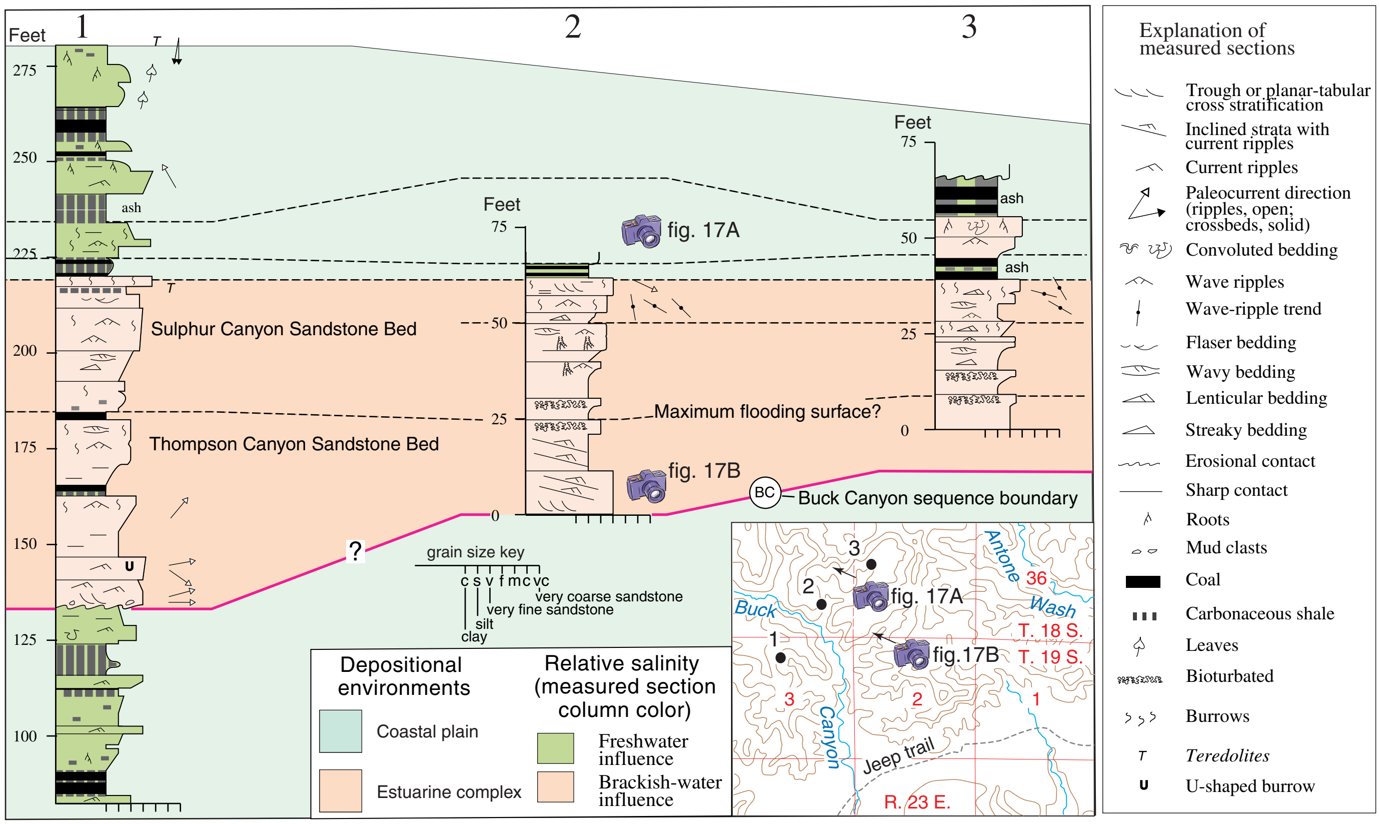


Figure 16. Cross section of measured sections of the Sulphur Canyon Sandstone and Thompson Canyon Sandstone Beds in the Buck Canyon area. Section 1 is expanded version of part of the Buck Canyon section shown on plate 2. Sandstones are topped by coals to the southeast and have bioturbated tops to the northwest, indicating the presence of estuarine flooding surfaces at the top to each succession. Ash indicates position of a thin, kaolinitic altered ash deposit (tonstein). Locations of photographs shown in figure 17 are plotted in section and in inset map.

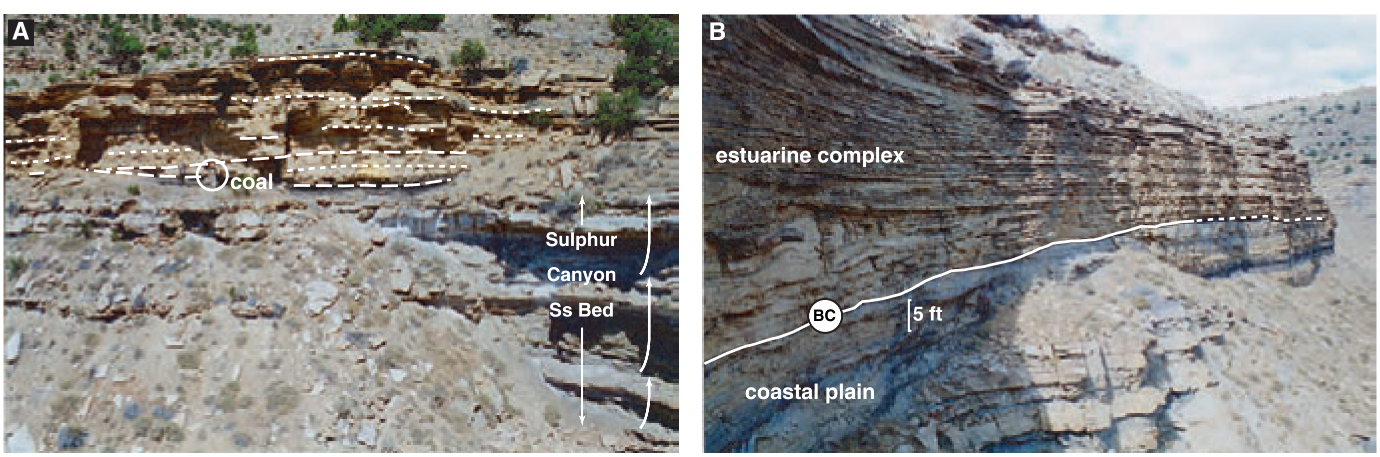


Figure 17. (A) Three coarsening-upward successions (curved arrows) of the Sulphur Canyon Sandstone Bed overlain by a thin coal and heterolithic facies in the area between sections 2 and 3 (see fig. 16). (B) Heterolithic facies of a continuous unit that is extensively exposed in the Buck Canyon area. Contains sigmoidal sandstones and erosion as deep as 6 feet. BC, Buck Canyon/lower Cozzette sequence boundary.

Mount Garfield Formation

Anchor Coal Zone

The Anchor coal zone is the stratigraphically lowest coal zone in the Mount Garfield Formation. As noted by Young (1955), the Anchor is not part of the Mancos Shale as thought by Erdmann (1934) because the coal in question and the underlying carbonaceous shale rest on about 15 ft of wavy/lenticular bedded heterolithic strata and an underlying erosion surface that subtly cuts out HCS beds (fig. 18; also see Erdmann's photograph on his pl. 7B and our Coal Gulch section, pl. 1). The Anchor coal of the eastern study area corresponds to the Palisade coal of the western study area (Erdmann, 1934; Young, 1955).

Corcoran Member

Like the Sego Sandstone, the name Corcoran is somewhat ambiguously applied, and Young (1955) assigned several marine sandstones and associated coal-bearing strata to the Corcoran Member. Young (1955, p. 190) stated that (1) it was named from exposures near the old Corcoran Mine north of Palisade, which Erdmann (1934) had shown to be located in sec. 27, T. 9 S., R. 100 W., and (2) it first appears in Big Salt Wash (between our section at Ruby Lee Reservoir and Coal Gulch, see location fig. 1). We did not find a shoreface sandstone at Big Salt Wash but did describe a continuous fluvial and tidal unit that is most likely Young's Corcoran (see 70- to 140-ft levels in Coal Gulch section pl. 1 A–A′). The lowest prominent white-cap sandstone at Mount Garfield is undoubtedly the Corcoran of Young (see Young 1955, p. 191, discussion of "White Pioneer" sandstone).

Cozzette Member

The Cozzette Member was named for a prominent cliff-forming sandstone and overlying mudstones and interbedded sandstones below the Rollins Sandstone Member at the Cozzette Mine (Young, 1955) (our Grasso section, pl. 1; also see figs. 4 and 13C). Correlation of individual sandstones in the Cozzette is complicated by incision and removal of the sandstone between Book Cliffs Mine and Layton Wash, which has led to various correlation schemes (Gill and Hail, 1975; Young, 1983). Young's correlations are accurate in most respects but do not show the areas of complex scour and fill by tidal deposits.

Rollins Sandstone Member

The Rollins Sandstone Member was named by Lee (1909) for a prominent white sandstone at the top of the Mancos Shale in the Grand Mesa area southeast of Grand Junction. In later mapping, Lee (1912) miscorrelated the sandstone as he traced it westward into the Book Cliffs area; the 100-ft-thick unnamed sandstone at the top of the Bowie Shale Member in Lee's Grand River section is actually the Rollins (Lee, 1912, his fig. 7, p. 79; see Erdmann, 1934, his pl. 4). We traced the Rollins into Layton Wash where it is replaced by sandstones of estuarine origin (pl. 1). The Rollins is generally discussed in conjunction with the overlying Cameo coal zone, and they are thought to be genetically related. The strong forward-stepping architecture and lack of major pauses or backsteps in the Rollins support that interpretation. However, the Rollins has been eroded and replaced by estuarine deposits at several localities (pl. 1; Lee, 1912, his pl. 5B), and it has been replaced by a series of continuous sandstones (facies assemblage 3) and thin coals west of Lipan Wash. Both the erosion and estuarine fill indicate that part of the Rollins and the Cameo might have been deposited in separate sequences (see sequence stratigraphic interpretation of Rollins).

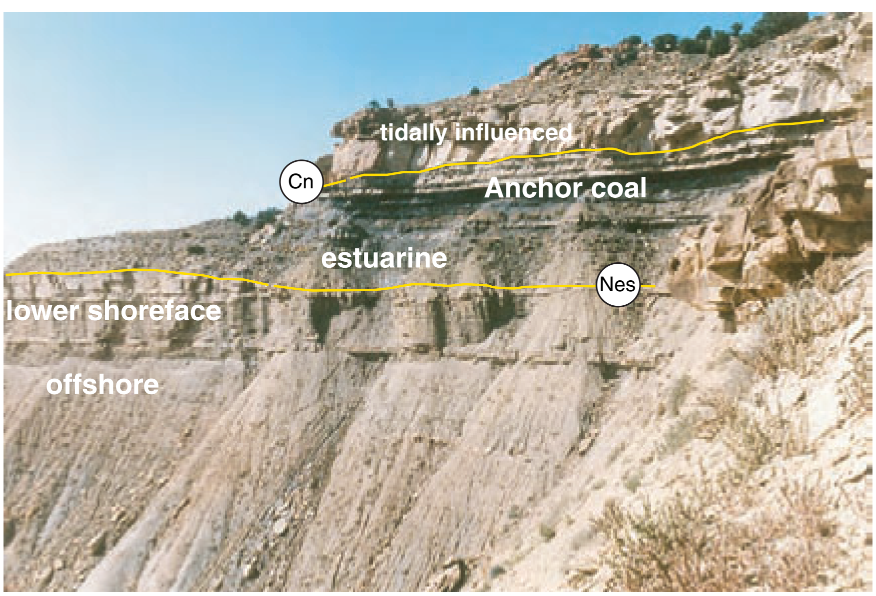


Figure 18. Lower shoreface facies cut out locally by overlying Neslen sequence boundary (Nes) in the Coal Gulch measured section (pl. 1). Prominent shadow under higher sandstone is the Anchor coal bed as defined by Erdmann (1934) and is the exposure where he showed the Anchor coal bed in the Mancos Shale (shown by him from a distance on his plate 7B). Corcoran sequence boundary (Cn) overlying the Anchor coal is the base of a valley-fill succession, which consists of convoluted sandstone with large and abundant *Teredolites* at the base. Laterally to the north (fig. 23) the fill is thicker with fluvial deposits at the base (pl. 1, A–A′). Location of the outcrop is in the NW1/4, NE1/4, sec. 24, T. 8 S., R. 102 W.

Sequence Stratigraphy

We interpret six stratigraphic sequences bounded by high-resolution sequence boundaries within the stratigraphic interval that includes the upper Sego Sandstone, Neslen Formation, Bluecastle Tongue of the Castlegate Sandstone, and the correlative basal 500–600 ft of the Mount Garfield Formation. In this report, we also discuss the possibility of additional high-resolution sequences in the Corcoran and Rollins Members. Recognition of these sequences, systems tracts, and their bounding unconformities is based on concepts shown in figure 19 and on the following observations: (1) regional truncation of strata, (2) basinward shifts in facies over erosion surfaces (fig. 20A), (3) recognition of downlap in subsurface well-log cross sections (fig. 20A), and (4) analysis of shoreface trajectories (fig. 20B). The sequences are named after major lithologic units discussed in the preceding section. In ascending order the sequences are (1) upper Sego sequence (uS), (2) Neslen sequence (Nes), (3) Corcoran sequence (Cn, Cn1, Cn2), (4) Buck Canyon/Cozzette sequence (BC), (5) Cozzette sequence (Cz), and (6) Cozzette/Rollins sequence (CR). Another sequence boundary, the Bluecastle (Blue) is named separately for the Bluecastle Tongue because of uncertainties in correlations with sequence boundaries identified in the eastern part of the study area. Systems tracts are defined on the basis of recognition of the sequence boundary, major and maximum flooding surfaces, and parasequence stacking patterns (figs. 19 and 20A and B). Interpretations of sequences and systems tracts are shown in figure 20C.

Definitions and Usage

Sequence stratigraphic usage generally follows that summarized by Van Wagoner and others (1990), Posamentier and Allen (1999), and Mitchum (1977). A sequence is a relatively conformable succession of genetically related strata bounded by unconformities or by their correlative conformities (Mitchum, 1977). The sequences are divided into lowstand, transgressive, highstand, and forced-regressive system tracts (fig. 19). The lowstand systems tract (LST) consists of strata deposited between the sequence boundary (SB) and the transgressive surface or first significant flooding surface (or the surface of maximum regression following Helland-Hansen and Gjelberg, 1994). The transgressive systems tract (TST) consists of strata deposited between the transgressive surface and the maximum flooding surface (MFS). The highstand systems tract (HST) is deposited between the maximum flooding surface and the next higher sequence boundary. The forced-regressive systems tract is identified where shoreface parasequences have a strongly progradational nature with an apparent falling trajectory and no associated coastal-plain deposits.

The designation of the first significant flooding surface is highly interpretive and problematic because of not knowing the seaward extent of erosion and sediment bypass within the basin. For example, major drops in relative sea level may have caused erosion and bypass across the Mancos Shale, with deposition of lowstand sandstones eastward of the study area. For this reason, we have attempted to identify the surface of maximum regression, following Helland-Hansen and Gjelberg (1994), as representing the change from the lowstand systems tract to transgressive systems tract (fig. 19).

Of considerable concern in our study was the difficulty in differentiating between highstand and lowstand systems tracts, especially with respect to any possible forced-regressive deposits in the successions. Forced regression is the process of shoreline progradation that is related directly to falling relative sea level (Posamentier and Morris, 2000). Forced-regressive deposits can be attached to, or detached from, shoreface or delta-front deposits of the highstand systems tract (Posamentier and Morris, 2000). However, it is difficult to distinguish forced-regressive deposits from other deposits in field and subsurface studies, especially those of the highstand systems tract, because (1) both systems tracts show overall a progradational stacking pattern (fig. 19), and (2) their interpretation relies on understanding the regional context in which these stacking patterns were deposited. In overall progradational successions (offlap), it is also difficult in some cases to identify the SB because of subsequent erosional modification by tidal and wave processes. It is not surprising, therefore, that there is much debate on what constitutes a forced-regressive deposit, and on where forced-regressive deposits lie within the hierarchy of sequence stratigraphy.

Posamentier and Morris (2000) developed seven criteria for the recognition of forced-regressive deposits, four of which are characteristic of some deposits of the Neslen and Mount Garfield Formations. These criteria include (1) significant downdip separation between successive episodes of shoreface progradation, (2) presence of sharp-based shoreface/delta-front deposits, (3) regression of the shoreface over a long distance, and (4) the absence of fluvial and(or) coastal-plain deposits capping the proximal parts of regressive deposits. Deposits with these characteristics are placed within a falling-stage systems tract by Plint and Nummendal (2000), a forced-regressive wedge systems tract by Mellere and Steel (1995), and an early lowstand systems tract by Posamentier and Allen (1999) (fig. 19). In this report, observations indicate the difficulty in differentiating forced-regressive deposits from the late highstand deposits because those transitions were available for study mainly in the subsurface; where exposed on outcrop, they tend to be eroded by the overlying fluvial regressive surface of erosion (that is, sequence boundary) or are modified by tidal or wave ravinement.

Accommodation Space Relative to Sediment Supply

A further criterion for the interpretation of systems tracts can be found in the stacking patterns of parasequences and parasequence sets (fig. 19). The interplay between accommodation space and sediment supply will result in distinct

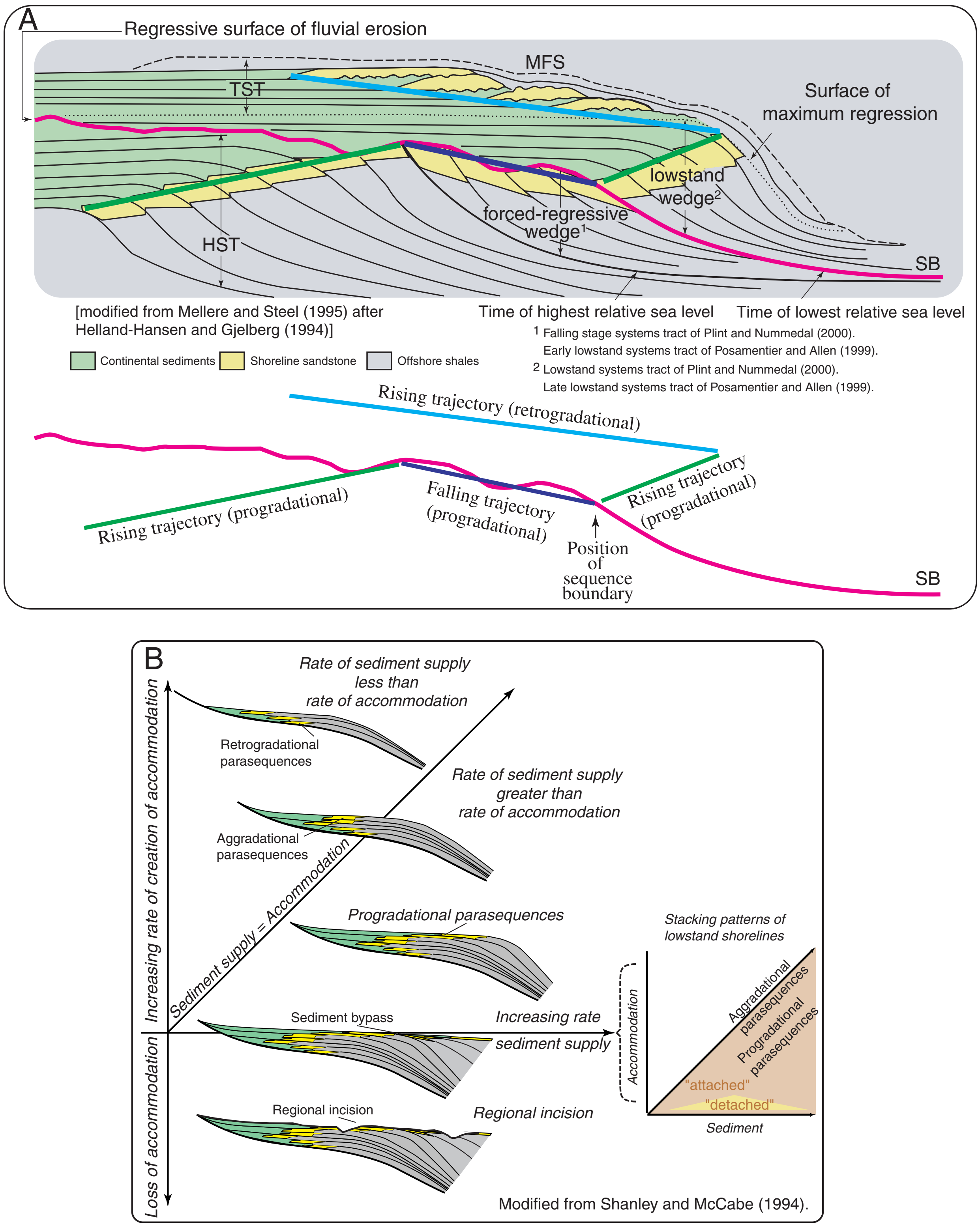


Figure 19. (A) Stacking patterns of shoreface parasequences and their relation to systems tracts, shoreline trajectory, and important sequence stratigraphic surfaces. Also shows the relative amounts of coastal-plain deposits preserved in relation to shoreface stacking patterns. Notice in this example that no coastal-plain deposits were preserved during deposition of the forced-regressive wedge. Abbreviations: SB, sequence boundary; TST, transgressive systems tract; HST, highstand systems tract; MFS, maximum flooding surface. (B) Stacking patterns of coastal-plain deposits, shoreface parasequences, and offshore deposits in relation to sediment supply and generation of accommodation space. Inset shows the stacking patterns of lowstand shorelines that are down depositional dip from incision points where accommodation is negative.

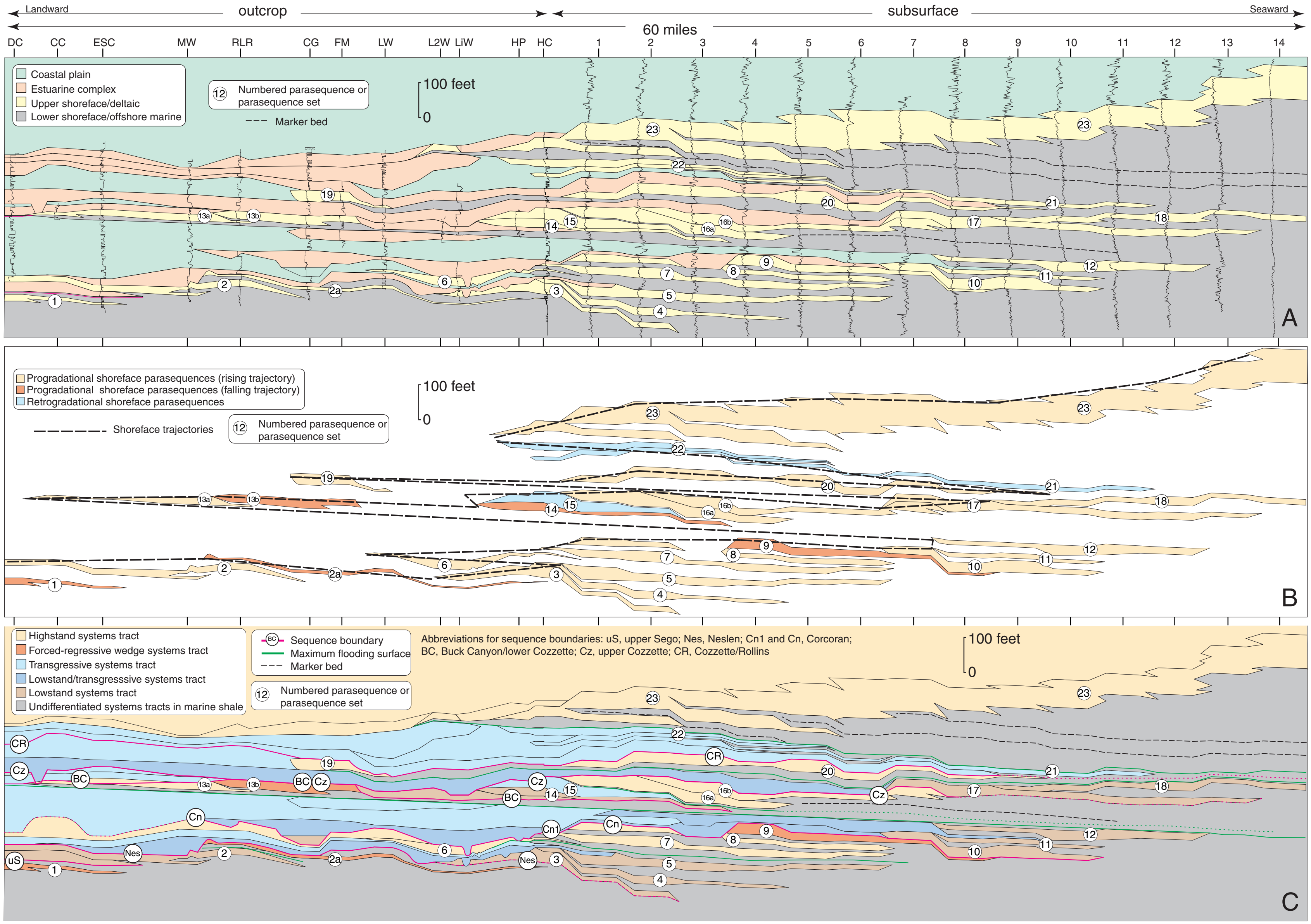


Figure 20. Interpretive diagrams of the study interval constructed from part of plate 1 and from plate 3 (location of individual sections shown in fig. 1). The diagrams are provided in a larger format and with a more detailed explanation on plate 7. The maximum flooding surface of the Corcoran sequence is used as an inclined datum. The cross section is oriented approximately parallel to depositional dip. (A) Lithostratigraphic units and numbered interpreted shoreface units (parasequences or parasequence sets). Gamma-ray logs are provided for the subsurface sections; grain-size profiles mimic gamma-ray logs for the outcrop sections; (B) stacking patterns of shoreface parasequences based on shoreline trajectory; (C) interpreted systems tracts and sequence boundaries.

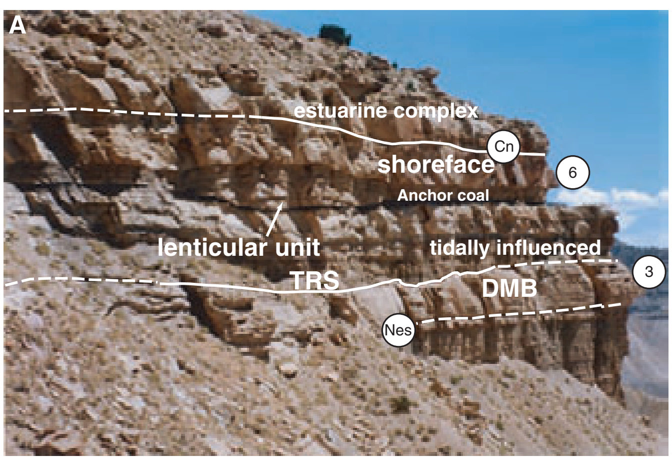
shoreface stacking patterns, depending on which component is dominant (fig. 19B). When there is an overall loss of accommodation space, sediment bypass and regional incision will take place. The sediment is transported across the erosional surface and deposited farther down depositional dip where accommodation space is available in the marine basin. Lowstand shorelines develop where subaqueous accommodation begins, and the resulting parasequences can exhibit progradational or aggradational stacking patterns, depending on the interplay of accommodation space and sediment supply (fig. 19B).

Stacking patterns of parasequences and parasequence sets in the Sego, Neslen, and Mount Garfield Formations are shown along a 60-mi-long transect (fig. 20) that was constructed from outcrop and subsurface sections selected from plates 1 and 3. Shoreface successions and their interpreted systems tracts are shown in figure 20C in order to emphasize relative positions of shoreface pinch-outs as well as stratigraphic rise and fall. Stratigraphic rise and fall are depicted by dashed lines (fig. 20B) that connect landward positions of shoreface pinch-outs and depict the overall shoreline trajectory. An idealized relation between shoreface trajectory and system tracts is shown in figure 19A, which is based on concepts described by Helland-Hansen and Gjelberg (1994). Figure 20B was then used as a model to test our systems-tract interpretations. Note however, that the method is to some extent compromised because the cross section has not been decompacted, and some landward pinch-out points are erosional (for example, see fig. 21B and C, unit 6).

Upper Sego Sequence

Sequence Boundary (uS)

Definition of the upper Sego Sandstone sequence boundary is based almost entirely on the work of Van Wagoner (1991, his figs. 3 and 4), and the present study supports those interpretations. He traced an erosion surface from Sulphur Canyon eastward 27 mi to near the Colorado border (fig. 1). Major facies dislocations of tidal deposits over lower shoreface or offshore strata are observed along this erosion surface (fig. 22A and B). Our San Arroyo Canyon section (pl. 2) was measured at the same locality as the Lion Bench section of Van Wagoner (1991, his fig. 3, number 24). At the San Arroyo Canyon section (pl. 2), burrowed and trough cross-stratified sandstone (probable facies assemblage 4) overlie swaley cross-stratified sandstone of upper shoreface origin (facies assemblage 6). The erosion surface is interpreted as far east as



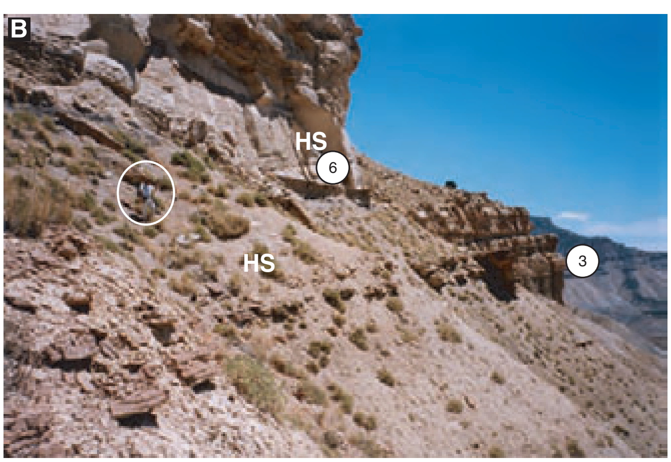


Figure 21. (A) Area west of Hunter Point measured section. Sego Sandstone (unit 3, circled number; see fig. 20A) and Corcoran Member of the Mount Garfield Formation (unit 6, circled number). Abbreviations: DMB, distributary-mouth bar; TRS, tidal ravinement surface. (B) Overview of strata 300 feet west of figure 21A showing both the Sego and Corcoran sandstones cut out and replaced by heterolithic strata (HS). Person (circled) for scale. (C) Closeup of erosional pinch-out of the Corcoran sandstone also shown in figure 21B. Persons (circled) for scale.

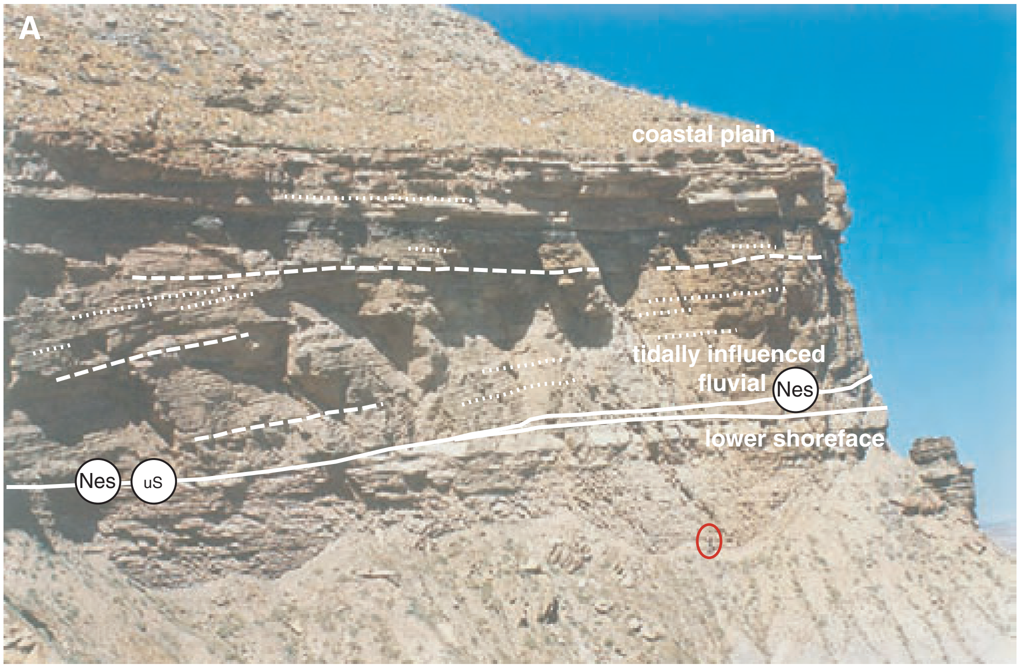
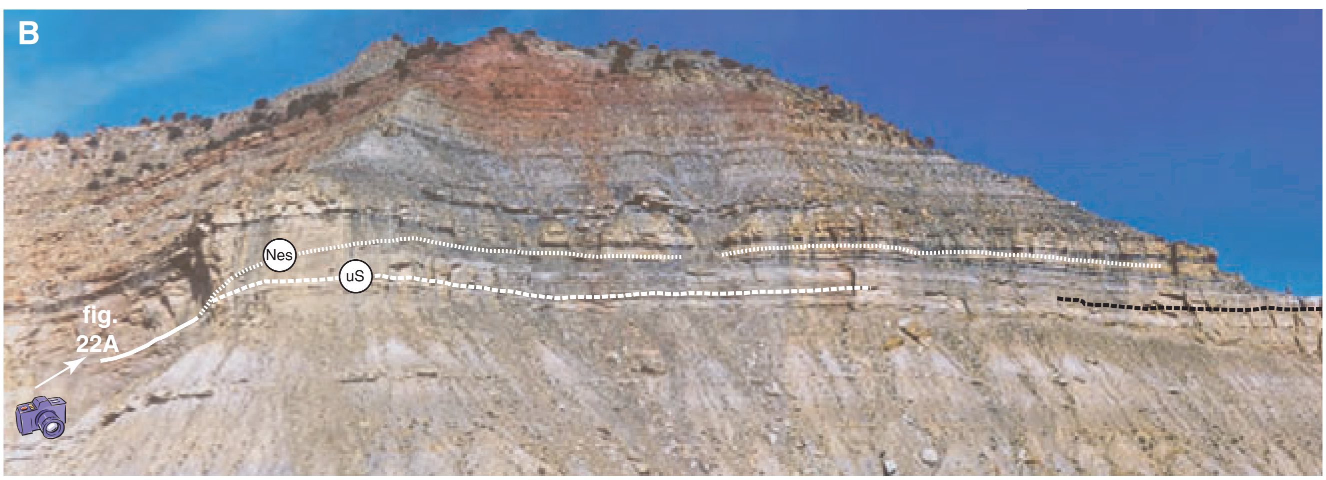


Figure 22. (A) Coastal-plain and estuarine complex (inclined heterolithic) strata above the Neslen sequence boundary (Nes) overlying lower shoreface deposits of the Sego Sandstone near Sulphur Canyon (NE1/4, sec. 19, T. 18 S., R. 24 E.). Prominent sandstone within the lower shoreface facies is 6 feet thick. Person (circled) for scale. (B) Eastward continuation of figure 22A. The Neslen erosion surface cuts abruptly to the west through the entire Sego section. The Sego sequence boundary (uS) is SB-8 of Van Wagoner (1991).



the East Salt Creek section (pl. 1, A–A′, near the 45-ft level) where there is a facies dislocation between estuarine complex deposits (facies assemblage 4) and lower shoreface deposits (facies assemblage 7).

Maximum Flooding Surface

Two flooding surfaces are present in the upper Sego sequence. The oldest is at East Salt Creek where a noticeable burrowed horizon is at the top of a cross-stratified sandstone that lies at the sequence boundary (pl. 1; fig. 20). The burrowed horizon is at the 60-ft level, within a thin, wavy-bedded unit that contains traces of *Ophiomorpha*, *Thalassinoides*, *Teichichnus*, *Scolithus*, and *Chondrites*. The second flooding surface is above lower shoreface sandstones in the Ruby Lee Reservoir section at about the 78-ft level. The youngest flooding surface exhibits a pronounced deepening of facies and is probably the best candidate for the MFS.

Systems Tracts

Van Wagoner (1991) interpreted deposits above the erosional surface within the Sego as estuarine valley fill and placed them within a lowstand systems tract. He showed burrowed and sigmoidal crossbedding to be common in the rocks overlying this erosion surface (Van Wagoner and others, 1990, their fig. 30; Van Wagoner, 1991, his figs. 3 and 4). Because these deposits are well beneath the maximum flooding surface, we also consider part of the fill to be within the lowstand systems tract. One shoreface parasequence is present above the tidal deposits (fig. 20, unit 2). The sandstone consists of SCS and trough cross-stratified sandstone of upper shoreface origin (facies assemblage 6). The arrangement of tidal and shoreface facies over offshore deposits is similar to those described by Mellere and Steel (1995) for their prograding lowstand wedge, and we place this unit within the lowstand systems tract.

The only remnant of the Sego strata preserved above the MFS in the study area is unit 2a (pl. 1, 90-ft level, Ruby Lee Reservoir; figs. 20A and B). We did not walk out units 2 or 2a to the east, but they were correlated by Young (1955, 1983). He showed a forward-stepping succession of littoral or delta-front sandstones (units 2–5) as far east as the Book Cliffs Mine area (fig. 1 and pl. 1, A–A′). Gill and Hail (1975) showed one continuous sandstone in the Sego that terminated at a similar seaward location, and they collected the ammonite *Baculites scotti* within the sandstone at several localities. We interpret unit 2a to be the remnant of a forced-regressive wedge, based on the downward trajectory of unit 2a with respect to unit 3 (figs. 20B and C), which were subsequently eroded by the overlying sequence boundary. The lack of coastal-plain deposits being associated with this fall indicates a loss of accommodation space in more landward localities, which is also indicative of a forced-regressive wedge systems tract.

Neslen Sequence

Sequence Boundary (Nes)

A major erosion surface is found within or at the top of the Sego Sandstone. Van Wagoner (1991, his figs. 3 and 4) interpreted and named the erosional surface the Neslen sequence boundary in the Sulphur Canyon area (fig. 22). His evidence for the boundary was based mainly on detailed work on the underlying Sego Sandstone. Young (1983) previously noted a surface of erosion within the Sego in western Colorado, interpreting the overlying deposits as distributary channels. Elsewhere in outcrops north of Grand Junction, Colo., the sequence boundary is recognized by a major facies dislocation where Erdmann (1934; his pl. 7B and pl. 4, section 8) mapped the Anchor coal zone within the Mancos Shale (fig. 18). Van Wagoner (1991) reinterpreted this facies dislocation to represent one of the most pronounced sequence boundaries within upper Campanian strata. He correlated the surface below the Anchor coal to the major surface at Sulphur Canyon and named this the Neslen sequence boundary. Our observations support this interpretation of a sequence boundary with minor modifications.

The erosion surface marking the Neslen sequence boundary is generally about 10–35 ft below the Anchor coal zone in the eastern part of the study area (pl. 1) and about 15–45 ft below the Palisade coal zone where traced for several miles in the Floy Canyon area (figs. 1, 6). The erosion surface has as much as 50 ft of relief in the Mack Wash area (pl. 1), and it completely cuts through tidal and shoreface deposits in the underlying Sego Sandstone in the Sulphur Canyon area (figs. 1, 22A and B; Van Wagoner, 1991). Evidence for the sequence boundary is most striking where tidally influenced deposits overlie offshore marine deposits. An example of this major facies dislocation is shown at the Layton Wash section (32-ft level) on plate 1. Elsewhere, facies dislocations are more frequently represented by the juxtaposition of tidally influenced strata (facies assemblages 2 and 4) over hummocky or swaley cross-stratified upper shoreface strata (facies assemblage 6) as shown at the East Salt Creek (80-ft level, pl. 1, A–A′) or at the Ruby Lee Reservoir section (92-ft level). At Coal Gulch and other localities, it is difficult to distinguish offshore heterolithic strata (facies assemblage 7) from tidally influenced heterolithic deposits (facies assemblage 2) unless HCS beds or an erosion surface is observed (fig. 18). The presence of a distinct erosion surface and *Teredolites* may be the only evidence of a major facies dislocation in some areas. This difficulty in distinguishing between tidal and offshore facies apparently led Erdmann (1934, his pl. 7B and pl. 4, section 8) to place the Anchor Mine coal within the Mancos Shale. The sequence boundary is increasingly difficult to trace eastwards of Lipan Wash (see discussion of lowstand systems tract below).

Maximum Flooding Surface

The maximum flooding surface in the Neslen sequence is defined at a high gamma zone a few feet above the top of the Sego Sandstone (pls. 3 and 4). On outcrop, the maximum flooding surface is interpreted to be represented by a concretion zone and lag deposit of shells and shark teeth as seen at the 185-ft level at the Hunter Canyon section (pl. 1). The maximum flooding surface is thought to extend to the ravinement surface between shoreface and coastal-plain deposits at the 45-ft level in the Lipan Wash section (pl. 1).

Lowstand Systems Tract

The stratigraphic position of the Neslen sequence boundary is problematic at seaward localities east of the Lipan Wash section. For example, the observed relations were initially interpreted to indicate that the sequence boundary overlies units 3, 4, and 5 (fig. 20). In these areas, the Hunter Canyon delta (unit 3) and the shoreface parasequences of units 4 and 5 (fig. 20) are scoured and locally removed by erosion, and the overlying fill is complex, consisting of sandstones in the form of ribbon bodies and IHS (figs. 9A and 21A). However, the rising shoreface trajectory of units 3, 4, and 5 contrasts markedly with slight down-stepping stacking pattern and falling shoreface trajectory described for unit 2a in the underlying upper Sego sequence. The change from stratigraphic fall in unit 2a to stratigraphic rise in units 3–5 is interpreted to reflect a change from a falling relative sea level to a subsequent rising relative sea level. We interpret, therefore, that unit 3 was sourced from the incision created during a falling stage in relative sea level, and units 4 and 5 were deposited during the subsequent rise in sea level that followed the turnaround of the base-level cycle. In this interpretation, the sequence boundary is placed conformably below unit

3, and the erosion surface above units 3–5 is interpreted to represent tidal ravinement (pl. 1). Units 3–5 are therefore placed within the lowstand systems tract.

Transgressive Systems Tract

The Neslen sequence boundary is overlain by tidally influenced or tidal channel deposits (facies assemblages 2 and 4) as described from East Salt Creek eastward for 18 mi to near the Corcoran 3 west section (pl. 1). The tidal deposits are overlain by coastal-plain strata (facies assemblage 1) that contain the Anchor coal zone in Colorado (fig. 18) and Palisade coal zone in Utah. The Anchor coal zone is divided by a thin shoreface sandstone (55-ft level at the Layton Wash section on pl. 1) that pinches out just west of Layton Wash, which represents the maximum marine transgression. We interpret the coastal-plain strata below the MFS to be within the transgressive systems tract of the Neslen sequence. A shell lag (85-ft level at Corcoran 3-W on pl. 1) observed locally at the top of the shoreface sandstone is interpreted to be the ravinement lag. The lag is overlain by a thin, coarsening-upward succession that represents a distal back-stepping parasequence. Near Lipan Wash there are numerous small lenticular sandstone bodies containing HCS preserved in the top of the coal zone. The lenticular bodies resemble gutter casts but are most likely related to differential compaction of storm beds on the depositional topography at the top of the coal mire following ravinement. These lenticular bodies are interpreted to represent preserved remnants of the back-stepping parasequences related to this sequence.

Highstand and Forced-Regressive Wedge Systems Tracts

Above the maximum flooding surface are four progradational units (units 6–9 in fig. 20A) that represent the highstand and forced-regressive wedge systems tract of the Neslen sequence. The highstand systems tract consists of thin carbonaceous shale and coal of coastal plain origin (facies assemblage 1) at landward localities west of Layton Wash. Shoreface deposits of the landwardmost parasequence (unit 6 in fig. 20) pinch out within the Anchor Mine coal zone near Layton Wash. The highstand systems tract is about 130 ft thick at the Book Cliffs Mine section (pl. 1), and the seawardmost shoreface pinch-out (unit 9 in fig. 20) is in the subsurface between drill holes 8 and 9 (pl. 3; fig. 20). The upper boundary of the highstand systems tract is a fairly substantial erosion surface that scours and cuts through all four parasequences (pl. 1; fig. 20). The erosion surface was traced into the subsurface, where it is interpreted to extend conformably under the base of unit 10 as shown in fig. 20C. The progradational character and rising trajectory of units 6–8 are interpreted to represent the highstand systems tract, and the slightly falling trajectory of unit 9 is interpreted to represent a forced-regressive wedge systems tract (fig. 20B and C).

Corcoran Sequence

Sequence Boundary (Cn, Cn1, and Cn2)

There are two major discontinuous erosion surfaces within the Corcoran Member that are candidates for sequence boundaries. They may represent two separate sequence boundaries, but not enough data were collected to adequately separate systems tracts. Without further evidence, we consider the two erosion surfaces as representing one stepped sequence boundary punctuated by a relative fall in sea level.

The lowest erosion surface (Cn) is represented by a widespread scour surface that cuts through all of the shoreface parasequences in the underlying Neslen sequence. The sequence boundary is most easily recognized where tidal deposits (facies assemblage 4) and localized fluvial strata (facies assemblage 2) overlie an erosion surface between the Ruby Lee Reservoir and Grasso Mine sections, a distance of 16 mi (pl. 1). The tidal deposits overlie coal-bearing coastal-plain strata in landward areas (see 70-ft level at Coal Gulch) and shoreface strata in seaward areas (see 150-ft level at Corcoran 3–W (fig. 1; pl. 1). The most prominent incision is between Lipan Wash and Hunter Point where erosion has locally removed the entire highstand systems tract of the Neslen sequence (pl. 1; figs. 21C and 23). The sequence boundary interpretation was based on its erosional extent, relief, and the basinward shift of tidal facies over lower shoreface mudrock in seaward areas.

The Cn erosion surface is difficult to trace where it extends into poorly exposed coastal-plain strata west of the Ruby Lee Reservoir section. In these landward areas, the sequence boundary is interpreted to be where organic-rich, freshwater coastal-plain deposits (facies assemblage 1) are overlain locally by tidally influenced strata characterized by lenticular and flaser bedding, possible double mud drapes, and *Planolites*, *Thalassinoides*, and *Ophiomorpha*, for example, at the East Salt Wash section (above the 135-ft level, pl. 1), Dry Canyon section (50-ft level, pl. 1), or in more landward section by bayhead delta deposits (110-ft level at the Floy Canyon section, figs. 6 and 7).

The Cn sequence boundary is also difficult to trace in the vicinity of the Grasso Mine section where it appears to be a correlative conformity (Cn1 on pl. 1) at the base of the Palisade coal zone (see 183-ft and 258-ft levels at Grasso Mine and Book Cliffs Mine sections, respectively; pl. 1). The interpretation is complicated by the presence of a second erosion surface (Cn2) that was traced intermittently between the Corcoran 3–W section and Mount Garfield.

Erosion surface Cn2 overlies the basal coal of the Palisade zone (pl. 1) between the Grasso Mine and Book Cliffs Mine sections, and it is well exposed just west of the Book Cliffs Mine section (fig. 24). This surface might represent a second sequence boundary (labeled Cn2 on pl. 1), or it may be a composite surface that merges with Cn1 in a landward

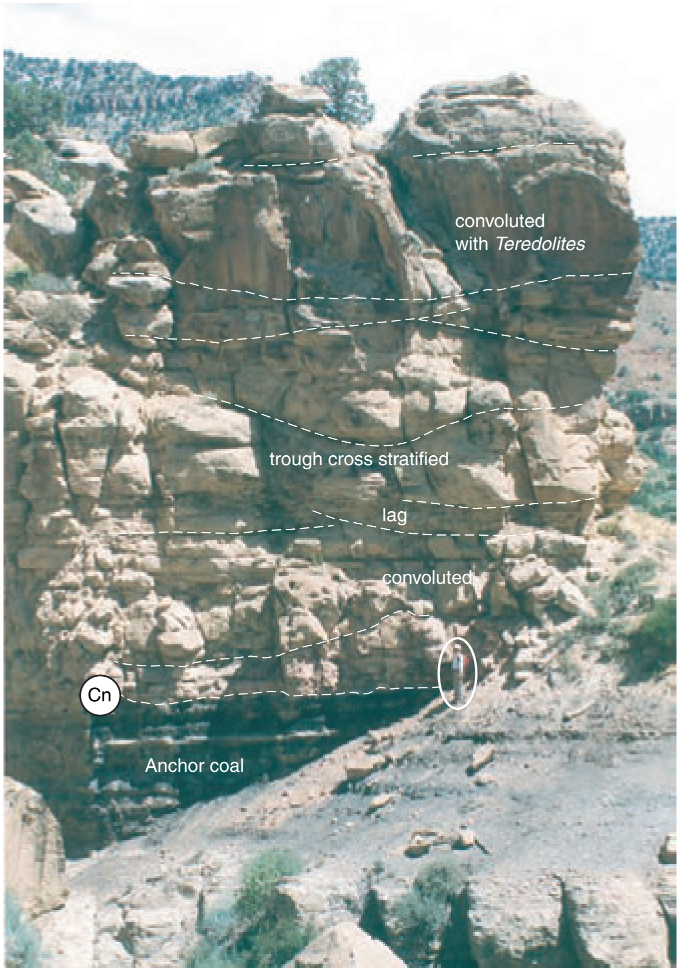


Figure 23. Amalgamated sandstone bodies above the Anchor coal zone in the Coal Gulch area interpreted to be a valley-fill deposit (location NW1/4, sec. 18, T. 8 S., R. 101 W.). The sandstone bodies consist of intraformational lags, convoluted bedding, and trough cross-stratification. The upper part contains abundant *Teredolites*. The sandstone is continuous over several square miles along both depositional dip and strike. The sandstone is also shown in figure 18, at a locality where it is thinner and contains abundant *Teredolites*. Cn, Corcoran sequence boundary.

or seaward direction that we did not recognize in the field. In either case, these relations indicate that a pause in erosion at the Cn1 surface was followed by a relative rise in sea level and deposition of coastal-plain deposits seen at the Book Cliffs section (257- to 283-ft level on pl. 1). These events were then followed by a subsequent fall in relative sea level and renewed downcutting that created the Cn2 erosion surface. The Cn2 erosion surface may become the main erosion surface east of the Book Cliffs Mine section (pl. 1) or could become conformable beneath shoreface deposits of unit 10, 11, or 12 in the eastern part of the study area (fig. 20C).

In the subsurface, the Corcoran sequence boundary (Cn) was interpreted where irregular signatures were recorded above well-defined coarsening-upward signatures on gamma-ray logs. The surface was also recognized at a depth of 1,330 ft in the CA–77–2 core (pl. 5, pl. fig. 5.1) where clay clasts separate a fairly clean burrowed sandstone containing *Ophiomorpha* and *Palaeophycus* from overlying inclined heterolithic sandstone and mudstone. The downward trajectory of the shorelines between units 9 and 10 (figs. 20B and C) is interpreted to represent initiation of a period of erosion and development of the sequence boundary in more landward areas.

Maximum Flooding Surface

The only widespread flooding surface of the Corcoran sequence is in an extensive thin tongue of Mancos Shale (facies assemblage 7) that separates the Corcoran Member from the overlying Cozzette Member (pls. 1–6, fig. 20). The maximum flooding surface is nearly coincident with a major ravinement surface that extends across a thin, hummocky cross-stratified sandstone observed in most outcrop sections (for example, see 270-ft level in the East Salt Creek section). The landwardmost expression of the surface is at the 185-ft level in the Dry Canyon section (pl. 1) where a burrowed horizon containing *Ophiomorpha* overlies well-sorted sandstone. This maximum flooding surface was extensively walked out, and its approximate location was traced on photos (figs. 4 and 5) from the Book Cliffs Mine section to the Dry Creek section (pl. 1). In the subsurface, the maximum flooding surface is interpreted on well logs where a high gamma zone lies within the thin tongue of Mancos Shale (see 5,960-ft level in drill hole 13, pl. 3).

Lowstand and Transgressive Systems Tract

Above the main sequence boundary (Cn) are fluvial and tidal facies interpreted to be valley-fill deposits (figs. 18 and 23). The tidal deposits are interpreted in core (pl. 5 and pl. fig. 5.2; well no. 18, 3,132-ft level), can be traced on geophysical logs, and are interpreted as equivalent to unit 10 (fig. 20). The change in shoreline trajectory from generally downward to upward between deposition of units 9 and 10 indicates the location of the sequence boundary, which corresponds to the time of lowest relative sea level. The surface of maximum regression is at the top of unit 12, and first significant marine flooding is above the coastal-plain deposits, thus placing the landward-equivalent fluvial and tidal deposits and some of the coastal-plain deposits into a LST, for example between the 73- to145-ft level in the Coal Gulch section; pl. 1, fig. 23) (assuming there are no detached lowstands eastward of the study area). The maximum flooding surface is above the parasequence (unit 12, fig. 20C) and thus places some of the more landward coastal-plain deposits into a transgressive systems tract, for example above the 145-ft level at Coal Gulch (pl. 1).

The transgressive systems tract of the Corcoran sequence consists of rocks deposited in fluvial, coastal-plain, estuarine complex, and shoreface environments. Amalgamated chan-

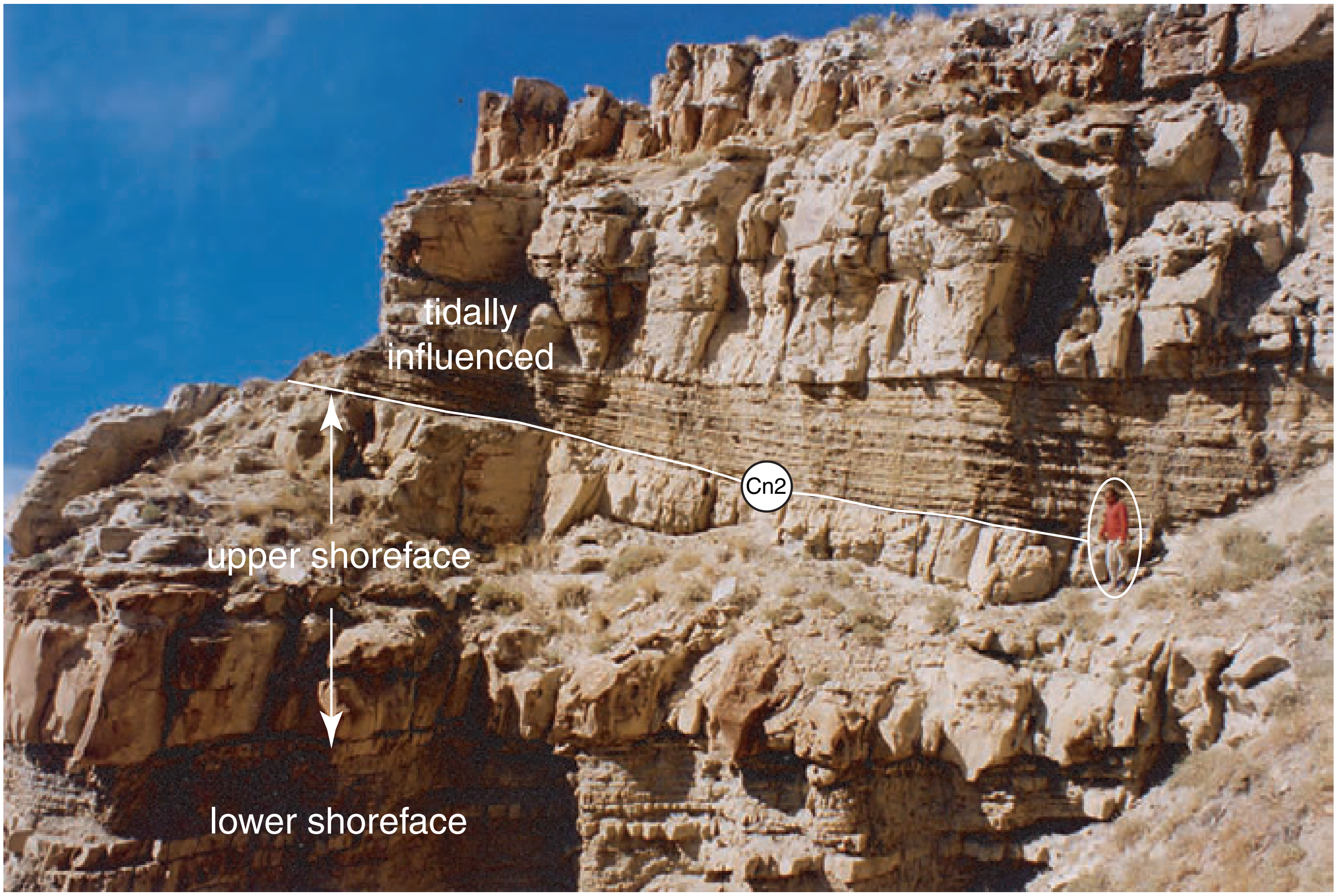


Figure 24. Exposure of sandstone of the Corcoran Member of the Mount Garfield Formation in the Book Cliffs Mine area. Corcoran 2 erosion surface (Cn2) cuts into trough and swaley cross-stratified upper shoreface deposits. The surface is overlain by inclined heterolithic strata. *Teredolites* commonly lies directly above the surface. Person (circled) for scale.

nel deposits consisting of cross-stratified sandstone (facies assemblages 2 and 4) and wavy to lenticular sandstone (facies assemblage 2) overlie the Corcoran sequence boundary between the Mack Wash and Grasso Mine sections (pl. 1); these strata have a maximum thickness of 72 ft at the Coal Gulch section (pl. 1, 73- to 145-ft-level Coal Gulch section; fig. 23). Trough cross-stratified (facies assemblage 2) channel deposits in the basal part of the systems tract (see 70- to 105-ft level in the Coal Gulch section, pl. 1) are interpreted to be fluvial, based on unidirectional paleocurrent, lack of tidal indicators, and lack of trace fossils. These strata may have been deposited, in part, during the lowstand of relative sea level. The upper parts of the channels have westerly (landward) paleocurrents and *Teredolites* that indicate a tidal influence.

Westward, the upper part of the transgressive systems consists of about 30–80 ft of coastal-plain strata (facies 1 and 2) that includes the Palisade coal zone. These strata lie between the amalgamated channels and the first marine flooding surface and extend eastward over two aggradationally stacked shoreface sandstones (units 10 and 11, fig. 20) (see pls. 3 and 4; fig. 20). The seaward pinch-out of the coastal-plain deposits is near drill hole 9 (pl. 3). The coal zone contains a tidal complex that is channeled into the top of a prograding parasequence set just west of Book Cliffs Mine (pl. 1; fig. 24). The estuarine complex consists of heterolithic strata and cross-stratified sandstone of facies assemblage 2 and contains abundant *Teredolites* (fig. 24). This tidal unit is also well exposed in the cliffs between Book Cliffs Mine and Mount Garfield. The tidal influence and depth of scour indicates another possible sequence boundary at the Cn2 erosion surface as discussed previously.

Highstand and Forced-Regressive Wedge Systems Tract

The highstand systems tract of the Corcoran sequence overlies the maximum flooding surface and is represented by a 5- to 18-ft-thick tongue of the Mancos Shale and by at least two progradational parasequences as thick as 28 ft that are exposed between Camp Creek and just west of Layton Wash (pl. 1; units 13a and b, fig. 20). From Layton Wash eastward, the entire shoreface succession is truncated by the basal sequence boundary of the Buck Canyon/lower Cozzette sequence. Because of this severe truncation, it is difficult to estimate the landward pinch-outs of parasequences; however, our best estimate is that 13a has a slightly rising trajectory typical of a highstand systems tract and 13b has a slightly falling trajectory representing a forced-regressive wedge systems tract (see figs. 19 and 20B–C).

Buck Canyon/Lower Cozzette Sequence

Sequence Boundary (BC)

The lower part of the Cozzette Member is erosionally to sharply based in areas just west of the Layton Wash section to just east of the Hunter Canyon section (fig. 13B), a distance of 7 mi (pl. 1). This surface was studied in outcrops that were walked out between Lipan and Layton Wash and most of the way to Hunter Canyon (see fig. 5). In this area, basal strata in the Cozzette Member are interpreted as tidal deposits based on the presence of *Teredolites* and compound cross-stratified sandstone (facies assemblage 4). The sharp juxtaposition of tidal deposits over marine mudrock of the Mancos Shale tongue is interpreted to represent a major facies dislocation and sequence-boundary unconformity. These deposits are similar to those described by Mellere and Steel (1995) as representing a prograding lowstand wedge. The sequence boundary is interpreted as a relative conformity where it passes below swaley bedded shoreface strata containing large gutter casts (fig. 13B) east of Hunter Canyon (fig. 20A, unit 14).

Both the stratigraphic position and existence of the BC sequence boundary were difficult to ascertain in the steep and rugged terrain between the Layton Wash and Ruby Lee Reservoir sections (pl. 1), a distance of about 5 mi. In that area, the BC sequence boundary is indistinguishable with the basal unconformity of the overlying sequence. The merged sequence boundaries have scoured into shoreface sandstone (unit 13b, fig. 20) in the underlying Corcoran sequence between the Layton Wash and Ruby Lee Reservoir sections. West of Ruby Lee Reservoir, the sequence boundaries diverge and the BC sequence boundary cuts through unit 13a across a distance of 7 mi to near the Dry Canyon section (pl. 1). At Dry Canyon, unit 13a has been eroded and completely replaced by cross-stratified sandstones and inclined heterolithic strata.

The extension of the BC sequence boundary for a distance of 65 mi along depositional strike from Camp Creek and Dry Canyon southwest to Floy Canyon (pl. 2) was based on our correlation of facies into the Buck Canyon area, mainly using the Sulphur Canyon and Thompson Canyon beds and the Chesterfield coal zone as markers. There is about 10–15 ft of erosional relief at Camp Creek (pl. 1) and as much as 12 ft of relief at San Arroyo Canyon (pl. 2). Regional downcutting along the sequence boundary is estimated to be a maximum of about 70 ft as determined from cross section B–B′ (pl. 2).

Maximum Flooding Surface

Three flooding surfaces were considered to be candidates for the maximum flooding surface of the lower Cozzette sequence: (1) the stratigraphically lowest coincides with the ravinement surface at the 310-ft level in the Hunter Canyon section, (2) the marine flooding surface is at the 300-ft-level in the Grasso Mine section, and (3) the highest marine flooding surface is just above a prominent burrowed horizon (*Diplocriterian*) at the 340-ft level in the Grasso Mine section. The stratigraphically highest flooding surface was chosen as the maximum flooding surface because it overlies a retrogradational parasequence (fig. 20, unit 15) between the 305- to 362-ft level in the Book Cliffs Mine section (pl. 1).

Along depositional strike (as shown on cross section B–B′ on pl. 2), the maximum flooding surface is represented by an estuarine flooding surface. The surface is interpreted to be at about the 220-ft level in the Floy Canyon section, but a clear distinction cannot be made from the data collected (pl. 2 and fig. 6). A rise in relative sea level is inferred to have caused extensive flooding of the coastal plain, which created a large estuary that was initially filled with heterolithic deposits (facies assemblage 3; see 130- to 165-ft level Buck Canyon, pl. 2; fig. 17B) or complex cross stratification (facies assemblage 4; see 200-ft level, San Arroyo Canyon section, pl. 2; or 300-ft level, Hunter Canyon, pl. 1).

Systems Tracts

In the depositional dip section (pl. 1), a thin estuarine sandstone above the BC sequence boundary is onlapped by an aggradational parasequence (unit 14, fig. 20), which is in turn overlain by a subtle retrogradational parasequence (unit 15, fig. 20) of the lower Cozzette sandstone (compare 300-ft level in Grasso Mine section to 350-ft level in Book Cliffs Mine section). These two parasequences are truncated by the overlying sequence boundary. On the depositional strike section (pl. 2), the BC sequence boundary is overlain by estuarine deposits consisting of inclined heterolithic strata (facies assemblage 2), sigmoidal beds (facies assemblage 4), wavy/lenticular bedding (facies assemblage 3), and coastal-plain deposits consisting of coal and carbonaceous shale (facies assemblage 1). In the Buck Canyon area, a unit of heterolithic strata (facies assemblage 2) with sigmoidal bedding (facies assemblage 4) is located about 5–10 ft below the Sulphur Canyon Sandstone Bed (fig. 17B) and is traceable for several miles. This heterolithic unit, informally called the Buck Canyon unit, overlies a basal scour with at least 6 ft of relief (fig. 17B). This extensive tidal deposit overlies coastal-plain deposits, indicating that deposition took place during a rise in relative sea level and that its deposition is associated with the aggradational to retrogradational arrangement of the lower Cozzette parasequences (units 14 and 15, fig. 20) observed in the Hunter Canyon area (see also pl. 1, Grasso Mine section, 300-ft level, and Book Cliffs Mine section, 350-ft level).

On the depositional-dip outcrop section (pl. 1), a progradational shoreface parasequence set is observed at the 375-ft level in the Book Cliffs Mine section (unit 16a in fig. 20). The lower Cozzette parasequences can be traced from outcrop into the subsurface, and their overall geometry changes from being (1) strongly progradational with a low shoreline trajectory (unit 16a), (2) slightly progradational with a falling trajectory (unit 16b), and (3) slightly progradational with a rising trajectory (units 17 and 18, fig. 20). The strongly progradational portion of unit 16a represents part of a highstand systems tract. Even though unit 16b appears to have overall falling trajectory, it is hard to correlate and is likely to be more complex than shown in figure 20B. The thick offshore marine succession associated with unit 16b (fig. 20) indicates an overall progradational succession, and we interpret the unit as a parasequence set also within the highstand systems tract. Unit 17 is sharp based, appears to truncate marker beds (pl. 3), and is interpreted to be within the lowstand systems tract of the next highest sequence.

Recognition of highstand deposits in more landward sections is more problematic and is dependent on where one places the maximum flooding surface. A large estuary formed during transgression. Bayhead deltas were deposited into the estuary, became reworked into tidal flats, and subsequently prograded into and filled the estuary. The estuarine sandstones were walked out in the Buck Canyon area (pl. 2; fig. 16) and were observed to shingle in a progradational stacking pattern from west to east. These shingled estuarine sandstones are interpreted as the early highstand systems tract of this sequence.

Upper Cozzette Sequence

Sequence Boundary (Cz)

The best evidence for a sequence boundary above the lower Cozzette parasequences is observed where trough cross-stratified sandstone is in erosional contact with underlying thin, hummocky cross-stratified beds at the 350-ft level of the Grasso Mine section and about the 70-ft level in the Adobe Wash section (pl. 1). The cross-bedded strata are interpreted as estuarine deposits (facies assemblage 4) on the basis of reactivation surfaces, multidirectional paleocurrents, and *Teredolites*. The juxtaposition of estuarine strata over lower shoreface HCS beds represents a basinward shift in facies along the basal sequence boundary of the upper Cozzette sequence. This erosional surface extends at least 12 mi from the Book Cliffs Mine section westward to the Lipan Wash area where it scours as much as 50 ft into shoreface parasequences (units 14–16) in the underlying sequence. West of Lipan Wash, mudstone predominates in the section (for example, approximately at the 250- to 280-ft level in the Coal Gulch section; pl. 1). These mudrocks have wavy/lenticular bedding with rarely preserved brackish-water clams (*Corbula*) and oysters. In the subsurface, we calibrated geophysical traces to depositional environment by describing two cores (pl. figs. 5.1 and 5.2). The sequence boundary unconformity is placed above generally upward decreasing gamma-ray traces and where there are fluctuating to blocky gamma-ray traces interpreted to represent tidal and shoreface deposits, respectively. Eastward of drill hole 7 (pl. 3; fig. 20), sequence boundary Cz was interpreted to be marked by the sharp base of the sandstone unit 17 (fig. 20), based on a change in shoreface trajectory from slightly falling to slightly rising (fig. 20B).

Maximum Flooding Surface

The maximum flooding surface is interpreted within a thin tongue of marine shale located about 50–100 ft above the upper Cozzette sequence boundary between the Book Cliffs Mine and Coal Gulch sections (pl. 1). It is placed where a deepening event is marked by intensely bioturbated, sandy mudrock at the 365-ft level in the Grasso Mine section (pl. 1) and is placed above local thin beds of HCS sandstone at the 80-ft level on Adobe Wash section (pl. 1). In the subsurface, the maximum flooding surface is interpreted from well logs where a high gamma-ray zone lies within the correlative tongue of marine shale (pls. 3 and 4).

Lowstand Systems Tract

Although evidence for lowstand shorelines in the upper Cozzette sequence is minimal, we suggest that two progradational parasequences (units 17 and 18, fig. 20) are potential candidates for the lowstand systems tract. However, placement of units 17 and 18 into a systems tract is problematic because it is unclear where the farthest progradation of the lower Cozzette sequence took place. It is possible that the units simply represent continued highstand deposition in the underlying sequence. If so, the sequence boundary would pass conformably over units 17 and 18, and the lowstand deposits could be well east of the study area where there is an isolated sandstone of the approximate age of the Cozzette (see "Summary of Sequence Stratigraphy"). However, we favor the lowstand interpretation for units 17 and 18 mainly because of the apparent truncation of marker beds beneath unit 17 and its sharped-based nature (fig. 20B; pls. 3 and 6).

Transgressive Systems Tract

As marine flooding began, initial deposition would be in the valley cut into the lower Cozzette parasequences (see Book Cliff Mine and Farmers Mine sections, pl. 1 and pl. 5). The first deposit preserved above sequence boundary Cz at the Book Cliffs Mine section is a cross-stratified sandstone located at the 390-ft level (pl. 1). The cross-stratified sandstone can only be seen at a few localities, for example the Grasso Mine, Book Cliffs Mine, and Farmers Mine sections, because of the rugged, precipitous cliffs. The exact depositional environment is debatable, and the possibilities range from upper shoreface to fluvial. Complex channeling within the unit seen at the Book Cliffs Mine section seems to rule out a shoreface interpretation, and a westerly paleocurrent direction appears to best fit a tidal rather than fluvial origin. Roots at the top of the unit clearly demonstrate that the succession had subaerial exposure. Landward (up depositional dip) from the Hunter East section (pl. 1), the cross-stratified sandstones change facies into lagoonal muds with brackish-water bivalves (*Corbula*) and oysters (facies assemblage 5). The lagoonal muds are underlain by clean, well-sorted, cross-stratified sandstone with mud drapes of facies assemblage 4 deposited within erosional scours that cut through older tidal deposits. The sandstone to mudrock succession represents a mixed-energy, tidally influenced deposit within an estuary that extended at least 35 mi between the Farmers Mine and Dry Canyon sections and places it within the transgressive systems tract (fig. 1). The succession is capped by shell-bearing shale that coarsens upward into streaky to flaser-bedded sandstone. The coarsening-upward succession can be traced westward to the Dry Creek area (fig. 8) over many miles and can be distinguished on geophysical logs. This succession is interpreted to represent relict lagoonal and washover deposits associated with back-stepping barrier islands as the area underwent flooding. A ravinement surface cuts across the top of the succession as far west as the Coal Gulch area.

Highstand Systems Tract

A single parasequence (unit 19, fig. 20) at the Coal Gulch and Fruita Mine sections (285-ft and 135-ft levels, respectively, pl. 1) was traced about 3 mi on outcrop before it was observed to have been eroded by the overlying sequence boundary and replaced by tidal deposits. A second, probably stratigraphically higher, shoreface sandstone reemerges between Grasso and Book Cliffs Mines (unit 20) and can be traced on outcrop for 12 mi before passing under Grand Mesa. This shoreface parasequence, or parasequence set, was traced for about 19 mi in the subsurface beneath Grand Mesa where it pinches out into marine shale at a depth of 2,900 ft in drill hole 9, Coors Energy 2–25 (pl. 3). Units 19 and 20 show an overall stratigraphic rise (figs. 20B and C) and are interpreted to represent deposition during a slow relative sea-level rise, placing it into the HST.

Cozzette/Rollins Sequence

Sequence Boundary (CR)

A major erosional surface cuts through shoreface parasequences (units 19 and 20, fig. 20) into the underlying highstand systems tract of the upper Cozzette sequence between the Book Cliffs Mine and Layton Wash sections, a distance of about 14 mi. Although this erosional surface is indistinct at the 465-ft level in Book Cliffs Mine section (pl. 1), it is more easily recognized and traced along the cliffs around Mount Garfield into the Farmers Mine section (pl. 5). In addition to extensive erosion, a major facies dislocation of tidal deposits (facies assemblage 4) over offshore mudrock (facies assemblage 7) between the Grasso and Layton Wash section (pl. 1) provides good evidence that this erosion surface represents the basal sequence boundary unconformity of the Cozzette/Rollins sequence. The most accessible places to see the maximum facies dislocation and observe the overlying tidal deposits are near the Hunter Canyon section (pl. 1) and about 1 mi west of the Farmers Mine section near I–70 (pl. 5) The facies dislocation is also recognized at depths of 1,130 ft in the CA–77–2 well (loc. 27 on pl. 5) and 3,097 ft in the Koch Horseshoe Canyon well (loc. 17 on pl. 4) where cores display a sharp contact between shoreface and superposed tidal deposits. The shoreface deposits are represented by very fine to fine-grained sandstone characterized by low-angle bedding interpreted as swaley cross-stratification (facies assemblage 6). The superposed tidal deposits are characterized by high-angle cross-stratification, horizontal to rippled bounding surfaces, scattered rip-up clasts, and mud or carbonaceous drapes (facies assemblage 4).

Maximum Flooding Surface

A deepening event and return to fully marine conditions is evident in strata 60 to 140 ft above the Cozzette/Rollins sequence boundary, where a tongue of Mancos Shale extends between the Farmers Mine and Lipan Wash areas (pls. 1, 3, and 5). The MFS is best expressed in cross section D–D′ (pl. 3) where moderately high gamma-ray zone in all drill holes is downlapped by an overlying high gamma zone within the Mancos tongue (see log signatures between wells 2 and 5, pl. 3, and fig. 20). The landward expression of the maximum flooding surface was not walked out on outcrop, but we believe that it terminates within a thick estuarine succession in the Layton Wash section (pl. 1). Apparently the incised valley was flooded during sea-level rise and a large lagoon was created behind retrogradational shoreface sandstones (figs. 20A–C, units 21 and 22).

Transgressive Systems Tract

The extensive nature and depth of scour along the Cozzette/Rollins sequence boundary provides good evidence for valley incision, and the characteristics of strata above the erosion surface indicate valley-fill deposition as well. Two separate types of valley-fill deposits were observed on outcrop. The lower one is mostly sandstone of facies assemblage 4 (tidal channel) with some well-developed lateral-accretion surfaces observed along the cliffs between the Book Cliffs Mine and Mount Garfield (fig. 1). The upper one, a distinct dark gray on outcrop, consists dominantly of wavy/lenticular sandstone and interbedded siltstone of facies assemblage 5 (open estuarine). These two units reflect a complex fill history, and the tidal interpretation and lateral continuity suggest a valley-fill deposit rather than a distributary channel. Tidal deposits within the transgressive systems tract of the Cozzette/Rollins sequence are most accessible for observation at the Hunter Canyon section and about a mile west of the Farmers Mine section near I–70 (pl. 5). Well-developed compound/complex bedding and sigmoidal beds (facies assemblage 4) are within a multistoried tidal sandstone body (fig. 25) at the Hunter Canyon section. Farther to the east near the Farmers Mine area, the sandstone-dominated tidal deposits change facies into a heterolithic facies.

The transgressive surface of erosion and first marine flooding within the sequence are recorded where marine mudrock (facies assemblage 7) in the Mancos Shale tongue sharply overlie the valley-fill complex. This well-defined deepening event was traced from the Farmers Mine section to more seaward localities along subsurface cross section D–D′ (pl. 3). At the seaward localities, both the transgressive and flooding surfaces lie close to or are coincident with sequence boundary CR, and no intervening lowstand shoreface deposits were observed. This merged transgressive surface and sequence boundary indicates the possible existence of detached lowstand shorelines seaward (eastward) of the study area as predicted in models of Posamentier and Allen (1999, p. 186–187 and their fig. 6.2). A candidate for these deposits is present in the Snowmass, Colorado, area (see "Summary of Sequence Stratigraphy").

Two or three well-developed retrogradational parasequences (units 21 and 22 in fig. 20) are interpreted in the subsurface cross sections (pls. 3 and 4), and two of these parasequences can be observed on outcrop at about the 460-ft and 500-ft levels in the Hunter Canyon section (pl. 1). The maximum flooding surface also can be seen in the subsurface where shoreface deposits of the Rollins Sandstone Member begin to step forward, and markers in the shale can be correlated down towards the MFS to the southeast.

Highstand Systems Tract

Ravinement and maximum flooding in the Cozzette/Rollins sequence are followed by deposition of sandstone in the Rollins Sandstone Member and its correlative marine mudrock in the tongue of Mancos Shale. The Rollins progrades to the east out of the study area and represents the last episode of nearshore deposition in the study area (Hettinger and Kirschbaum, 2002). Although the 60- to100-ft-thick Rollins Sandstone Member initially appears as one parasequence, detailed subsurface correlations in this report (pls. 3, 4, and 5) as well as those in Hettinger and Kirschbaum (2002) indicate that the sandstone is more likely represented by complex shingling within a progradational parasequence set similar to that observed by Hettinger and others (1993) or even high resolution sequences (see "Summary of Sequence Stratigraphy"). Marker beds, consisting of a high gamma response on geophysical logs, show the Rollins to be discrete facies packages that offlap to the southeast. In the subsurface, marker beds are interpreted to downlap to within 45 ft of the first flooding surface (see pl. 3).

Figure 25. Exposure of tidal deposits of upper sandstone of the Cozzette Member of the Mount Garfield Formation in Hunter Canyon. Three erosionally bounded units are present. The two lower units are characterized by complex cross-stratification (facies assemblage 4). Bounding surfaces of cross-stratification are wave rippled. Sketches and descriptions of this unit were provided by Helle Midtgaard. Arm of geologist is 2 feet for scale. CR, Cozzette/Rollins sequence boundary.

Bluecastle Sequence Boundary (Blue)

Several workers have placed a major sequence boundary at the top of the Neslen Formation where it is in erosional contact with fluvial deposits in the Bluecastle Tongue of the Castlegate Sandstone in the Uinta Basin (Olsen and others, 1995; Yoshida and others, 1996; McLaurin and Steel, 2000). Yoshida and others (1998) revised their original interpretation and placed the sequence boundary at a stratigraphically higher position within the Bluecastle, and they interpreted the sequence boundary to extend as far east as Thompson Canyon (fig. 1). However, physical correlation of the Bluecastle farther eastward into the shoreface sandstones in the Grand Junction area is not possible because it appears to pinch out in exposures between Floy and Thompson Canyons (fig. 1, pl. 2). Its pinch-out is attributed to north and northeastwardly changes of paleoflow direction as indicated by paleocurrent analyses by Lawton (1986).

There are at least four hypotheses for correlating the Bluecastle sequence boundary eastward (basinward): (1) it is equivalent to erosion observed cutting into the top of the Rollins Sandstone Member (see discussion regarding Rollins Sandstone Member in the section “Lithostratigraphy”), (2) it is related to tidally influenced deposits between the Cameo and Carbonera coal zones, (3) it is correlative to the Cozzette (Cz) sequence boundary, and (4) it is correlative to the Cozzette/Rollins (CR) sequence boundary (Hettinger and Kirschbaum, 2002; see fig. 3 and pl. 2). The first two hypotheses would require the Bluecastle unconformity to become a correlative conformity that passes through the Rollins. An additional complication is that a stratigraphically higher unconformity might also be contained within the Bluecastle as suggested by Yoshida and others (1998).

The first hypothesis is supported by observations that the Rollins has been cut out at several localities. For example, our investigations show that the Rollins was eroded west of Lipan Wash as well as between Layton Wash and Hunter Canyons (pl. 1 A–A′). A photograph by Lee (1912, his pl. 5B, surface “a”) also showed incision into the Rollins (sandstone below “a”) as well as a stratigraphically higher angular unconformity that may simply be related to the presence of inclined heterolithic strata in the succession. The second hypothesis is supported by correlating the large basinward shift in facies associated with the Bluecastle with the progradation of the Rollins shoreline down depositional dip. The orientation of the fluvial systems in the Bluecastle indicates that sediment was being transported to the northeast and possibly feeding Rollins shorelines by longshore processes. A major difference is that the low-accommodation fluvial deposits of the Bluecastle would be correlated with higher accommodation deposits of the Rollins.

The third and fourth hypotheses are possibilities because of similar stratigraphic positions of the Cozzette (Cz), the Cozzette/Rollins (CR), and the Bluecastle (Blue) sequence boundaries to the tops of the Sulphur Canyon and Thompson Canyon Beds (pl. 2). The Cz sequence boundary erodes into the Sulphur Canyon Bed between Dry Canyon and Camp Creek (pl. 1), whereas the Bluecastle sequence boundary remains about 50 ft above the Thompson Canyon Bed at Floy Canyon (pl. 2). Stratigraphic rise of the Thompson Canyon and Sulphur Canyon Beds to the east could bring the Cz to a similar stratigraphic position in relation to the top of the Thompson Canyon Bed. At East Salt Creek, the CR sequence boundary is also at a similar stratigraphic position to the Bluecastle when the large horizontal distances between sections are considered, being only about 85 ft above the top of the Sulphur Canyon Bed as opposed to the Bluecastle being just 50 ft above the Thompson Canyon Bed over a distance of 50 mi. All three erosion surfaces show similarity in magnitude of sea-level drops and rate of accommodation space when interpreted from stratal geometries. Both the Cz and CR sequences have large basinward shifts and major incision whereas the Bluecastle has amalgamated fluvial sandstones, all indicative of being deposited during relatively low rates of creation of accommodation space. This correlation can only be resolved by careful mapping between Floy Canyon and East Salt Creek, a major undertaking.

Summary of Sequence Stratigraphy

Six sequences are present in the Neslen and Mount Garfield Formations and parts of the upper Sego Sandstone and Bluecastle Tongue in the Book Cliffs over a distance of about 120 mi in western Colorado and eastern Utah. (fig. 1). The orientation of the outcrops and distribution of subsurface data allow a view for about 60 mi along depositional dip and about 60 mi on depositional strike. Several previous studies have focused on exposures west of, and up depositional dip from, our studied interval, and correlative strata in those westward areas include the middle member and Bluecastle Tongue of the Castlegate Sandstone (Fisher and others, 1960; Olsen and others, 1995; Yoshida and others, 1996; and McLaurin and Steel, 2000) (fig. 3). The last three cited papers place the units into a sequence stratigraphic context, and all the papers (except Yoshida and others, 1998) consider the bases of the Castlegate Sandstone and Bluecastle Tongue to represent major third-order sequence boundaries that are overlain by coarse-grained fluvial deposits. The fluvial deposits represent major basinward shifts in facies over coastal-plain, tidal, or shoreface strata. Several papers placed the third-order maximum flooding surface within the Buck Tongue of the Mancos Shale, and McLaurin and Steel (2000) placed the surface slightly higher within the Anchor Mine Tongue of the Mancos. Interestingly, this puts all of our studied sequences with an overall third-order highstand systems tract (fig. 3). Five of our six sequences, with the exception being the uppermost Cozzette/Rollins sequence, represent high-resolution sequences within the third-order Castlegate sequence.

In the five lower sequences, there is a distinct partitioning of the systems tracts. Most of the coal and coastal-plain deposits are within high-resolution transgressive system tracts located in more landward areas, and most of the shoreface deposits are in lowstand or forced-regressive wedge systems tracts located seaward of their corresponding coastal-plain deposits. The low preservation of coastal-plain deposits within the highstand systems tracts may be due to low accommodation space in the coastal plain following maximum flooding as well as some erosion by the overlying sequence boundary. Therefore, the lack of a prominent highstand coastal plain is a function of relatively rapid base-level fluctuations. Marine depositional topography allowed the necessary accommodation for preservation of the shoreface deposits (that is, progradation into the Cretaceous Western Interior seaway).

The uppermost Cozzette/Rollins sequence differs from the five lower sequences in that it has a much greater number and thickness of preserved retrogradational parasequences. Maximum flooding created a large estuary landward, and then highstand deposits represented by the Rollins are much thicker than most of the other highstands. All of these factors point to a higher rate of accommodation than for the other studied sequences. The strong progradation of the Rollins indicates sedimentation rates continued to exceed the rate of accommodation.

The Rollins highstand is probably more complicated than being in just one highstand system tract. Continuous progradation is indicated by bentonite-capped clinoform surfaces that extend from the Rollins into the underlying tongue of Mancos Shale as demonstrated in subsurface cross sections (pls. 3 and 4). As the bentonite marker beds extend down depositional dip from shale breaks in the Rollins, they initially downlap and then parallel the maximum flooding surface in the Mancos tongue. Similar stratal geometries have been interpreted as the topsets, foresets, and bottomsets of large, prograding, clinoform-bound units within multiple high-resolution sequences (Plink-Björklund and Steel, 2002). By analogy, the Rollins may represent multiple sequences rather than one HST. Development of high-resolution sequences within this unit would be hard to distinguish unless truncation of marker beds could be demonstrated. It is possible that some of the major bentonite marker beds in the Mancos tongue represent combined MFS and condensed intervals of high-resolution sequences.

Few lowstand deposits have been preserved on outcrop in the study area, as most are located farther down depositional dip in the subsurface or to the southeast of the study area. Fluvial deposits in the base of the Corcoran valley fill (pl. 1, Coal Gulch section, 70- to 100-ft level) are the only preserved lowstand fluvial deposits described from outcrops. Evidence for possible lowstand shorelines are present on plates 3 and 4 (see discussion of Cozzette sequence). We have interpreted attached lowstand shoreline deposits for four of the sequences: the Neslen (Nes), a composite Corcoran (Cn), Buck Canyon/Cozzette (BC), and Cozzette (Cz). The Cozzette/Rollins (CR) sequence lacks attached shoreface deposits seaward of valley incision, and the transgressive surface of erosion merges, or nearly merges, with the sequence boundary. This sequence is a candidate to have detached lowstand shorelines located farther seaward from the study area (see discussion by Posamentier and Allen, 1999, p. 186–187). Possible evidence for one lowstand shoreline comes from east of the Piceance Basin near the town of Snowmass, Colorado (see inset index map, fig. 1). Two sandy intervals are present in the Mancos Shale; one is within the *Baculites perplexus* zone and the other is within the *Didymosceras stevensoni* zone and was mapped as the upper sandstone member of the Mancos by Freeman (1972). The sands in the *B. perplexus* zone are approximately equivalent to the Castlegate or lower Sego Sandstones and are not pertinent to this discussion. The upper sandstone member at Snowmass is about 40 ft thick, can be traced for about a mile, and pinches out to the west on outcrop (Freeman, 1972; Bryant, 1979). The sandstone is described as fine grained, with low-angle crossbeds, contains phosphatic nodules at its top, and was interpreted as an offshore bar (Freeman, 1972; Bryant, 1979).

The sandstone within the *D. stevensoni* zone is time equivalent to the Cozzette Member. The sandstones in the Snowmass area were not examined during the present study, but stratigraphic position, age, and magnitude of relative sea-level drop favors correlation with the Cozzette/Rollins sequence rather than any other sequence. Another Cozzette sandstone (or the same sandstone as the one at Snowmass) is shown within the Mancos by Gill and Hail (1975, their sections 15 and 16) also dated within the *D. stevensoni* zone (Gill and Hail, 1975), and a similar sandstone is shown in the Mancos in Coal Basin, but not dated, by Collins (1977, his figs. 1, 5, and 6). All of these are candidates for lowstand shorelines.

Conclusions

Six high-resolution stratigraphic sequences are interpreted within upper Campanian strata of the Book Cliffs in Colorado and Utah. The sequences are informally named for prominent stratigraphic units; in ascending order, they are the upper Sego, Neslen, Corcoran, Buck Canyon/lower Cozzette, upper Cozzette, and Cozzette/Rollins sequences. Each is bounded by major surfaces of erosion except for the upper sequence boundary of the Cozzette/Rollins, which may be a correlative conformity. The erosional surfaces are interpreted as sequence-boundary unconformities that allowed bypass of sediment to either attached or detached lowstand shorelines. The point of incision in landward settings is predicted by the change in stratal geometries of shoreface parasequences from an overall stratigraphic fall to stratigraphic rise. Lowstand and transgressive deposits within incised valleys generally consist of tidally influenced strata that were deposited during an overall base-level rise. Tidal erosion associated with deposition in the valley may have modified, and in places become coincident with, the sequence boundary. Retrogradational shoreface parasequences are well preserved only in the Cozzette/Rollins sequence. Transgressive surfaces can be traced (or inferred) into estuarine deposits above and landward of the shoreface deposits, and maximum flooding surfaces can be traced (or inferred) into coastal-plain deposits. Coastal-plain deposits associated with progradational parasequences are thick in the Cozzette/Rollins sequence but are thin in the rest of the sequences.

Most sequences have been affected by relatively low rates of creation of accommodation space as indicated by incised valleys, a lack of preservation of retrogradational parasequences, low preservation of coastal-plain strata in the highstands, and a low angle of stratigraphic climb in the highstand parasequences. In contrast, the Rollins/Cozzette sequence had higher accommodation space as indicated by a lack of valley incision at the top of the sequence, well-developed retrogradational parasequences, high preservation of coastal-plain strata in the highstands, and a high angle of stratigraphic climb in the highstand parasequences.

Acknowledgments

Peter McCabe was especially generous with his time, providing discussions on facies and sequence stratigraphy in the office and field. We also thank the following people for their discussions, advice, and encouragement: Mike Boyles, Russell Dubiel, Mike Gardner, Tim Lawton, Penny Patterson, Ron Steel, Chris Schenk, John Van Wagoner, and Brian Willis. George Pemberton and Jason Lavigne identified trace fossils in the field. Kat Beryk, Helle Midtgaard, and Peter Reiners ably assisted in the field. Thanks to Chris French for his work on the Book Cliffs photo mosaic and Wayne Husband for the CD–ROM layout and cover design. Oblique aerial photographs were provided by Bill Keighin and Jack Dyni and are the results of their flying the Book Cliffs (Jack as pilot and Bill as photographer) from just east of Hunter Canyon to near the Book Cliffs mine. We appreciate technical reviews by Russell Dubiel, Ron Johnson, and Ron Steel, a review of the geologic names by Tom Judkins, and editing by William Keefer and Mary Kidd.

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