WAVE-TO-TIDE FACIES CHANGE IN A CAMPANIAN SHORELINE COMPLEX, CHIMNEY ROCK TONGUE, WYOMING–UTAH, U.S.A.

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ABSTRACT: The Upper Cretaceous, Campanian Chimney Rock Tongue is exposed in a dip-oriented outcrop belt ca. 15 km long in the Flaming Gorge area, Utah–Wyoming, U.S.A. The Chimney Rock Tongue has three distinct stratigraphic intervals: (1) wave-dominated-delta deposits, (2) mixed-energy-estuary deposits as an incised-valley fill, and (3) tide-dominated-estuary deposits.

The wave-dominated delta succession, ca. 95 m thick, consists of eastward-prograding clinoforms. The clinoforms are dominated by wave deposits, but in places sediment-gravity-flow and mass-transport deposits, as well as fluvially dominated mouth-bar deposits, occur. Tops of the individual clinoforms are locally cut by distributary channels. The distributary channels are filled with fluviatile and tide-dominated fluvial deposits. Tops of the youngest deltaic clinoforms are severely eroded by a subaerial unconformity that can be walked out across the whole outcrop belt for 15.5 km. The subaerial unconformity cuts down at least 30 m across the outcrop belt. The unconformity is locally marked by roots (locally calcite filled), calcite concretions, limonite precipitation, and mottling.

An estuarine succession onlaps the unconformity in the landward and lateral directions, indicating that the estuary was confined in an incised valley. The estuarine succession, ca. 30 m thick, consists of tide-influenced fluvial channels, bay-head deltas, inner-estuarine tidal bars, central-basin mudstones, flood-tidal deltas, estuary-mouth-barrier deposits, and tidal-inlet deposits. The inner-estuary tidal bars consist of fluvially derived but tidally reworked sands with ubiquitous single and double mudstone drapes. The wave-generated estuary-mouth barrier indicates wave dominance in the estuary mouth. This distribution of tide and wave deposits indicates that the estuarine succession is of mixed-energy type. The mixed-energy estuary succession is retrogressive, except for the very top of the succession, which is regressive within the inner-estuary setting. This latter suggests in situ infilling of the incised valley.

The third and uppermost stratigraphic unit, ca. 60 m thick, consists of three transgressive-regressive units in an overall aggradational setting. The transgressive-regressive units consist of tide-influenced fluvial deposits, tidal-flat and marsh deposits in inner-estuary reaches, and upper-flow-regime tidal-flat and tidal-sand-bar deposits in outer-estuary reaches. The transgressive-regressive units, 16–26 m thick, are based by tidal ravinement surfaces, and indicate flooding and consequent in situ infilling of the river mouths.

The transition from a wave-dominated delta to a mixed-energy estuary and then to a tide-dominated estuary suggests an apparent change in process regime from wave dominance to tide dominance triggered by a relative sea-level rise. The tidal influence was, however, also present during the deposition of the wave-dominated deltaic succession, as seen by the tide-influenced fluvial infill of the distributary channels. Thus, the tidal influence did not switch on when the depositional system changed from deltaic to estuarine. Nor did the wave influence switch off, as the estuary mouth was wave-dominated in the mixed-energy estuary. Instead, the effect of tides was locally increased. Due to valley incision and later drowning, the inner areas of the valley were protected from waves. The tidal range, however, increased, as the mixed-energy estuary was replaced by a tide-dominated estuarine system, commonly assigned to macrotidal settings. This change in process regime occurred after the incised valley was filled, and the tide-dominated estuaries occupied river mouths in a high-subsidence regime.

KEY WORDS: mixed-energy estuary, tide-dominated estuary, wave-dominated delta, incised valley, drowned river mouth

INTRODUCTION

The Campanian Chimney Rock Tongue is a regressive-transgressive shoreline complex that records facies changes from a wave-dominated delta, to a mixed-energy estuary, and then to a tide-dominated estuary (sensu Dalrymple et al., 1992). This apparent process-regime change from wave to tidal dominance seems to support the common notion (Yoshida et al., 2003) that transgressive coastlines tend to be more tide influenced than regressive systems (e.g., Dalrymple, 1992; Shanley and McCabe, 1991; Shanley et al., 1992; Dalrymple et al., 1992, 1994; Allen and Posamentier, 1993; Shanley and McCabe, 1994; Yoshida, 2000; Shennan and Andrews, 2000). Wave regime is considered to be increasingly important during regression in basins with a shelf-slope break because narrowing of the shelf is accompanied by more exposure to ocean waves (Suter, 2001; Porebski and Steel, 2006). Conversely, tidal influence would be relatively more important while the deltas were still in an inner-shelf location (Suter, 2001). In shallow ramp basins, like the Western Interior Seaway, however, decreasing water depth during the regressive transit has been suggested to cause an increase in tidal influence and a decrease in wave influence, not least because falling relative sea level in an already shallow basin would tend to enhance topography in the basin (Martinsen, 2001, 2003).

The facies change in the Chimney Rock Tongue from wave-dominated delta to mixed-energy and then tide-dominated estuary also seems to support an assumption that wave-to-tide changes in process regime occur across regressive-transgressive turnarounds. Detailed facies analyses show, however, that the vertical wave-to-tide facies changes in the Chimney Rock Tongue occur in three different stratigraphic positions: (1) within the regressive succession, (2) on regressive-to-transgressive turnaround, and (3) within the transgressive succession. An actual increase in tidal range accompanied by the most prominent tidal ravinement surface occurs within the transgressive succession rather than on the regressive-transgressive turnaround.
Regressive to transgressive transits of depositional systems do potentially cause the depositional environments to be exposed to varying process regimes, e.g., river-, tide-, or wave-dominance, but these changes depend on how the regressions–transgressions affect basin bathymetry or coastal configuration. Tidal energy may increase through (1) increased tidal prism as the rising sea level gradually accesses a greater surface area (e.g., Dalrymple, 1992); (2) increased tidal range associated with an increased width of continental shelf (e.g., Pugh, 1987); (3) increased tidal range where the tidal wave is constricted, whether laterally or vertically (Archer and Hubbard, 2003); (4) increased tidal range as a function of the tidal wave entering into resonance with the configuration of the basin (e.g., Dalrymple and Zaitlin, 1994); (5) dissipation of wave energy due to the frictional effect on a shallow continental shelf (e.g., Swift and Thorne, 1991; Emery and Myers, 1996); or (6) due to existence of areas protected from waves, like laterally restricted coastal invaginations (Archer and Hubbard, 2003). Thus, changes in process regime can happen any time, inasmuch as a slight change of sea level can modify the shape of a coastline significantly, especially in valley-dissected shorelines (e.g., Bay of Fundy; Dalrymple and Zaitlin, 1994). The highest modern tidal ranges occur in such invaginations (Archer and Hubbard, 2003). Consequently, waves may be dominant on the open coastline, whereas tides may have a larger effect in areas protected from waves. Such laterally restricted environments may function as wave-protected areas, where the relative tidal energy is higher, or they may actually experience locally higher tidal ranges.

The paper aims to (1) highlight how to recognize and differentiate a large variety of tidal depositional sub-environments; (2) argue that not every change from wave- to river-, or tide-dominated facies reflects a change in process regime in a basin, but may rather be a function of lateral variability due to differences in local basin geometry and morphology; (3) show that not all changes in process regimes from wave to tide or fluvial processes occur across regressive-to-transgressive turnarounds, but may occur at any time as a function of relative sea-level change, sediment supply, and local paleogeography, through relative (sensu) Davis and Hayes, 1984; Harris et al., 2002) as well as bulk (Porter-Smith et al., 2004) effects of river power, waves, and tides; and (4) discuss the conditions for the formation of thick, vertically aggrading estuarine successions, such as seen in the Chimney Rock Tongue.

**STRATIGRAPHY OF THE CHIMNEY ROCK SANDSTONE**

The Western Interior basin formed as a response to Late Cretaceous thrust-sheet loading in the Sevier thrust belt (Jordan, 1981; Willkoch and Dorr, 1983; DeCelles et al., 1995), dynamic loading (Liu and Nummedal, 2004; Liu et al., 2005), and a high Cretaceous eustatic sea level (Haq et al., 1988). Sediments were sourced from the Sevier Orogenic Belt at the western margin of the basin (Kauffman, 1977). Shorelines periodically advanced into the basin and retreated (McGookey et al., 1972; Williams and Stelck, 1975; Kauffman, 1977).

The Lower Campanian Chimney Rock Tongue (Fig. 1) belongs to the Rock Springs Formation (Fig. 2). The Chimney Rock Tongue overlies the Blair Sandstone and is overlain by the Black Butte Shale, and the Brooks, McCourt, and Ericson Sandstones (Fig. 2). The Chimney Rock Tongue is exposed in the southern ridge of the Glades in the Minnies Gap area, by the Flaming Gorge Reservoir (Fig. 1). The Chimney Rock Tongue crops out in three exposures, here called “West of Flaming Gorge Reservoir”, “Main exposure”, and “East of Minnies Gap”, separated by the Flaming Gorge reservoir and Highway 191 through the Minnies Gap, respectively (Fig. 1C). Together the three outcrops form an exposure belt more than 15 km long. The Chimney Rock Tongue has three distinct stratigraphic units, separated by prominent erosion or ravinement surfaces and recognized by specific combination of sedimentary facies and geometries. The lowermost stratigraphic unit, 25–95 m thick, is continuously exposed on the steep cliff face, and is characterized by eastward-dipping clinoforms and dominantly wave-generated deposits (Fig. 2B). The second stratigraphic unit, ca. 30 m thick, crops out on the top of and behind the Glades southern ridge (Fig. 2B), and is bounded below by a prominent subaerial erosion surface that merges with a wave-ravinement surface in the east. Stratigraphic Unit 2 is characterized by a retrogradational to progradational set of tide- and wave-generated sedimentary facies. The third and uppermost stratigraphic unit, ca. 60 m thick, is exposed on the north (dip) side of the southern Glades ridge (Fig. 2B), bounded below by a prominent tidal ravinement surface, and is characterized by overall aggradationally stacked tide-dominated deposits with three retrogradational-to-progradational depositional units. The Chimney Rock Tongue is overlain by the Black Butte marine shales.

The Chimney Rock Tongue was studied by measuring detailed sections, lateral mapping, and careful “walk-out” of stratigraphic units and bounding surfaces, supplemented by numerous photomosaics. The Chimney Rock Tongue records facies changes from a wave-dominated delta, to a mixed-energy estuary, and then to a tide-dominated estuary. The mixed-energy estuary (sensu Dalrymple et al., 1992) succession is based by a prominent subaerial unconformity that cuts more than 30 m into the underlying delta succession. The mixed-energy-estuary deposits onlap landwards and laterally into the unconformity. The unconformity is interpreted as an incised-valley base, and the mixed-energy-estuary succession as an incised-valley fill. The unconformity merges eastwards with a wave-ravinement surface. The overlying tide-dominated-estuary (sensu Dalrymple et al., 1992) succession is based by a prominent tidal-ravinement surface, and consists of three depositional units. Each of these depositional units is based by a tidal-ravinement surface.

**STRATIGRAPHIC UNIT 1: WAVE-DOMINATED CLINOFORMS**

Stratigraphic Unit 1 is the lowermost stratigraphic package of the Chimney Rock Tongue. It comprises eight eastward-prograding clinoform sets, each 10–40 m thick (Figs. 3–5). Each clinoform set consists of a series of clinoforms 5–20 m thick and 200–1000 m long (Figs. 3–5). The clinoform sets as well as the individual clinoforms coarsen upwards, and thin eastwards to their pinch-out area. The clinoform sets interfinger eastwards (seaward) with offshore mudstones. The individual clinoforms are defined by minor discontinuity surfaces (sensu Hampson, 2000; Hampson et al., 2001; Hampson and Storms, 2003; Storms and Hampson, 2005).

**Facies Successions in Individual Clinoforms**

Stratigraphic Unit 1 is dominated by wave-generated deposits (Fig. 5). The individual clinoforms within the clinoform sets (Fig. 6) contain characteristic vertical and updip facies successions: from Facies Association 1.1 at the toes of clinoforms, through Facies Association 1.2–1.5, and to Facies Association 1.6 at the clinoform tops. Lenticular sandstones of Facies Association 1.7, coals or coaly mudstones of Facies Association 1.8, and sandstones of Facies Association 1.9 occur at the tops of some
clinoforms. In some places, in the lower and seaward segments of individual clinoforms, or throughout the clinoforms, there occur interbedded sandstones and mudstones of Facies Association 1.10 (Fig. 5).

**Facies Association 1.1: Bioturbated Mudstones**

Facies Association 1.1 consists of bioturbated mudstones (Fig. 6) that occur in the lowermost and eastward (seaward) parts of the individual clinoforms. Bioturbation is common and locally intense, including *Chondrites, Cylindrichnus, Planolites, Palaeophycus, Teichichnus, Terebellina*, and *Zoophycos*.

**Interpretation.**

The bioturbated mudstones are interpreted as offshore mudstones, deposited below the depths of observed storm influence (e.g., Elliott, 1986; Hampson and Storms, 2003).

**Facies Association 1.2: Mudstones with HCS Sandstone Interbeds**

The mudstones of Facies Association 1.1 grade landward and upward into mudstones interbedded with 5–20 cm thick beds of hummocky-cross-stratified, current- and wave-ripple-laminated siltstones, and very fine-grained sandstones (Fig. 6). The sandstone beds characteristically thicken, and the mudstone beds thin upsection. Siltstone and sandstone beds commonly have sharp bases and sharp tops. Bioturbation by *Chondrites, Cylindrichnus, Terebellina, Zoophycos*, and *Palaeophycus* is common.

**Interpretation.**

The interbedded mudstones, siltstones, and sandstones are interpreted to have been deposited where occasional storms affected deposition between fair-weather and storm wave base (e.g., Elliott, 1986, Cant, 1991; Walker and Plint, 1992).

**Facies Association 1.3: Alternating HCS and Bioturbated Sandstones**

Facies Association 1.3 consists of hummocky-cross-stratified (HCS), plane-parallel-laminated, and wave- and current-ripple-laminated very fine- and fine-grained sandstones. The sandstone beds are 10–30 cm thick and are interbedded with intensely bioturbated mudstone, siltstone, or sandstone beds, 20–40 cm thick (Fig. 6). The mudstone intervals decrease and sandstone intervals increase in thickness upwards and updip. The mud-
stone interbeds are gradually replaced by bioturbated siltstone and sandstone interbeds upsection. Bioturbation with *Rosselia*, *Palaeophycus*, *Schaubcylindrichnus*, *Skolithos*, *Ophiomorpha*, *Arenicolites*, *Terebellina*, *Planolites*, *Chondrites*, *Cylindrichnus*, and *Bergaueria* is intense in some layers.

**Interpretation.**—

The non-amalgamated HCS sandstones are interpreted to have been deposited above storm-wave base, where deposition was controlled by episodic storm-wave processes (e.g., Walker and Plint, 1992). This facies association is similar to the lower-shoreface deposits of Elliott (1986) and Howell and Flint (2003) and to the distal lower-shoreface and inner-shelf or ramp deposits of Van Wagoner et al. (1990), Kamola and Van Wagoner (1995), and Hampson and Storms (2003).

**Facies Association 1.5:**

**Amalgamated Plane-Parallel-Laminated and Wave-Ripple-Laminated Sandstones**

Facies Association 1.5 consists of amalgamated beds, 2–5 m thick, of plane-parallel- and wave-ripple-laminated, trough- and swaly-cross-stratified, fine- to medium-grained sandstones (Fig. 6). Plane-parallel-laminated beds with wave-ripple-laminated interbeds dominate the Facies Association 1.5. In some places the plane-parallel beds are interbedded with trough-cross-stratified sandstones. Swaly-cross-stratified beds occur locally. Bioturbation is rare, and limited to only a few trace-fossil types, like *Ophiomorpha*, *Thalassinoides*, and *Skolithos*.
Fig. 3.—Photomosaic and line drawing from the west-to-east-trending “Main exposure” (see Fig. 1). The outcrop on the mosaic is 8 km long, and the visible cliff face is more than 50 m high. The clinoforms of the lowermost stratigraphic unit are continuously exposed in the steep cliff face, whereas stratigraphic units 2 and 3 are exposed on the top and the back side of the ridge. Numbers mark the positions of the measured sections (see also Fig. 1).
Interpretation.

The amalgamated nature and lack of intensely bioturbated intervals, and the occurrence above Facies Association 1.4 (storm deposits) and below 1.6 (foreshore deposits, see below), indicate that Facies Association 1.5 was deposited above fair-weather wave base. Deposition above fair-weather wave base is commonly interpreted to be dominated by shoaling fair-weather waves and longshore currents, and interpreted as upper-shoreface deposits (e.g., Elliott, 1986; Cant 1991; Walker and Plint, 1992) or shoreface deposits (Clifton, 2000). The dominant alternation of plane-parallel-laminated and wave-ripple-laminated intervals in Facies Association 1.5 is, however, different from the above-cited upper-shoreface deposits, but is similar to a modern upper-shoreface environment documented by Hill et al. (2003). Deposition of plane-parallel-laminated sand was documented to occur during storm episodes when the maximum orbital velocities, as well as mean residual current velocities, were high (Hill et al., 2003). Dunes and ripples formed during waning phases of storms, and flow conditions tended to remain longer in equilibrium for ripples than for dunes (Hill et al., 2003). During fair-weather conditions there occurred only weak reworking of the seabed into wave ripples (Hill et al., 2003). This implies that in the Chimney Rock shallow-marine environments, even above fair-weather wave base, deposition dominantly occurred under storm conditions.

Facies Association 1.6: Plane-Parallel Wedging Laminated Sandstones

Facies Association 1.6 consists of sandstones with plane-parallel and wedging laminations that dip seaward at an angle of a few degrees. The sandstones are fine to medium grained (Fig. 7). In places the laminae are highlighted with heavy minerals. Facies Association 1.6 is locally based by pebble layers. The sandstones are in places rooted at the top of the facies association. Facies Association 1.6 forms characteristic white caps at the tops of some individual clinoforms.

Interpretation.

Facies Association 1.6 is interpreted as foreshore deposits, accumulated in the swash zone, where deposition was dominated by swash and backwash of breaking waves (e.g., Clifton, 1969).

Facies Association 1.7: Lenticular, Cross-Stratified Sandstones

Erosionally based, lenticular sandstone bodies 2–5 m thick and 25–100 m wide erosi-
Fig. 5.—Correlation panel based on measured sections, photomosaic correlations, and “walking out” of stratigraphic surfaces and units (see Fig. 1 for location). Geometry of clinoform sets and clinoforms is drawn from the photomosaics (see Figs. 3 and 4). Vertical exaggeration is almost 70 times.
nated clinoforms, in places (Figs. 5, 7). Some of these sandstone bodies can be traced for several hundreds of meters in dip-direction outcrops. The basal erosion surfaces are lined by clay-clast conglomerates or wood fragments. Some of the lenticular sandstones consist of unidirectional, eastward-oriented (75–90°) fine- to coarse-grained trough-cross-stratified sandstones. Other lenticular sandstone bodies consist of compound-cross-stratified and locally bidirectional cross-stratified fine- to medium-grained sandstones with reactivation surfaces and occasional mudstone drapes (Fig. 7). The dominant paleocurrent directions, even in the latter type, are towards the east (75–90°), whereas the subordinate directions are towards the west (245–270°). All paleocurrent measurements are derived from cross strata. The compound-cross-stratified sandstones contain dominantly eastward-inclined master surfaces with superimposed dunes or ripples that climb up or down the master surfaces. Locally coaly mudstones and coals occur at the tops of the lenticular sandstones.

**Interpretation.**

The channel-shaped geometries, the unidirectional cross-stratification, and the lack of marine trace fossils indicate deposition in fluvial channels. The channel fills with bidirectional but dominantly eastward paleocurrent directions, and compound or bidirectional cross-stratified sandstones with occasional mud drapes and reactivation surfaces, indicate deposition in tide-influenced fluvial channels (e.g., Allen, 1991). A fluvial channel changes seaward into a tide-influenced fluvial channel below the upstream tidal limit (Dalrymple et al., 1992). The paleocurrent measurements on cross-strata with reactivation surfaces as well as the dip direction of the compound cross-strata reflect a dominant eastward current and a subordinate westward current, as the fluvial effluent dominated the deposition. The bidirectional cross strata indicate that currents of approximately equal strength occurred occasionally.

**Facies Association 1.8: Plane-Parallel-Laminated and Climbing-Ripple-Laminated Sandstones**

Lateral to Facies Association 1.7 occur, fine- to medium-grained sandstone bodies, 2–5 m thick, and a few tens to ca. 100 m long, with locally convex-up upper surfaces (Fig. 7). These sandstones are dominated by plane-parallel-laminated sandstones with trough-cross-stratified, current-ripple-laminated, or climbing-ripple-laminated intervals. They commonly display internal erosion surfaces that cut down a few decimeters. Paleocurrent directions derived from cross strata and ripples are towards 58–150°. In places wave-rippled and swaley-cross-stratified sandstone intervals occur.

**Interpretation.**

The current-rippled, cross-stratified, and plane-parallel-laminated beds indicate deposition by unidirectional currents. The association with distributary-channel mouths, together with the convex-up geometry and the sedimentary structures, suggest that Facies Association 1.8 was deposited as fluvially dominated mouth-bar deposits. The origin of the plane-parallel lamination is unclear, and may be related to deposition from dense underflows (Best et al., 2005), or deposition by traction currents under upper-flow-regime conditions (e.g., Miller et al., 1977), due to flow expansion and high sediment fallout rates (see also Arnott, 2007) or deposition by passing of low-relief bedforms (e.g., McBride et al., 1975; Bridge and Best, 1997).

**Facies Association 1.9: Normally Graded and Laminated Sandstones and Mudstones**

Facies Association 1.9 consists of upwards-fining sandstone to mudstone beds 5–15 cm thick. The sandstone intervals are current-ripple laminated, climbing-current-ripple laminated, normally graded, plane-parallel laminated, or ungraded (Fig. 7). The sandstone intervals are sharp based, and show scouring, loading structures, and flute and groove marks. The sandstones grade upward into mudstones. The upwards-fining beds are interbedded with soft-sediment-deformed sandstone and mudstone beds up to 1.5 m thick. The soft-sediment-deformed beds display folds, and overturned folds. In some places Facies Association 1.9 alternates with Facies Association 1.2 or Facies Association 1.3. Facies Association 1.9 is overlain erosionally by Facies Association 1.4 or it grades upwards into Facies Association 1.8 (Fig. 7). The paleocurrent directions derived from ripples and flute marks are dominantly towards 80°.

**Interpretation.**

The upwards-fining sandstone to mudstone beds with current ripples, climbing ripples, normal grading, and sole marks indicate deposition by turbidity currents (e.g., Bouma, 1962). The soft-sediment-deformed beds were deposited by slumping. Facies Association 1.9 is interpreted as distal mouth-bar and delta-front deposits. Facies Association 1.9 is more mud rich compared to the wave-dominated intervals of the clinoforms, and is interpreted to have been fed by the fluvial system.

**Depositional Environment**

The dominance of storm- and fair-weather-wave deposits (Facies Associations 1.2–1.6) in the clinoforms suggests a wave-dominated depositional system (Fig. 5). The presence of the distributary channels, mouth bars, and sediment-gravity-flow-dominated delta-front deposits indicates that the eastward-prograding wave-dominated clinoforms were deposited in a wave-dominated delta rather than a strandplain complex. The preserved fluvially dominated intervals reflect deposition close to a distributary mouth. Such fluvially dominated intervals are most likely to be preserved downdrift of a distributary mouth, where wave-protected areas form due to buildup of barriers from longshore transport of sand (see Bhattacharya and Giosan, 2003).
Bhattacharya and Giosan (2003) assigned facies associations of this kind to asymmetric wave-dominated deltas. The presence of the bidirectional-cross-stratified and compound-cross-stratified sandstones with reactivation surfaces and occasional mudstone drapes in distributary-channel deposits of Facies Association 1.7 indicates tidal action in distributary mouths. Tidal influence has not been documented in other parts of the clinoforms, and seems to have been restricted to areas protected from waves. The occurrence of tide-influenced deposits only in distributary channels may indicate high wave energy along the more open coastline. Alternatively, tidal energy may actually have been increased in areas where the tidal wave entered into laterally constricted distributary mouths.

**SUBAERIAL UNCONFORMITY**

The unconformity that cuts into the tops of Clinoform Sets 4–6 is spectacularly exposed across the more than 15-km-long outcrop belt (Figs. 3–5). The depth of downcutting is more than 30 m across the dip-parallel exposures (Fig. 5). Strike-parallel sections are limited, but ca. 10–20 m of local relief along the unconformity has been documented in several places (Fig. 5). The unconformity is locally marked by ubiquitous roots (locally calcite filled), calcite concretions, limonite cement, and mottling (Fig. 9), indicating subaerial exposure. Wood fragments and even whole tree trunks are common above this surface. The unconformity cuts severely into Clinoform Sets 4–6. Eastwards of the landward pinchout of the Clinoform Set 7, the subaerial unconformity is reworked by waves and is lined by large pebbles, shells, and wood fragments (Fig. 8E).

**Interpretation**

The subaerial unconformity is interpreted as an incised-valley base, because of (1) the regional extent of the unconformity (across the 15 km of exposure), (2) the depth of downcutting of more than 30 m, compared to only 2–5 m at the bases of distributary channels, (3) the lateral correlation into paleosols, inter...
FIG. 8.—Subaerial unconformity. A) Photo from the main outcrop showing the subaerial unconformity that cuts into delta clinoforms (white sandstones) and is overlain by fluvial deposits (dark sandstones). B) Photo from the exposure west of the Flaming Gorge showing the unconformity (black line). C) The subaerial unconformity from which there extend long root traces. D) The subaerial unconformity, showing root traces (closed arrows) and Fe precipitates (open arrows). E) Photo from the exposure east of the Minnies Gap showing wave-rewrored unconformity with large pebbles and sand-size shell fragments. F) Photo from the main outcrop showing estuarine deposits onlapping the unconformity. SU—subaerial unconformity. Numbers refer to the facies associations.
interpreted as interfluve areas, and (4) the landwards and lateral onlap of estuarine deposits of Stratigraphic Unit 2 into the unconformity (Fig. 8F).

**STRATIGRAPHIC UNIT 2: MIXED-ENERGY-ESTUARY DEPOSITS**

Stratigraphic Unit 2 onlaps landwards into the subaerial unconformity west of the Flaming Gorge reservoir and along the “main exposure” (Figs. 5, 8F) and is based by a wave-ravinement surface east of Minnies Gap (Fig. 5). This ca. 30-m-thick interval consists of three retrogradational depositional units (MDU 1–3 in Figure 5) and a topmost regressive depositional unit (MDU 4 in Figure 5). Each of the depositional units is based by a wave-ravinement surface in the eastern areas (east of section 22 in MDU 1, east of section 15 in MDU 2 and 3; Fig. 5). Each depositional unit comprises similar downdip facies transitions. In the dip-oriented exposure, the coarsest deposits occur in western (landwards) and eastern (seawards) ends of the depositional units, and the finest-grained sandstones as well as mudstones occur in the middle parts of the depositional units (Fig. 5). The downdip facies transitions (from west to east) are from Facies Association 2.1 in the westernmost parts to Facies Associations 2.2–2.5 towards the east. Facies Associations 2.6–2.8 occur in the easternmost exposures of the depositional units.

**Facies Association 2.1: Erosionally Based Cross-Stratified Sandstones and Conglomerates**

In the westernmost (landward) part of each of the depositional units there occur erosionally based dark brown coarse-grained sandstones and conglomerates 2–12 m thick (Fig. 9A, D). They consist of erosionally based, and in places upwards-fining, sandstone units, 2–5 m thick, dominated by unidirectional trough cross strata 15–25 cm thick (in places 50 cm thick). In several places lateral accretion beds, 2–3 m thick, occur. Basal as well as internal erosion surfaces are commonly lined with clay clasts and wood fragments. Paleocurrent directions derived from cross-strata are dominantly between 64 and 100°. Lateral-accretion directions are dominantly between 10 and 160°. Tops of the sandstone units are in places rooted.

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Fig. 9.—A close-up from MDU1, inner-estuarine facies of the mixed-energy estuary association (see Fig. 5 for location). A) The basal fluvial deposits (dark) above the subaerial unconformity that has cut into delta deposits (white). B) Wood fragments bored by *Teredolites* in the inner-estuarine tidal bars of FA 2.3. C) Bidirectional trough-cross-stratified and compound-cross-stratified sandstones of the inner-estuarine tidal bars, FA 2.3 D) Unidirectional trough cross-stratification in fluvial deposits, FA 2.1. E) Compound-cross-stratified sandstones with double mudstone drapes and ripples climbing up the cross strata, inner-estuarine tidal bars of FA 2.3. F) Mudstone drapes in the inner-estuarine tidal bars, FA 2.3.
Interpretation.—

The unidirectional trough-cross stratification, coarse grain size, roots and wood fragments, as well as absence of marine trace fossils, suggest that these are fluvial channel-fill deposits. The multiple erosion surfaces indicate repeated episodes of channel incision. The lateral-accretion beds are interpreted as obliquely downcurrent-migrating bars. The absence of point-bar deposits, the coarse grain size, lateral and vertical amalgamation of the channel fills, the lack of overbank deposits, and relatively low paleocurrent variability suggest that the channels had low sinuosity (see also Bridge et al., 2000). Cross-set thicknesses suggest flow depths (see Leclair and Bridge, 2001, for methodology) of 2.6–4.4 m for channels with cross sets of 0.15 m, and 4.4–7.3 m for channels with sets of 0.25 m. These calculated water depths are consistent with the thickness of individual sandstone units of 2–5 m, interpreted as individual channel fills, as well as the thickness of lateral-accretion beds of 2–3 m (e.g., Bhattacharya and Tye, 2004). The lateral-accretion beds and the amalgamated sandstones are commonly eroded at the top and show thicknesses less than original thickness. This suggests that most of the fluvial channels were about 3–6 m deep, though parts of the channels may have reached a depth of 7–8 m.

Facies Association 2.2: Lenticular Compound-Cross-Stratified Sandstones

Facies Association 2.1 can be walked out eastwards into dark brown, coarse- to medium-grained, erosionally based sandstones 2–4 m thick (Fig. 9). These sandstones are dominated by trough cross strata, but inclined accretion surfaces with superimposed cross-strata or ripples (compound cross-strata) are also common. Paleocurrent directions derived from cross-strata are dominantly towards 80–85°. The subordinate current was towards 260–280°. Mudstone drapes are rare. These sandstones are very similar to those of Facies Association 2.1, except for the subordinate westward paleocurrent indicators and somewhat finer grain size. Tops of these sandstone units are in places rooted.

Interpretation.—

The channel shape, extensive trough cross-stratification, coarse grain size, bidirectional but dominantly eastward paleocurrents, compound cross-strata, occasional mud drapes, together with the walked-out transition from fluvial channels, presence of plant roots, and absence of marine fossils, indicate deposition in tidally influenced fluvial channels (e.g., Allen, 1991), where the fluvial channel changes into a tidal fluvial channel below the upstream tidal limit (Dalrymple et al., 1992).

Facies Association 2.3: Lenticular Cross-Stratified Sandstones with Mudstone Drapes

Directly eastwards (seaward) of Facies Association 2.2 occur erosionally based sandstone bodies 2–7 m thick and 1000–3500 m long (Fig. 9). These sandstone bodies have a convex-up geometry, contain lateral accretion beds, and thin and pinch out both landwards and seawards (Fig. 10). The sandstone bodies consist of trough-cross-stratified bedsets, 20–30 cm thick, and compound-cross-stratified upper-fine-grained bedsets 50–150 cm thick (Fig. 9C, E, F). The inclined surfaces of the compound cross-strata have superimposed decimeter-scale cross strata or current ripples that climb up or down the surfaces. The cross strata are draped by thin single or double mudstone laminae (Fig. 9E, F). The occurrence of mudstone drapes increases significantly eastwards within individual sandstone bodies. The mudstone drapes are ubiquitous in the eastern parts of the
sandstone bodies. Roots and wood fragments bored by *Teredolites* occur in places (Fig. 9B).

The sandstone bodies characteristically consist of lateral-accretion beds, with accretion directions dominantly towards 20–40° and 220–240° (Fig. 10, 11A). Paleocurrent measurements derived from cross strata are dominantly towards 80–100° and 240–280°.

**Interpretation.**—

Oblique lateral accretion, convex-up geometry, bimodal paleocurrent directions, and ubiquitous mudstone drapes indicate deposition in tidal bars. The occurrence just seawards of a river mouth (Facies Association 2.1 and 2.2) and the ubiquitous mudstone drapes suggest deposition in an inner-estuary setting.
These deposits have been interpreted as inner-estuarine tidal bars. The ubiquitous occurrence of mudstone drapes reflects deposition within the turbidity-maximum zone (e.g., Dalrymple et al., 1990; Allen, 1991; Dalrymple, 1992).

**Facies Association 2.4:**
**Wavy- to-Flaser-Bedded Prograding Clinoforms**

Facies Association 2.3 erodedly overlies upward-coarsening organic-rich mudstone to fine-grained brown sandstone clinoforms 2–3.5 m thick (Fig. 11). Westwards (landwards), these clinoforms indicate deposition by tide-influenced fluvial channels (Facies Association 2.2) or by inner-estuarine tidal bars (Facies Association 2.3). The clinoforms grade eastwards (seawards) into organic-rich mudstones of Facies Association 2.5 (Fig. 5). The clinoform consists of flaser- to wavy-bedded sandstones and organic-rich mudstones, and inclined strata with superimposed current ripples, climbing current ripples, and ubiquitous mudstone drapes (Fig. 11B, C, D). In places the upward-coarsening deposits (Fig. 11B) are cut by channels up to 1.5 m deep, filled with bidirectional cross-stratified sandstones. Coal layers or roots occur in many places at the tops of the upward-coarsening deposits. Wave ripples and bioturbation (*Planolites*) occur in some intervals. Paleocurrent directions derived from current ripples and cross-strata are rather scattered but are dominantly towards 60–100°. The subordinate current was towards 220–295°. The clinoforms are gentle (1–2°) and prograde generally eastwards (seawards).

**Interpretation.**

The bipolar but dominantly eastward paleocurrent directions, flaser to wavy bedding, compound and bimodal cross-strata, the ubiquitous mud drapes, and occurrence seawards from Facies Association 2.3 and 2.4 suggest deposition of fluvially derived material in a tide-influenced environment. The upward-coarsening nature, moderate thickness of the association, and seaward progradation into the organic-rich mudstones of Facies Association 2.5 suggest deposition in bayhead deltas (e.g., Dalrymple et al., 1992).

**Facies Association 2.5:**
**Organic-Rich Mudstones**

Facies Association 2.4 can be walked out eastwards into organic-rich mudstones (Fig. 11). The mudstones extend 1–7 km from west to east and are in places vertically stacked into a 15-m-thick succession. The mudstones are interbedded with siltstone or sandstone beds a few decimeters thick.

**Interpretation.**

The ubiquitous organic matter and the landward transition into the bayhead-delta deposits (Facies Association 2.4) indicate deposition in a low-energy, sheltered (lagoonal) basin seaward of the river mouth. The mudstones interfinger eastwards with an estuary-mouth barrier (Facies Association 2.7) and are interpreted as estuarine central-basin deposits (e.g., Dalrymple et al., 1992).

**Facies Association 2.6:**
**Swaly- and Trough-Cross-Stratified Sandstones**

Facies Association 2.5 can be walked out eastwards into complex amalgamated sandstone bodies 4–15 m thick and 2.5–4 km long. These sandstone bodies are based by wave-ravinement-surfaces (Figs. 11, 12). These sandstone bodies thin landwards into the central basin mudstones (Facies Association 2.5) or grade into flood-tidal-delta deposits (Facies Association 2.7 below) (Figs. 11, 12). The sandstone bodies consist of gently (< 1°), eastwards-dipping clinoforms 4–15 m thick. The sandstone bodies stack vertically to form a succession up to 22 m thick. The clinoforms are upward-coarsening units of swaly- to trough-cross-stratified fine- to medium-grained sandstones with occasional wave ripples. The sandstones are in places intensely bioturbated with *Ophiomorpha*, *Terebellina*, *Planolites*, *Arenicolites*, *Teichichnus*, and *Zoophycos*, especially below the surfaces separating the individual clinoforms. The wave-ravinement surfaces are extensive and in many places are lined by clay clasts, quartz pebbles, and shell fragments.

**Interpretation.**

The swaly- to trough-cross-stratified and wave-rippled sandstones in upward-coarsening units are interpreted as wave-generated barrier deposits. Their occurrence seawards of the central-basin mudstones (Facies Association 2.5) and the bayhead delta (Facies Association 2.4) indicates deposition in a wave-generated estuary-mouth barrier (e.g., Dalrymple et al., 1992). The intensely bioturbated surfaces occur at the tops of individual barrier units and record hiatus. The extensive erosion surfaces are interpreted as wave-ravinement surfaces at the bases of individual barrier units.

**Facies Association 2.7:**
**Bidirectionally Cross-Stratified and Climbing-Ripple Cross-Laminated Sandstones**

Facies Association 2.6 is landward (westward) interbedded with gently dipping (0.5–1°), westward-prograding clinoforms 1–3 m thick. These clinoforms are a few hundred meters to a thousand meters long, and consist of bidirectionally trough-cross-stratified and climbing-ripple cross-laminated fine-grained sandstones (Fig. 12D, E). Dominant paleocurrent directions derived from cross-strata and ripples are towards 240–255°, and subordinately towards 30–5°. These sandstones fine westwards into central-basin mudstones.

**Interpretation.**

The bidirectional cross stratification, climbing-ripple cross-lamination, dominant southwestward paleocurrents, westward progradation, and the eastward interfingering with estuary-mouth-barrier deposits (Facies Association 2.6), and the westward transition into the central-basin mudstones (Facies Association 2.5), suggest deposition in flood-tidal deltas (e.g., Dalrymple et al., 1992).

**Facies Association 2.8:**
**Lenticular Bidirectionally Cross-Stratified Sandstones**

Facies Association 2.7 overlies erosionally based lenticular units with bidirectional trough-cross-stratified fine- to medium-grained sandstones 3–5 m thick (Fig. 12). The basal erosion surface has a relief of up to 5 m. The erosion surfaces are lined by clay clasts, quartz pebbles, and shell fragments. Tops of individual lenticular units are intensely bioturbated with *Ophiomorpha*.

**Interpretation.**

The bidirectional cross-stratification together with the severe basal erosion and the association with estuary-mouth-
barrier deposits (Facies Association 2.6) suggest that these are tidal-inlet deposits (e.g., Dalrymple et al., 1992). The erosion surfaces are interpreted as tidal-ravinement surfaces. The tidal-ravinement surfaces have more local relief but are more restricted in their extent compared to wave-ravinement surfaces (Figs. 11, 12).

Depositional Environment

The lateral facies transitions within individual depositional units show a grain-size change from conglomeratic to fine- and very-fine-grained sandstone from west to east, from fluvial sandstones (Facies Association 2.1) to inner-estuarine tidal bars (Facies Association 2.3) and bay-head deltas (Facies Association 2.4; Figs. 9, 11). A similar decrease in sand grain size occurs from east to west from medium-grained sandstones in tidal inlets (Facies Association 2.8) and estuary-mouth barrier (Facies Association 2.6) to fine-grained sandstones in flood-tidal deltas (Facies Association 2.7; Figs. 11, 12). Grain size is commonly assumed to decrease in the direction of sediment transport. This interpretation is confirmed by the dominantly eastward paleocurrent directions in the paleo-landward part of the depositional system, and the dominantly westward paleocurrent directions in the paleo-seaward part of the depositional system. These seaward-landward transitions in facies and grain size reflect bedload convergence into the inner part of the system, and suggest the presence of two different sediment delivery systems. Sediment was delivered to the bayhead-delta complex (including the inner-estuary tidal bars) from a fluvial source, whereas the deposits of estuary-mouth barrier complex were derived from a marine source to the east. Note that although the inner-estuarine tidal-bar deposits were fluviolacustrine, their depositional regime was dominated by tidal currents. Mudstone drapes are most ubiquitous in the inner-estuary tidal bars and the bayhead-delta clinoforms, but they also occur in flood-tidal deltas, indicating increased mud transport and decreasing energy levels towards the inner part of the estuary, where the turbidity maximum occurred and the central-basin mudstones were deposited. Bedload convergence, accompanied by maximum mud deposition in the inner reaches is a characteristic feature of estuaries (Roy et al., 1980; Dalrymple et al., 1990; Dalrymple et al., 1992).

The well-developed tripartite facies distribution with a wave-built barrier and tidal-inlet complex, muddy central basin, and fluviolacustrine deposits that dominate the box-estuary delta suggest that Stratigraphic Unit 2 accumulated in a mixed-energy estuary, similar to, for example, the modern Gironde estuary (Allen and Posamentier, 1993). In such estuaries, a marine sandbody accumulates in the estuary mouth, where the wave energy is high (Roy et al., 1980). The bayhead delta in the mixed-energy estuaries may adopt tide-dominated morphology, in contrast to the fluviolacustrine character of the bayhead delta in the wave-dominated estuaries (Allen, 1991; Dalrymple et al., 1992).

Stratigraphic Unit 3: Tide-Dominated-Estuary Deposits

Stratigraphic Unit 3 overlies Stratigraphic Unit 2 with a prominent tidal-ravinement surface. Stratigraphic Unit 3 is overlain by offshore mudstones of the Black Butte Shale. Stratigraphic Unit 3 consists of four aggradational depositional units (TDU 1–4 in Figure 5). TDU 1 is an erosional remnant and is only ca. 10 m thick (Fig. 5). Each of the depositional units (TDU 2–4) consists of retrogressive to regressive parts and are 17, 24, and 22 m thick, respectively (Fig. 5). Each depositional unit is based by a prominent tidal-ravinement surface, and there are several tidal-ravinement surfaces also within the depositional units. The whole stratigraphic unit is ca. 60 m thick.

Similarly to Stratigraphic Unit 2, all the individual depositional units (TDU 1–4) show similar downdip facies transitions, with coarsest grain sizes in the paleo-landward and paleo-seaward ends of the system, and the finest grain sizes in the middle (Fig. 5). The downdip facies transitions (from west to east) are from Facies Association 3.1 in the westernmost parts to Facies Associations 3.4 towards the east. Facies Associations 3.5 and 3.6 occur lateral to Facies Associations 3.1–3.4.

Facies Association 3.1: Lenticular Coarse-Grained Cross-Stratified Sandstones

Facies Association 3.1 is exposed in the westernmost (landward) reaches of Stratigraphic Unit 3. Facies Association 3.1 consists of dark brown, erosional based, lenticular, coarse- to medium-grained sandstones 1.5–2 m thick (Fig. 13). These sandstones are dominated by bidirectional trough cross-strata (Fig. 13C). Inclined accretion surfaces with superimposed cross-strata or ripples (compound cross strata) also occur. Paleocurrent directions derived from cross-strata are dominantly towards 80–100°. The subordinate current was towards 230–260°. Sandstones of Facies Association 3.1 are very similar to Facies Association 2.1, except for the subordinate westwards paleocurrent indicators and somewhat finer grain size. Tops of these sandstone units are in places rooted.

Interpretation.—

The lenticular shape, erosional base, extensive trough cross-stratification, coarse grain size, bidirectional and dominantly eastward (seaward) paleocurrent indicators, and the presence of plant roots and absence of marine fossils indicate deposition in tidally influenced fluvial channels (e.g., Allen, 1991), where the fluvial channel changes into a tidal–fluvial channel below the upstream tidal limit (e.g., Shanley et al., 1992; Dalrymple et al., 1992).

Facies Association 3.2: Lenticular Compound Cross-Stratified Sandstones with Mudstone Drapes

Facies Association 3.1 can be walked out eastwards into erosional based lenticular, fine-grained sandstones 1–3 m thick (Figs. 13, 14). The sandstones of Facies Association 3.2 contain inclined master surfaces with superimposed current ripples and dunes (compound cross strata), and bidirectional cross strata. Mudstone drapes are ubiquitous. Paleocurrents derived from cross strata are bidirectional, towards 80–100° and 230–260°. In some places the tops of the channels are rooted; in other places sporadic bioturbation with Thalassinoides occurs.

Interpretation.—

The occurrence just seaward of the tide-influenced fluvial deposits (Facies Association 3.1), ubiquitous mudstone drapes, compound and bidirectional cross stratification, and marine or brackish trace fossils suggest deposition in tidal channels in an inner-estuary setting. The ubiquitous occurrence of mudstone drapes may reflect deposition within the turbidity-maximum zone (e.g., McCave, 1979; Jouanneau and Latouche, 1981; Dalrymple et al., 1990; Allen, 1991; Dalrymple, 1992).
Facies Association 3.3:
*Plane-Parallel-Laminated Sandstones*

Facies Association 3.2 can be walked out eastward into erosionally based, upper-fine-grained sandstones 1–3 m thick, dominated by plane-parallel lamination (Fig. 14). In places parting lineations occur (Fig. 14C), as well as occasional interbeds of bidirectionally trough-cross-stratified sandstones. In a few places Facies Association 3.3 is bioturbated at the tops of the depositional units.

**Interpretation.**—

Plane-parallel-laminated fine-grained sandstones with parting lineations and with occasional bidirectional cross strata indicate upper-flow-regime traction deposition by tidal currents. The plane-parallel-laminated intervals formed at maximum tidal flow velocities, whereas the cross strata developed during accelerating or waning flow conditions (e.g., Kreisa and Moiola, 1986). Upper-flow-regime (UFR) tidal sand flats have been reported from the axial parts of modern tide-dominated macrotidal estu-
Facies Association 3.4:
Lateral-Accretion Beds with Cross-Stratified Sandstones

Facies Association 3.3 can be walked out eastwards, as well as laterally and vertically into, is laterally and vertically into erosionally based light-colored, upper-fine- to medium-grained sandstones of Facies Association 3.4 (Figs. 13, 14). These sandstones occur as obliquely landward-accreting master beds with superimposed bidirectional trough cross-strata and cross strata with reactivation surfaces (Figs. 13, 14). The cross sets are 20–85 cm thick, in places up to 1.2 m thick. Mudstone drapes are extremely rare in the easternmost parts of the sandbodies but occur occasionally in the westernmost parts. In a few places, in the easternmost parts of the
sandbodies, swaly-cross-stratified intervals occur. Paleocurrent directions derived from cross strata are dominantly towards 225–280°. Subordinate paleocurrents are towards 75–130°, and the lateral-accretion direction is dominantly towards 23–45°. Bioturbation occurs locally, especially at the tops of individual sandbodies, and is of low diversity (Palaeophycus, Ophiomorpha).

**Interpretation.**—

The erosional bases, extensive bimodal trough cross stratification, lateral accretion, relatively coarse grain size, bidirectional paleocurrent directions, and the significant height and length of the sandbodies suggest deposition in subtidal bars. Such large tidal bars are characteristic of the seaward parts of most macrotidal environments (Hayes, 1975; Harris, 1988; Dalrymple et al., 1990). Tidal sand bars have been described from tide-dominated estuaries, tide-dominated delta fronts, and tide-dominated inner-shelf settings (sand ridges; Swift, 1975; Stride et al., 1982; Twichell, 1983; Dalrymple et al., 1990; sand waves; Allen, 1980).

The bioturbation and occasional wave reworking in the eastern parts of the bars suggest connection to a more open-marine environment. Wave reworking occurred after abandonment of tidal bars or during major storm events. The bioturbation and wave reworking occurred after abandonment of bars. Lack of intense or widespread bioturbation or mudstone drapes is because of the high energy and rapid migration of the large bedforms (Amos et al., 1980; Amos and Lang, 1980; Yeo and Risk, 1981). The higher quartz proportion and better sorting of the sandstones indicates an active marine supply by flood currents.

**Facies Association 3.5:**

*Flaser- to Wavy-Bedded Mudstones and Sandstones*

The above described facies associations of Stratigraphic Unit 3 are laterally and vertically associated with flaser- to wavy-bedded mudstones, siltstones, and very fine-grained sandstones 0.5–4 m thick. The mudstone drapes are ubiquitous. The flaser- to wavy-bedded deposits are interbedded with coal layers up to 1 m thick, of Facies Association 3.6 (Fig. 14). Facies Association 3.5 gradationally overlies deposits of Facies Associations 3.1–3.4, whereas it is erosionally overlain by Facies Associations 3.1–3.4. Rooted horizons are common. In some places bioturbation with Planolites occurs. In places lenticular sandstone bodies, 0.5–1 m thick, occur. These sandstone bodies are typically basied by a lag of mud clasts and consist of compound-cross-stratified, fine-grained sandstones.

**Interpretation.**—

Flaser, wavy, and lenticular bedding with marine or brackish trace fossils indicates deposition from tidal currents (Reineck and Wunderlich, 1968; Reineck and Singh, 1980) and Facies Association 3.5 represents an intertidal succession of decreasing current energy (Dalrymple, 1992). Ripple-laminated sandstones were deposited during maximum tidal flow, whereas mud drapes formed during slack-water periods. The small-scale channeled units of compound-cross-stratified sandstones indicate deposition in tidal gullies that drained the tidal flats (Dalrymple et al., 1991). The occurrence of the tidal-flat deposits along the whole length of the system and the persistently erosional contacts with the other facies associations of the Stratigraphic Unit 3 suggest that the tidal flats occurred marginal to the above described axial succession of Facies Associations 3.1–3.4 (see also Dalrymple et al., 1992).

**Facies Association 3.6:**

*Organic-Rich Mudstones and Coals*

Deposits of Facies Association 3.5 are laterally and vertically associated with organic-rich, coaly, black mudstones, interbedded with coal layers up to 1 m thick (Fig. 14). Rooted horizons and paleosols are common throughout the facies association. In many intervals roots have destroyed all the sedimentary structures, and are associated with rusty patches.

**Interpretation.**—

Organic-rich mudstones and coals, rich in plant fragments and roots, and reworked by pedogenic processes, associated with tidal flats are interpreted as the uppermost, supratidal parts of the marginal tidal mudflats and marshes (e.g., Dalrymple et al., 1992).

**Depositional Environment**

The above described downdip facies transitions show a grain-size change from medium-coarse to fine- and very fine-grained sandstones from west to east from the tide-influenced fluvial sandstones (Facies Association 3.1) to the inner-estuary tidal channels (Facies Association 3.2; Figs 13, 14). The grain size also decreases from east to west from medium-grained sandstones in tidal-bar deposits (Facies Association 3.4) to upperfine-grained UFR tidal-flat deposits (Facies Association 3.3) and into fine- and very fine-grained tidal-channel sandstones (Facies Association 3.2; Figs. 13, 14). These two sediment transport trends are confirmed by the dominant eastward paleocurrent directions in the paleo-landward part of the depositional system, and the dominant westward paleocurrent directions in the paleo-seaward part of the depositional system. These downdip facies transitions reflect bedload convergence into the inner part of the system, into the tidal channel (Facies Association 3.2), and suggest the presence of two different sediment delivery systems, as sediment from the fluvial and from a marine source converge into the tidal channel. Mudstone deposits are most ubiquitous in inner-estuary tidal-channel deposits, indicating increased mud transport and decreased energy levels towards the inner part of the estuary, where the turbidity maximum occurred. Large amounts of mud were deposited on the marginal tidal flats and marshes.

The described downdip facies transitions suggest that Stratigraphic Unit 3 was deposited in a tide-dominated estuary (sensu Dalrymple et al., 1992). Modern examples of tide-dominated estuaries include Cobequid Bay and the Salmon River (Dalrymple and Zaitlin, 1989; Dalrymple et al., 1990; Dalrymple et al., 1991), the Severn River, England (Hamilton, 1978; Harris and Collins, 1985), and the South Alligator River, northern Australia (Woodroffe et al., 1981; Woodroffe et al., 1993). Most modern tide-dominated estuaries are macrotidal, although tidal dominance can occur at much smaller tidal ranges if wave action is limited or the tidal prism is large (Hayes, 1979; Davis and Hayes, 1984). The presence of UFR tidal flats, however, strongly suggests macrotidal (i.e., tidal range is higher than 4 m; Davies 1964) conditions (Dalrymple et al., 1992).

**DIFFERENTIATING TIDAL DEPOSITIONAL ENVIRONMENTS**

Tidal deposits occur in three different depositional environments in the Chimney Rock Tongue: (1) distributary channels of a wave-dominated delta, (2) in a mixed-energy estuary, and
(3) in a tide-dominated estuary. The complexity and variability of tidal sedimentary facies and geometries commonly makes it difficult to recognize specific tidal sub-environments, especially in limited outcrops and cores. It is suggested here that the specific combination of lithologic properties, sedimentary structures, geometries, paleocurrent direction indicators, and presence or absence of marine trace fossils or roots are useful for prediction of the tidal sub-environment along a depositional (downdip) profile.

**Tide-Influenced River or Distributary-Channel Deposits**

The tide-influenced river (Facies Association 2.2 and 3.1) or distributary-channel (Facies Association 1.7) deposits are recognized by (1) relatively coarse grain size and poor sorting, (2) dominant unidirectional trough cross-stratification, commonly with reactivation surfaces, (3) locally bidirectional but dominantly seaward unidirectional paleocurrents, (4) common presence of wood and plant material, coal, and clay clasts, (5) scarcity of mud drapes, (6) absence of marine or brackish trace fossils, (7) channel geometry, and (8) updip association with fluvial deposits and downdip association with mouth-bar or shoreface deposits, or bayhead delta, or tidal-channel deposits. Mouths of tide-influenced rivers or distributaries are dominated by fluvial processes. The current energy is high, but mainly due to the discharge of the river or distributary. Tidal reversals occur at times, but the depositional environment is dominated by fluvial discharge. Well-developed slack-water periods occurred only occasionally. There is no clear difference between the distributary-channel deposits of the progradational delta complex, as compared to the tide-influenced fluvial deposits of the retrogradational estuaries. In the Chimney Rock Tongue, grain size of tide-influenced river deposits is coarser than the grain size of distributary-channel deposits.

**Inner-Estuary Tidal-Channel Deposits**

The inner-estuary tidal-channel deposits in the tide-dominated estuaries in the Chimney Rock Tongue are recognized by (1) fine and very fine sand grain size, and rather poor sorting, (2) presence of ubiquitous mudstone drapes and clay clasts, (3) dominance of trough cross stratification and compound cross stratification, (4) clearly bidirectional paleocurrent indicators, (5) channel geometry, and (6) updip association with tide-influenced fluvial or with fluvial deposits, and downdip association with upper-flow-regime tidal-flat or tidal-bar deposits. These inner-estuary deposits occur in the tide-dominated estuaries, where the fluvial and tidal current energies are lowest and the turbidity maximum occurs (see Dalrymple et al., 1992); consequently sand grain size is small and mud content is high. Slack-water periods are most well defined here, as seen by the ubiquitous mud drapes. Although the morphology of the inner-estuary tidal bars is controlled by tidal currents, sand is derived from the fluvial system, inasmuch as the central basin lies seaward of the inner-estuary bars. The inner-estuary bars of the mixed-energy estuary and the inner-estuary channel deposits of the tide-dominated estuary in the Chimney Rock Tongue are very similar. The main differences are bar and channel shape, respectively, and the updip and downdip facies transitions.

**Outer-Estuary Tidal Bars**

The outer-estuary tidal bars occur in the seaward ends of the tide-dominated estuaries and are recognized by (1) good sorting and coarse grain size of sandstones, (2) dominance of trough cross strata, (3) occurrence of upper-flow-regime plane beds, (4) general lack of mudstone drapes, (5) bidirectional or dominantly landward paleocurrent indicators, (6) lateral-accretion beds and bar geometry, (7) local wave reworking in the most seaward parts, and (8) updip association with UFR tidal flats or inner-estuary tidal-channel deposits, and downdip association with marine mudstones. The outer-estuary tidal bars are supplied with sand from a marine source outside the estuary. The tidal energy is high, and slack-water periods are not well developed, as seen by the lack of mud drapes. Association with upper-flow-regime tidal flats is a characteristic feature.

**DIFFERENTIATING WAVE-DOMINATED ENVIRONMENTS**

**Wave-Dominated-Delta or Strandplain Deposits**

Although dominated by storm-wave and fair-weather-wave deposits (Facies Associations 1.2–1.6), the clinoforms of Stratigraphic Unit 1 are interpreted as a wave-dominated delta complex, based on (1) the documentation of distributary channels, fluvial mouth bars, and local sediment-gravity-flow-dominated delta-front deposits, and (2) the steepness of individual clinoforms within the clinoform sets.

**Wave-Dominated-Delta or Estuary-Mouth-Barrier Deposits**

The common occurrence of plane-parallel-laminated and wave-rippled sandstones in the upper-shoreface position of the wave-dominated delta of Stratigraphic Unit 1 suggests that the Chimney Rock paleo-shoreslines were of relatively low energy during fair-weather conditions. Consequently, most of the deposition occurred during storm events. On the contrary, the upper-shoreface deposits of the wave-dominated estuary-mouth barrier of Stratigraphic Unit 2 are dominated by trough-cross-stratified sandstones, interbedded with only occasional swaly cross strata. This suggests a generally higher energy and active deposition during fair-weather conditions compared to the shorelines of Stratigraphic Unit 1.

**CHANGE OR LATERAL VARIABILITY OF PROCESS REGIME**

The Chimney Rock Tongue exposes an apparent change in process regime, notably a “switch-on” of tides, from wave domi-
Fig. 14.—Close-up of TDU 2 and TDU 3 in the tide-dominated estuary (see Fig. 5 for location). A) Original and B) annotated photomosaic of inner-estuary channel deposit (FA 3.2; light brown), cut by a tidal ravinement surface, and overlain by an outer-estuary bar deposit (FA 3.4; white). C) Photo showing parting lineations at the base of a bed from UFR tidal-flat deposits (FA 3.3). D) Photo showing plane-parallel-laminated sandstones, characteristic of UFR tidal-flat deposits (FA 3.3), with trough-cross-stratified interbeds. E) Fine-grained, marginal-tidal-flat and marsh deposits (FA 3.5 and 3.6).
nance in the deltas of Stratigraphic Unit 1, to mixed-energy conditions in the estuaries of Stratigraphic Unit 2, and into tide dominance in Stratigraphic Unit 3 (Fig. 15). Moreover, the change in process regime seems to occur at the regressive–transgressive turnaround, inasmuch as the volume of tidal deposits in Stratigraphic Unit 2 is considerably higher than in Stratigraphic Unit 1. It is argued below, however, that the actual change in process regime occurred when the mixed-energy estuary changed into the tide-dominated estuary. This change was caused by enhancement of the tidal range into macrotidal conditions. Relative sea-level fall and rise affects sediment supply to coastlines, through forcing river systems out towards the basin or back towards the land, and through changing the shape and bathymetry of the coastline. These are also the factors that have the potential to change process regime and to enhance tides, waves, or fluvial processes. However, the changes in process regime may be laterally restricted, and reflect a spatial rather than a temporal change in a basin. Consequently, apparent process-regime changes in a stratigraphic section may reflect a lateral variability in the system.

River- to Wave-Dominated Facies Change: Lateral Variability

Detailed documentation of the Chimney Rock Tongue reveals that in the Stratigraphic Unit 1 wave-dominated delta complex both wave- and river-dominated intervals occur (Facies Associa-
tions 1.1–1.6 and 1.7–1.9, respectively). This apparent temporal shift in process regime between fluvial and wave dominance is more likely to reflect downw ard–upw ard position in relation to the distributary mouth, rather than a temporal change in process regime in the basin (Fig. 15). River-dominated mouth-bar and delta-front deposits have been documented to be preferentially preserved downw ard from distributary mouths, where protected by spits or barriers (see Bhattacharya and Giosan, 2003).

Wave- to Tide-Dominated Facies Change: Lateral Variability

The distributary-channel deposits in the delta of Stratigraphic Unit 1 reflect strong tidal influence in the distributary mouths. This implies that the tides were not "switched off" at that time, and "switched on" later during the infilling of the estuaries of the Stratigraphic Units 2 and 3. The tides operated also during deposition of the wave-dominated delta, but in areas sheltered from waves. Tidal energy may also have been increased locally where the tidal wave was laterally constricted into the distributary mouths.

There is, however, a marked increase in the volume of tidal deposits and a decrease in the volume of wave deposits in the mixed-energy estuary of Stratigraphic Unit 2, as compared to the underlying Stratigraphic Unit 1. This apparently suggests a significant increase in tidal energy. However, the tidal influence in the distributary-channel fills of Stratigraphic Unit 1 and the wave-dominated character of the estuary-mouth barrier in Stratigraphic Unit 2 suggest that there was no change in process regime. Nor did this documented facies change require an actual change in general tidal range or tidal prism. Instead, the area which was protected from waves had increased, due to the increased coastline irregularity after the valley incision, and the formation of the estuary-mouth barrier. The general wave and tide regime did not necessarily change. The fair-weather wave energy may actually have increased, as suggested by the larger proportion of the fair-weather deposits in the estuary-mouth barrier compared to the wave-dominated delta.

Change in Process Regime from Wave to Tide Dominance

Stratigraphic Unit 3 consists of tide-dominated-estuary deposits, and wave-generated deposits are practically missing. The mouths of such estuaries are not protected by wave-generated barriers, but are of open-mouth type. Disappearance of the wave-generated estuary-mouth barriers requires a relative increase in tidal energy or decrease in wave energy. The majority of modern tide-dominated estuaries are macrotidal (Wright et al., 1973, 1985; Coleman and Wright, 1978; Hamilton, 1979; Bouma et al., 1980; Lambiase, 1980a, 1980b; Bartsch-Winkler and Ovenshine, 1984; Harris and Collins, 1985; Dalrymple and Zaitlin, 1989; Woodroffe et al., 1989; Dalrymple et al., 1990; Amos et al., 1991). Also, the occurrence of upper-flow-regime tidal flats is commonly considered diagnostic of macrotidal estuarine environments, inasmuch as they have been reported only from the axial parts of modern tide-dominated macrotidal estuaries (Hamilton, 1979; Lambiase, 1980a, 1980b; Dalrymple et al., 1990; Dalrymple, 1992). This evidence suggests that tidal range increased from Stratigraphic Unit 2 to 3. Tidal range may increase with an increased width of a shelfal platform (e.g., Pugh, 1987), or with a "switch on" of tidal resonance (Pugh, 1987; Dalrymple, 1992; Emery and Myers, 1996). Similar change in process regime from a wave-dominated to tide-dominated estuary because of the onset of tidal resonance occurred in the Holocene to modern estuary of the Bay of Fundy, where the tidal wave entered into resonance with the configuration of the basin because of a slight rise in sea level (e.g., Dalrymple and Zaitlin, 1994). When a mixed-energy estuary becomes filled with sediment, the bay-head-delta system progrades seawards and the flood-tidal delta extends progressively farther up the estuary, and the central basin shrinks and ultimately ceases to exist. At this point, the tidal channels in the flood-tidal delta merge with the river channel, thereby allowing tidal energy to penetrate into the inner estuary more easily (see Dalrymple et al., 1992).

THICKNESS OF ESTUARINE DEPOSITS

The thickness of mixed-energy-estuary deposits of the Chimney Rock Tongue and the regressive character of the uppermost depositional unit suggest that the incised valley, cut during the preceding relative sea-level fall, was filled in situ (see Dalrymple et al., 1992). This implies that the overlying succession of the tide-dominated estuary occupied a drowned river mouth rather than an incised valley. The latter is confirmed by the transgressive-to-regressive nature of each individual depositional unit of Stratigraphic Unit 3. Each depositional unit then reflects an episode of tidal ravinement and reshaping of the river mouth, and in situ infilling. There are multiple tidal ravinement surfaces, with the most prominent cuts at the base of each of the depositional units.

The total thickness of the estuarine deposits in the Chimney Rock Tongue is ca. 90 m. The 30-m-thick mixed-energy-estuary deposits filled an incised valley. Above lie vertically aggrading, tide-dominated estuarine deposits ca. 60 m thick. There is no evidence for fluvial incision within Stratigraphic Unit 3 to create local accommodation for such a thick estuarine package. The global long-term change in the Late Cretaceous was sea-level fall (Abreu et al., 1998). The Western Interior Basin experienced, however, high rates of subsidence between 84 and 78.5 Ma, because of flexural subsidence created by early Absaroka thrusting, further enhanced by dynamic subsidence (Liu and Nummedal, 2004; Liu et al., 2005). The latter was especially significant from about 83.9 to 78.5 Ma, and occurred due to sublithospheric loading and cooling induced by the shallowly subducted Farallon Plate (Liu and Nummedal, 2004; Liu et al., 2005). The aggradation of the 60-m-thick tide-dominated estuarine succession is also evidence for a high sediment supply that maintained infill of the subsiding basin.

CONCLUSIONS

1. The Chimney Rock Tongue is a regressive–transgressive shoreline complex, and contains a wave-dominated-delta succession, overlain by a mixed-energy-estuary complex and a tide-dominated-estuary complex.

2. The volume of tide-generated deposits increases across the regressive–transgressive turnaround. This facies change from wave dominance to tide dominance is interpreted to reflect change in shoreline configuration due to erosion and later flooding of an incised valley, rather than a change in process regime change in the basin. A mixed-energy estuary with a wave-dominated estuary mouth and tide-dominated inner estuary occupied and filled the incised valley.

3. After in situ infilling of the incised valley, a change in process regime occurred as the tidal range increased to macrotidal. The river mouth was occupied by a tide-dominated estuary and experienced severe tidal ravinement.

4. The aggradational, 60-m-thick tide-dominated-estuary succession accumulated due to high rates of flexural and dynamic subsidence.
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