TIDAL SEDIMENTOLOGY AND ESTUARINE DEPOSITION OF THE PROTEROZOIC BIG COTTONWOOD FORMATION, UTAH

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ABSTRACT: The Mesoproterozoic to Neoproterozoic Big Cottonwood Formation of north-central Utah contains some of the oldest known (~ 900 Ma) examples of cyclic tidal rhythmites. Despite mild metamorphic overprinting, there is excellent preservation of sedimentary structures. The thick formation (4.8 km) has been previously interpreted as a shallow-water, intracratonic basin deposit. Five distinct facies are recognized. Two quartz arenite facies are dominated by dune (meter-scale) cross-bedding recording westward flow, but distinguished by different large-scale geometries: (1) thick, tabular bodies (10–20 m thick by 600+ m long) and (2) channeled beds (0.3–0.3 m thick by hundreds to thousands of meters long). Channeled beds have scoured bases and coarse-grained lags or rip-up clasts. Stacked channel beds form upward-fining successions up to 50 m thick. Three distinct argillite facies contain different structures and cyclicities, and are also characterized by color. Dark, laminated argillites contain abundant heterolithic rhythmites (with thick couplets up to 1 cm per lamina), syneresis cracks, flame structures, internal truncation scours, intraformational blocks/clasts, and diagenetic pyrite. The other two argillite facies commonly occur overlying channelized quartzites in large-scale upward-fining successions. A transitional argillite composed of thin intertidal beds grades upward into mud-cracked argillite of massive to weakly bedded intertidal to supratidal beds characterized by wave ripples and abundant mud cracks. Important diagnostic tidal features recognized in the Big Cottonwood Formation include: (1) heterolithic tidal rhythmites, (2) current ripples with crests rounded by backflow, (3) sigmoidal bundles, and (4) abundant clay-draped reactivation surfaces. Other structures that corroborate the tidal interpretation include: (1) flaser bedding, (2) mud cracks, and (3) mud-draped wave ripples.

The sedimentary structures and genetic sequence relationships recognized in this study suggest deposition in a tide-dominated estuary. The laminated argillites with heterolithic rhythmites indicate subtidal deposition in tidal channels. Sand-filled tidal channels are represented in stacked quartzite beds that grade to transitional argillite and thin successions of mud-cracked argillite. Thicker units of mud-cracked argillite may represent deposition in tidal flats with periodic exposure. Tabular sheet quartzites suggest deposition as sand sheets near the mouth of the estuary. Our documentation of tidal rhythmites and estuarine deposition suggests previously unrecognized Mesoproterozoic to Neoproterozoic tidal deposition in north-central Utah.

INTRODUCTION

Recent interest in the Big Cottonwood Formation was sparked by the discovery of some of the oldest known examples of tidal rhythmites, and related tidal structures (Chan et al. 1994; Archer and Johnson 1997; Kvale et al. 1997). This study documents Proterozoic estuarine deposition and provides a new perspective on the paleogeography of the unit, as well as insight into Proterozoic Earth–Moon orbital mechanics (Sonett et al. 1996; Kvale et al. 1997).

The best exposures of the late Mesoproterozoic to Neoproterozoic Big Cottonwood Formation are located in Big Cottonwood Canyon, just east of Salt Lake City, Utah (Fig. 1). The formation received little attention since the 1970s. However, despite mild metamorphic overprinting (greenschist facies), sedimentary features are well preserved. The Big Cottonwood Formation and correlative Uinta Mountain Group (Fig. 2) were previously interpreted as shallow-water intracratonic-basin deposits, fed from the east by a braided fluvial system of the Uinta Mountain Group (Wallace 1972; Crittenden 1976; Sanderson 1978; Link et al. 1993). These intracratonic generalizations predate the discovery of tidal signatures (Chan et al. 1994) in the Big Cottonwood Formation. The purpose of this study is a detailed analysis of the sedimentology and estuarine interpretation of the depositional setting encompassing the tidal influence.

REGIONAL BACKGROUND AND STRATIGRAPHY

The Big Cottonwood Canyon area lies astride the Cordilleran hinge line (Wasatch Line) (Crittenden 1976, p. 363), where Neoproterozoic and Paleozoic passive-margin strata thicken drastically westward. Outcrops in Big Cottonwood Canyon lie structurally below the far-traveled Absaroka, Willard, and Charleston thrust sheets of the Sevier orogenic belt. Despite the

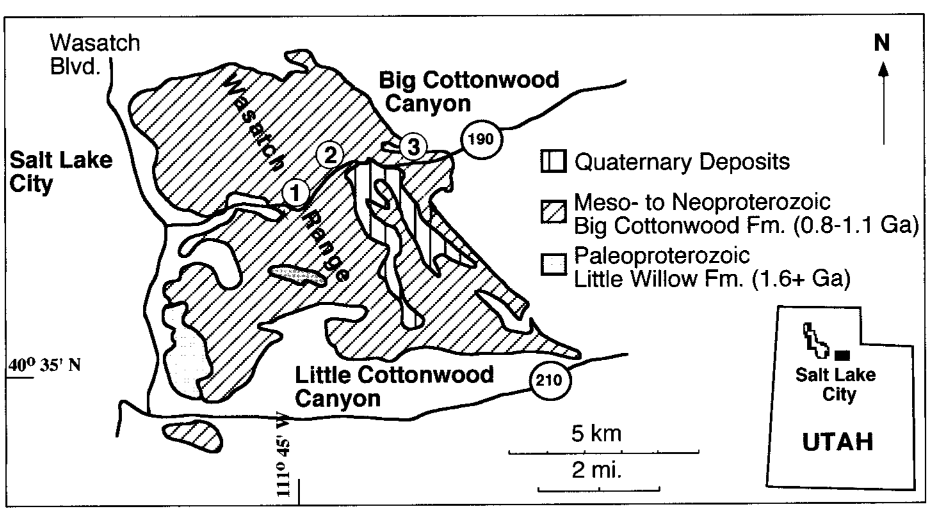

FIG. 1.—Generalized location map of Big Cottonwood Canyon, southeast of Salt Lake City. Circled numbers refer to measured sections of: 1, Storm Mountain (Fig. 7); 2, S-curve (Fig. 9B); 3, Moss Ledge (Fig. 9A).

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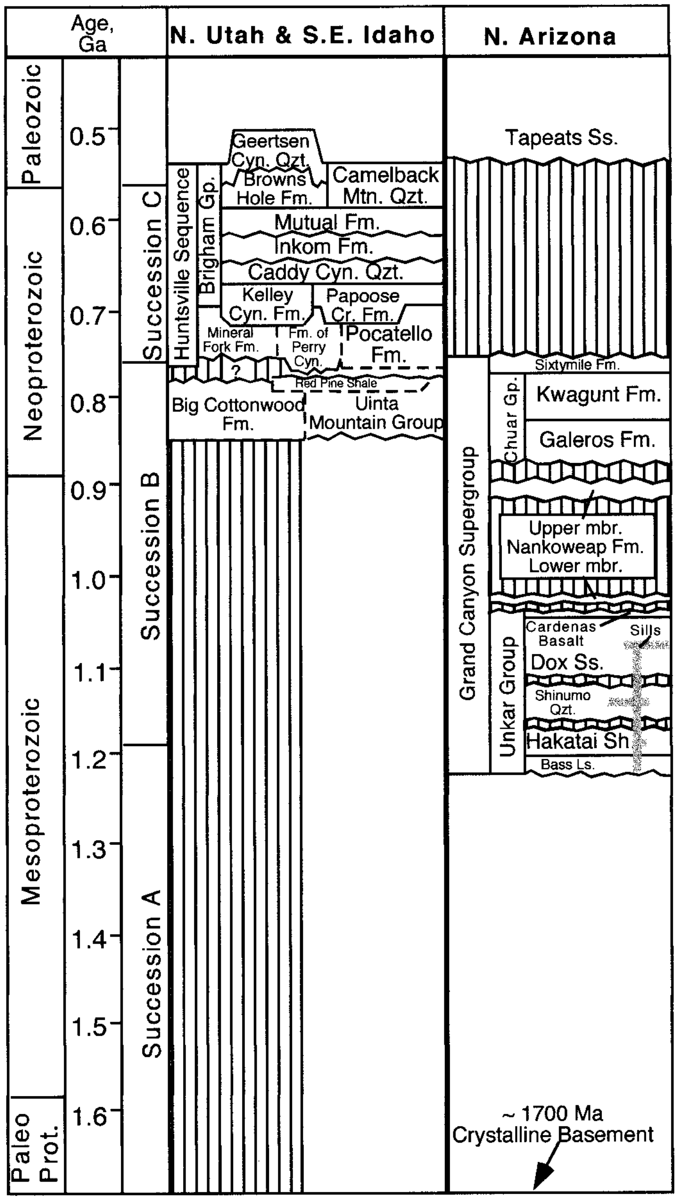

FIG. 2.—Stratigraphic correlation chart of Proterozoic succession B and C of western North America. Blank areas represent missing record, or igneous rocks not shown on diagram. Modified from Link et al. (1993).

overlying thrust-sheet displacements on a scale of tens of kilometers, the Big Cottonwood outcrops have limited displacement and are parautochthonous. The Big Cottonwood Formation was deposited tens of kilometers east of the bulk of the largely allochthonous Mesoproterozoic and Neoproterozoic strata exposed along the western margin of North America (Young 1979; Levy and Christie-Blick 1989, 1991; Winston 1991; Link et al. 1993; Rainbird et al. 1996).

Previous geologic studies of the Big Cottonwood Formation included mapping and general lithologic distinctions of quartzites and argillites (Crittenden 1965a, 1965b, 1965c, 1965d, 1976; Crittenden and Wallace 1973). James (1979) later summarized the geology and history of the Big Cottonwood mining district, with emphasis on the mineral deposits.

The thickest and best preserved exposure of the Big Cottonwood Formation is located in the type area of Big Cottonwood Canyon (Fig. 1, 3), with less complete sections (800 m or less) exposed elsewhere in Utah (Slate Canyon, East Tintic Mountains, Stansbury Island, and Carrington Island). The scope of this study focuses only on the thick and relatively continuous exposures in Big Cottonwood Canyon. The unconformable base of the Big Cottonwood Formation, where accessible, is defined by a thin conglomerate with clasts derived from the underlying Paleoproterozoic Little Willow Formation (Crittenden 1976). The Big Cottonwood Formation is unconformably overlain by the Neoproterozoic Mineral Fork Formation where present, and by the Neoproterozoic Mutual Formation elsewhere.

Regionally, the Big Cottonwood Formation is correlated to the Uinta Mountain Group of northeast Utah and the Chuar Group of northern Arizona (Fig. 2; Elston 1989; Uphoff 1997). Correlations are based on paleomagnetic data (Elston 1989; Link et al. 1993) and on commonality of microfossils, including acritarchs and *Melanocyrillium* (Hofmann 1977; Knoll et al. 1981; Vidal and Ford 1985). The Big Cottonwood Formation and Uinta Mountain Group have been interpreted as deposited in the same tectonic and paleogeographic setting (Ehlers et al. 1997). The Big Cottonwood Formation, Uinta Mountain Group, and Chuar Group are collectively placed in the late Mesoproterozoic to early Neoproterozoic (Link et al. 1993).

TIDAL CYCLICITIES

There is a well-established literature on tides and tidal systems (for excellent summaries see Nio and Yang 1991, and Dalrymple 1992). Recent studies of tidal rhythmites and bundles have contributed to the recognition of tidal environments and tidal cycles (e.g., Archer et al. 1991; Williams 1991; Archer 1996). The tidal periodicities in rhythmites have been used to interpret orbital mechanics (e.g., Sonett et al. 1988). Although harmonic analyses from drilled cores (Fig. 4A, B) were previously performed on the Big Cottonwood Formation rhythmites (Chan et al. 1994; Sonett et al. 1996; Archer 1997; Kvale et al. 1997), this paper provides the sedimentologic and paleogeographic context of the tidal deposits.

The best preserved tidal rhythmites are vertically stacked cyclic alternations of light (silt/sand-rich) and dark (mud-drape) laminae. Herein we refer to these alternating laminae as heterolithic rhythmites because of the contrasting grain sizes. Individual laminae represent diurnal semidaily/daily tides with the silt/sand deposited by the dominant tide, and mud deposited by the slack and/or subordinate tide. Individual laminae are vertically organized into repeating packages of thick and thin laminae (neap–spring cycles). Individual laminae can be counted and measured with respect to lamina thickness. The thickest laminae (dominated by thicker silt/sand laminae) are deposited by stronger spring tides when the greatest gravitational pull occurs with alignment of the Moon, Earth, and Sun. These spring tides occur during new-Moon and full-Moon cycles. Thin laminae (dominated by mud) are deposited by neap tides, when the Moon is out of phase with the Earth and Sun and the gravitational pull. Thus, alternating packages of thin mud laminae and thicker sand laminae constitute a neap–spring cycle, or a half month (e.g., Archer 1996; Kvale et al. 1997). Four groups of laminae (two mud-laminae packages and two sand-laminae packages) constitute a full lunar month (synodic month). Harmonic analyses were used to determine these monthly and additional tidal periodicities, with various smoothing and interpolation programs employed where laminae were truncated or difficult to distinguish (Fig. 4B; Chan et al. 1994; Archer 1997).

Tidal rhythmites were identified at eight different stratigraphic zones (Fig. 3) within the Big Cottonwood Formation, and are either laterally continuous from hundreds to thousands of meters or truncated because of scour. Rhythmite thicknesses range from approximately several millimeters (Fig. 4C) to 20 cm (Fig. 4D) per neap–spring cycle. The thickest groups of tidal rhythmites contain neap–spring cycles with about 14–16 dominant subordinate couplets per neap–spring cycle (e.g., Fig. 4C). In general, neap–spring cycle thicknesses tend to cluster around 26 cm (Chan et al. 1994; Archer 1997).

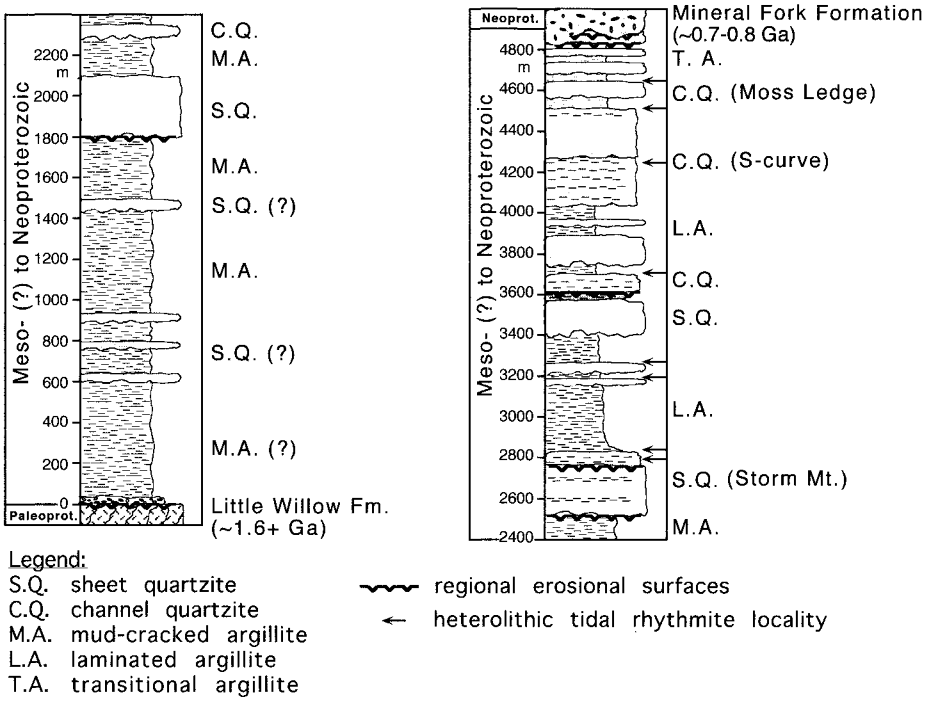

FIG. 3.—Generalized measured stratigraphic section of the Big Cottonwood Formation. Identified lithofacies discussed in text are shown to the right of each column. Erosional unconformities are shown by seven thick lines throughout the section.

BIG COTTONWOOD LITHOFACIES

Our stratigraphic and sedimentologic studies utilized measured sections, paleocurrent analysis, aerial photographs, photomosaics, and petrography (visual estimates from thin section). A composite stratigraphic section (Fig. 3) is based on detailed measurements of the accessible upper two-thirds of the formation. Lithofacies within the less accessible lower third of the formation were assigned thicknesses based on geologic map outcrop width (James 1979) supplemented by reconnaissance studies at scattered outcrops.

Five distinct sedimentary lithofacies are identified: two quartzite facies (channeled and sheet quartzite), and three argillite facies (mud-cracked argillite, laminated argillite, and a transitional argillite). The lithofacies alternate throughout the stratigraphic section (Fig. 3); the section is roughly half quartzite and half argillite. The two quartzite facies (slightly metamorphosed quartz arenites) are similar in lithology and internal structure but differ in lateral geometry. The three argillite facies are slightly metamorphosed mudstones to siltstones characterized by distinctly different internal structures. Characteristic stratigraphic position, geometries, lithology, and sedimentary structures for each facies are summarized in Table 1. Although some sedimentary structures are well preserved, others appear to be obscured by metamorphic overprinting. The formation experienced Sevier-age folding and tilting, which resulted in its present exposure as an eastward-plunging anticline (Crittenden 1976). One hundred and fourteen paleocurrent measurements from cross-bedding and current ripples in the upper two-thirds of the formation were corrected for folding and tilting to arrive at a dominant westward paleoflow direction (Fig. 5).

Quartzite Lithofacies

Channeled Quartzite.—The channeled quartzite facies constitutes 31% of the 4.8 km, composite, Big Cottonwood Formation section (Fig. 3) and is very light to light gray in color. The quartz arenites of this facies consist of 95% or more quartz (grains plus overgrowth cement) with minor clay matrix of $\sim$ 5% or less (Fig. 6A). This arenite is well sorted, and grain size is dominantly fine to medium-grained, with the exception of some local coarse-grained beds and lags. Individual quartz grains are subrounded to rounded, indicating significant mechanical transport. Tabular cross-bed sets (Fig. 6B) are common within the channeled quartzite. Throughout the formation, bed set thicknesses are 0.3–1.0 m. Individual channels are tens of meters wide by several meters high. Stacked bedsets tens of meters thick display upward fining of grain size and thinning of cross-bed sets. Sigmoidal bundles in the channeled quartzite contain cross-stratified sand layers separated by mud and finer-grained drapes, suggesting alternating flow conditions with tidal deposition. Other sedimentary structures observed in the channeled quartzite facies include current ripples with a dominant westward flow direction, and scoured bases with lags and coarse-grained rip-up clasts. Soft-sediment deformation is common and includes convolute laminae. This quartzite facies typically grades upward into transitional argillite or is overlain by laminated argillite facies described later.

The channeled quartzite facies is interpreted to represent tidal–fluvial channels. The fluvial character is evident from the erosional channel geometry, upward fining and thinning of cross-bedding, presence of lags along scoured bases, and current ripples. Sigmoidal bundles suggest alternating flow conditions typical of tidal channels. Soft-sediment deformation and bank-collapse structures containing ''blocks'' of rhythmites from the overlying laminated argillite facies indicate tidal influence associated with the channels.

Sheet Quartzite.—Approximately 19% of the composite formation (Fig. 3) is composed of the sheet quartzite. This facies is very light to light gray in color. The sheet quartzite is compositionally similar to the channeled quartzite. The sheet quartzite differs from the channeled quartzite in the lack of channel geometries and associated sedimentary structures (e.g., lack of sigmoidal bundles, current ripples, and soft-sediment deformation). In general, internal sedimentary structures are difficult to distinguish in the sheet quartzite (Fig. 7). Thick (tens of meters), seemingly massive sections are common. Faint cross-bedding is visible in some locations and most likely was originally prevalent throughout the facies but is not well preserved or is obscured by weathering. This facies occurs in stacked tabular bodies 10–20 m thick by 600+ m long. Tabular beds have sharp, planar contacts and lack coarse-grained lags. Normal grading is visible within 10 m intervals, and wave ripples with amplitudes and ripple-crest spacings of about 0.7 cm and 3.1 cm, respectively, are exposed on some bedding

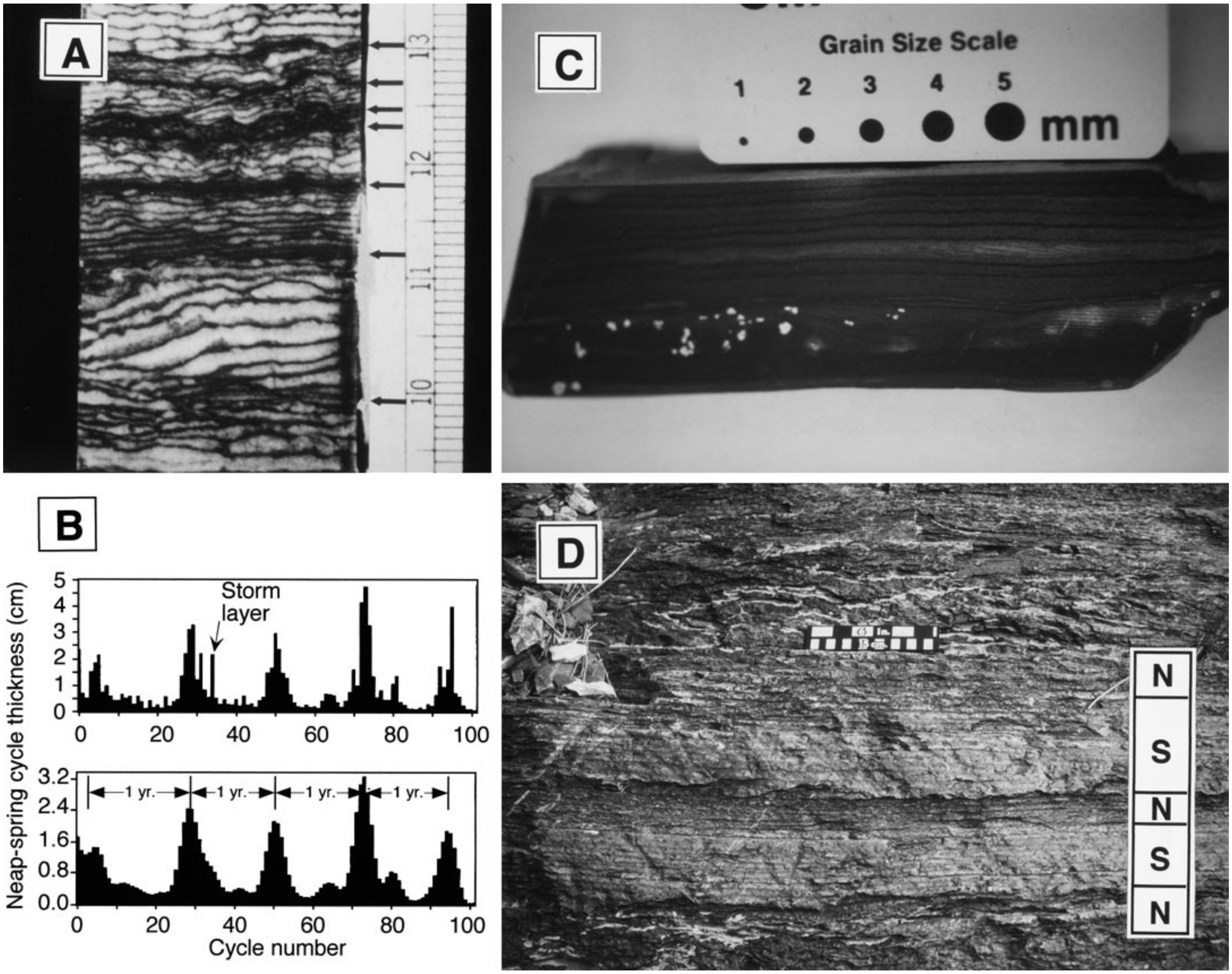

FIG. 4.—**A)** Tidal rhythmites with climbing ripples collected from core. Dark arrows represent the location of neap cycles (from Chan et al. 1994). **B)** Histogram showing thickness variations in a core sample of tidal rhythmites (modified from Chan et al. 1994). Top panel shows the raw data including an anomalous peak at cycle 34, which is a massive unit with rip-up clasts at base. This cycle is interpreted as a storm event. The lower panel of B is a five-term smoothed version of the raw data that illustrates four major annual cycles. **C)** Thinly laminated tidal rhythmites from the base of the laminated argillite facies. Thicknesses of neap–spring cycles in this example are about 3 mm. Diagenetic pyrite (bright spots) are present in the lower half of the sample. **D)** Planar-laminated rhythmites located in the Big Cottonwood Formation. Neap–spring (N, S) cycles shown here have thicknesses of about 1520 cm.

planes. Symmetric megaripples present in this facies have amplitudes and wavelengths of $\sim$ 310 cm and 22–52 cm, respectively.

The depositional environment recorded by the sheet quartzite is difficult to interpret because of the lack of distinguishable sedimentary structures. However, the presence of wave ripples and tabular geometries, with a corresponding lack of channel forms of this facies, suggest that it was deposited as sand sheets, most likely between the mouths of tidal–fluvial channels and a large body of water. The vertical proximity (within 100–200 m, Fig. 3) of this facies to the channeled quartzite in addition to compositional similarity between facies and internally similar westward-dipping cross-bed sets suggests that the tidal–fluvial channels fed the seaward sand sheets.

Argillite Lithofacies

Mud-Cracked Argillite.—The mud-cracked argillite is exposed in stratigraphic successions 100–500 m thick in the lower half of the section, and in thinner ($<$ 20 m) successions in the upper half of the section where it overlies the transitional argillite. This facies constitutes 41% of the composite Big Cottonwood Formation (Fig. 3). This facies is generally grayish red purple in color. It is the most abundant argillite within the section, and is developed predominantly in the lower half of the formation. This argillite contains 10–55% quartz and 45–90% clay. Bedding is weakly defined, but where present it is thickly laminated to thinly bedded. Although the facies is largely argillite, it contains some fine-grained sandstone beds. Polygonal silt to sand-filled mud cracks are common, with polygon diameters of 5–30 cm. Raindrop impressions were reported by Crittenden (1976). On some bedding planes wave ripples are weakly superimposed on mud-cracked beds. Small irregular and crinkly laminae of fine to medium-grained sand are interpreted as adhesion structures. The mud-cracked facies overlies either the sheet quartzite or transitional argillite.

Sedimentary structures preserved in the mud-cracked argillite indicate shallow-water deposition to subaerial exposure. The wave ripples suggest subaqueous deposition and oscillatory flow. Mud cracks, raindrop impres-

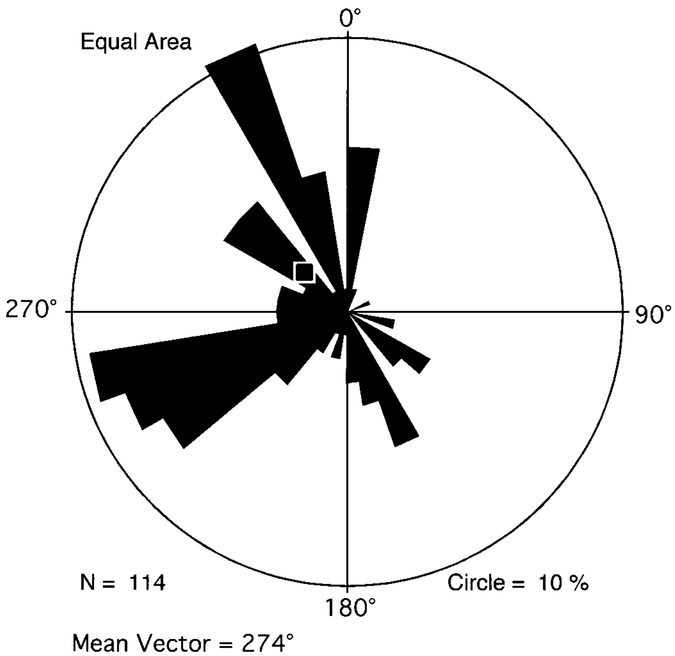

FIG. 5.—Rose diagram showing northwestern paleoflow direction determined from cross-bedding and current ripples.

TABLE 1—*Big Cottonwood Formation Lithofacies Summary*

Facies Name	Sedimentary Structures	Facies Association	Interpretation
Channelized Quartzite	• Channeled, upward-fining successions 10s of m thick • Cross-bed sets 0.3–1.0 m thick • Sigmoidal bundles* • Scoured bases, lags • Current ripples	• Grades into all the argillite facies	• Tidal fluvial channel
Sheet Quartzite	• Thick tabular bodies: 10–20 m thick by 600+ m long • Internal, upward-fining • Wave ripples	• Overlies and underlies all facies	• Sand sheet or tidal sand bar
Mud-cracked Argillite	• Mud cracks, rain drop impressions • Adhesion structures • Weakly bedded • Wave ripples	• Overlies channeled quartzite or green-gray argillite	• Intertidal to possibly supratidal mudflat
Laminated Argillite	• Thinly laminated at base with heterolithic rhythmites* • Diagenetic pyrite • Syneresis cracks • Some erosional truncations and rotated blocks	• Generally overlies channeled quartzite	• Subtidal channel to intertidal mudflat
Transitional Argillite	• Heterolithic rhythmites at base (with annual cycles) • Thin (<30 cm) discontinuous quartzite and argillite beds • Current ripples with crests rounded by backflow* • Clay-draped reactivation surfaces* • 10–20 m thick • Small soft-sediment deformation and load structures	• Overlies channeled quartzite	• Intertidal at base to supratidal at top. Tidal-channel flood plain
OVERALL SETTING	• Estuary (transition from fluvial to tidal)		

* Indicates diagnostic tidal structure.

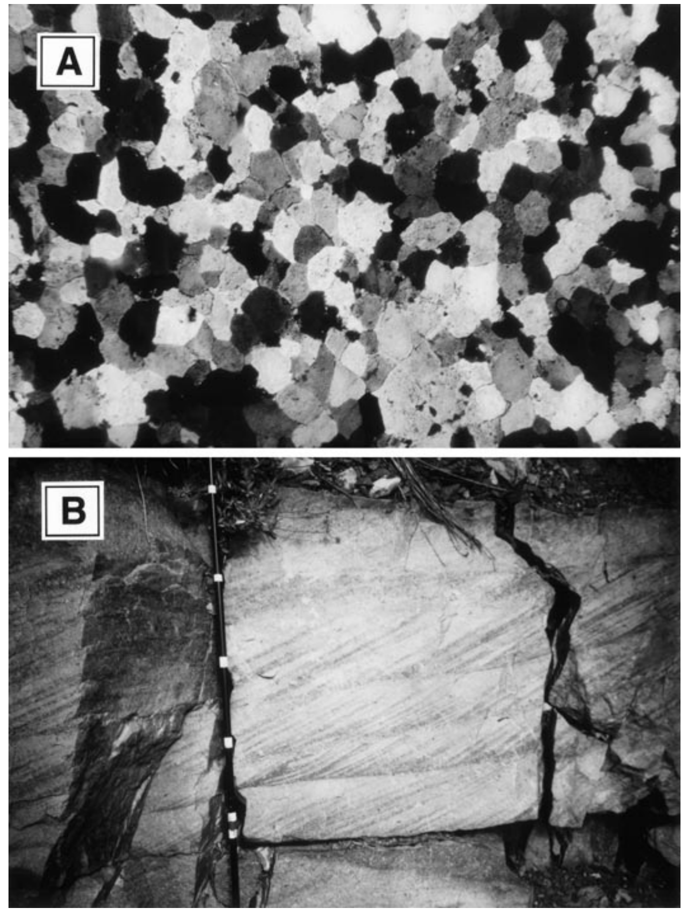

FIG. 6.—Channeled quartzite facies: **A)** representative thin section in crossed-polarized view (field of view is 4 mm); **B)** tabular planar cross-beds.

sions, and adhesion structures imply intermittent wet and dry conditions with probable deposition in an intertidal to supratidal environment.

Laminated Argillite.—The laminated argillite lithofacies constitutes 15% of the stratigraphic section (Fig. 3) and is recognized only in the upper half of the formation. The facies contains a mix of lithologies, with the fine-grained argillite being less indurated than parts containing fine-grained sand. The facies is black to gray in color and compositionally resembles the mud-cracked argillite with 35–65% quartz and 45–65% clay. Alternating laminae of black silt and light-colored fine-grained sand are present in stacked successions up to 3 m thick. These packages of laminae are interpreted to be tidal rhythmites on the basis of spectral analysis techniques, which demonstrate periodicities within stacked successions that match modern daily and semimonthly lunar cycles (Fig. 4; see also previous studies of Chan et al. 1994 and Archer 1997). Rhythmites are present at the base of this facies, where it overlies channeled quartzite. Syneresis cracks, or subaqueous shrinkage cracks (Fig. 8), are common along the bases of argillite beds. Diagenetic pyrite cubes occur (e.g., see Fig. 4D) in the lower parts of the facies and commonly crosscut the laminae. Deformation features in this facies include small load casts, flame structures, and contorted and truncated laminae. Large (0.7 by 1.5 m) rotated slump blocks of laminated argillite are present within the channel quartzite facies. This argillite is fissile, and overlies the channeled quartzite facies.

The laminated argillite is interpreted to represent deposition in a subtidal to intertidal environment. The base of the facies contains structures that suggest subtidal conditions (e.g., syneresis cracks, rhythmites). The channeled quartzite facies commonly fines upward into the laminated argillite,

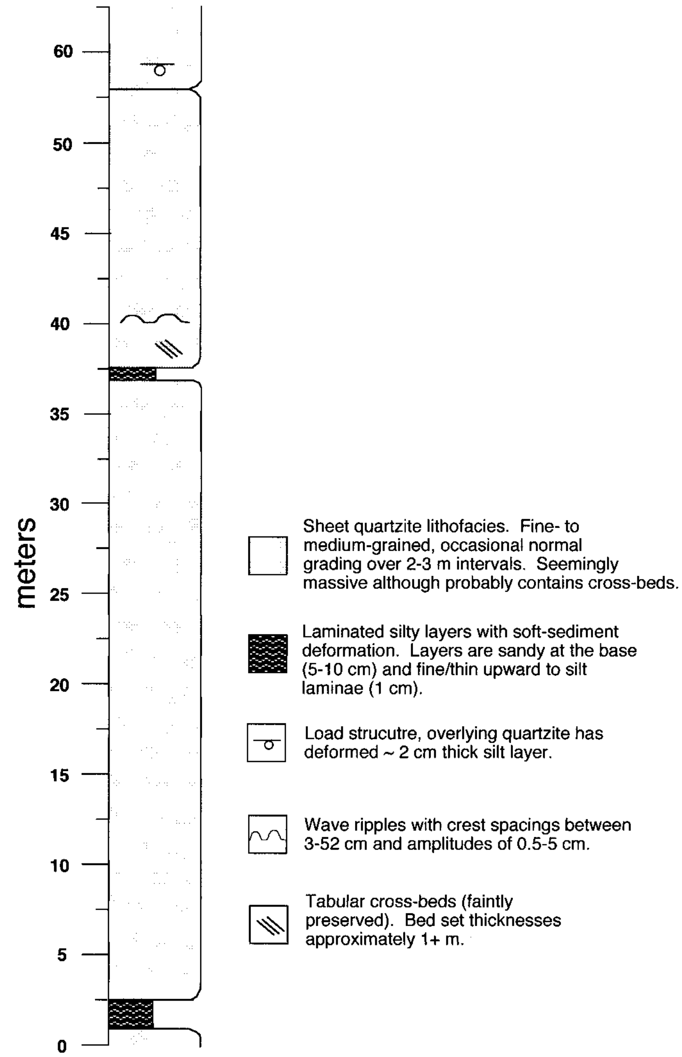

FIG. 7.—Detailed stratigraphic column of the sheet quartzite lithofacies, Storm Mountain locality of Figure 1.

FIG. 8.—Bedding-plane exposure of syneresis cracks in the laminated argillite.

suggesting deposition of the argillite in close proximity to tidal–fluvial channels. The dark color of the shale and the diagenetic pyrite imply reducing conditions, which are possible at subtidal depths.

Transitional Argillite.—The transitional argillite constitutes only 4% of the stratigraphic section (Fig. 3), and is located in the top 300 m of the formation, where it commonly overlies the channeled quartzite lithofacies. Some transitional argillite was likely removed where the erosional unconformity occurs at the top of the section (Fig. 3). This facies is typically 30–40 m in thickness. Siltite and greenish gray argillite at the base gradually fine upwards to a mud-cracked argillite. The transitional argillite is composed of 7–85% quartz and 15–90% clay with minor amounts of altered clay and detrital muscovite. At the base of the transitional argillite, alternating sand and silt laminae occur in 13 m successions. Spectral analysis of these laminae indicate they are heterolithic tidal rhythmites that contain weakly developed neap–spring cycles and annual cycles (Erik Kvale, personal communication 1996). Other abundant sedimentary structures present include current ripples with crests rounded by back flow and clay–draped reactivation surfaces. Thin sand lenses (10–30 cm thick by ~ 2 m wide) with scoured bases and small-scale channel geometries are locally present. Soft-sediment deformation is preserved as load casts and small flame structures.

Sedimentary structures in the transitional argillite indicate deposition by both fluvial influences (shown by current ripples) and tidal processes (shown by ripple crests rounded by back flow, and clay-draped reactivation surfaces). The heterolithic nature of the rhythmites indicates a strong tidal signature. The gradational contact between this facies and the underlying channeled quartzite, as well as the presence of small-scale sand channels or scours in the argillite, suggests deposition in adjacent environments between the transitional argillite and the tidal–fluvial channel quartzites. We interpret the base of this facies where the rhythmites occur to represent deposition in an intertidal environment. The upward fining of this facies to the mud-cracked argillite implies a transition from intertidal to supratidal conditions.

FACIES RELATIONSHIPS AND GEOMETRIES

Vertical Facies Relationships

Several important vertical relationships of facies and transitions are recognized: (1) The sheet quartzite generally has relatively straight and sharp upper and lower contacts with adjacent argillite facies. Although the contacts are sharp, there is little evidence of scouring (lags, rip-up clasts) at the base of the facies. (2) The channeled quartzite characteristically has a scoured base with rip-up clasts and lags of gravel and pebble size. The channeled quartzite fines upward into overlying transitional argillites. The thinning and fining-upward nature as well as preservation of rhythmites with annual cyclicities in the transitional argillite suggests gradual change from a high-energy to relatively low-energy environment. Examples of this relationship are present at the Moss Ledge locality (Fig. 9A), where there

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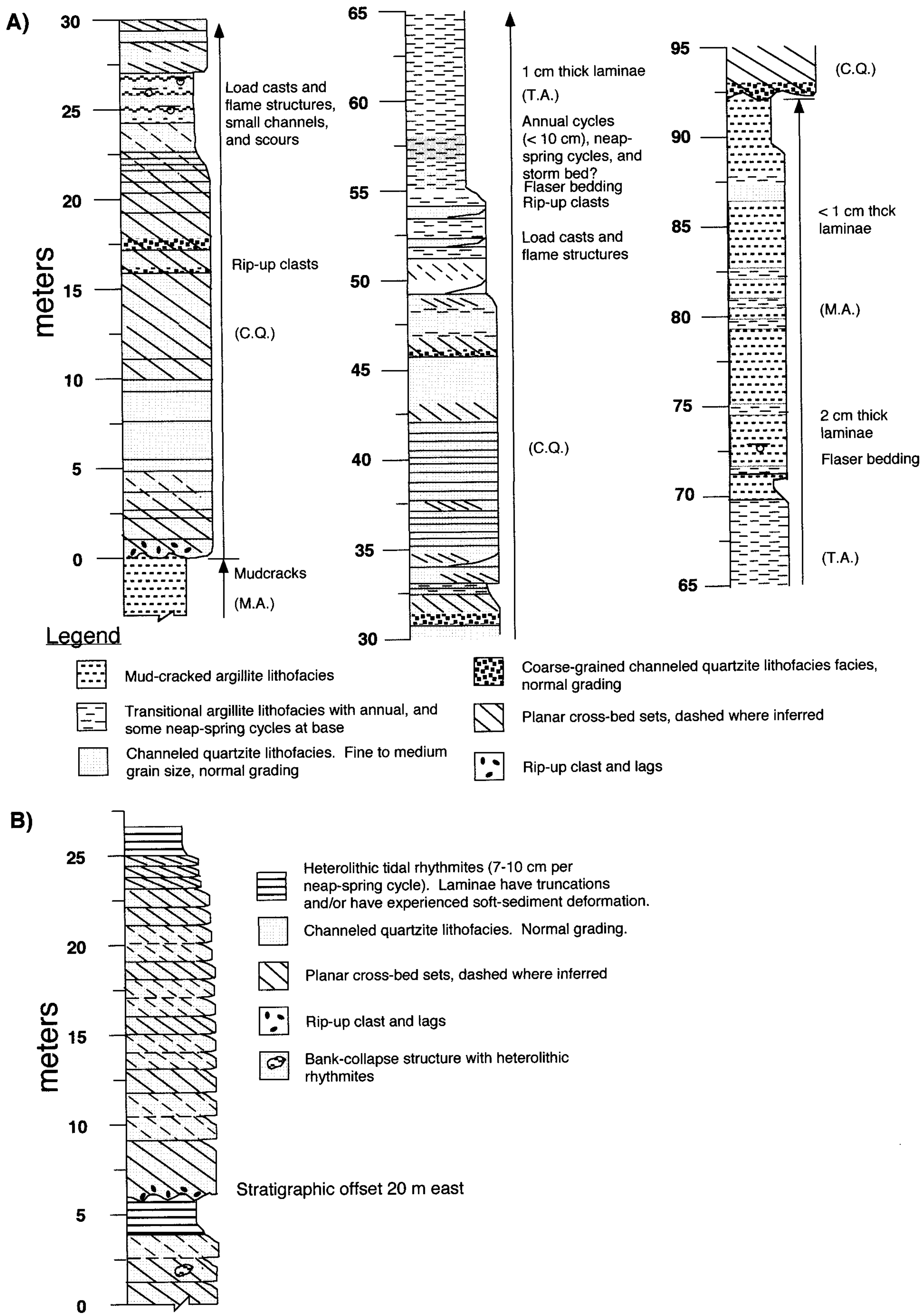
FIG. 9.—Stratigraphic sections of the Moss Ledge and S-Curve localities (Fig. 1). **A)** Moss Ledge locality channeled quartzite and transitional argillite succession. There are four of these stacked successions in the upper 300 m of the formation (Fig. 3). Successions are typically 60–90 m in thickness. Arrows denote large-scale upward-fining succession (see Figure 3 for facies abbreviations). Vertical relationships similar to those shown for the S-curve locality **(B)** occur throughout the Big Cottonwood Formation in the thickness interval 2500–4500 m of Figure 3.



A)
meters
Load casts and flame structures, small channels, and scours
Rip-up clasts
(C.Q.)
Mudcracks
(M.A.)
1 cm thick laminae
(T.A.)
Annual cycles (< 10 cm), neap-spring cycles, and storm bed?
Flaser bedding
Rip-up clasts
Load casts and flame structures
(C.Q.)
(C.Q.)
< 1 cm thck laminae
(M.A.)
2 cm thick laminae
Flaser bedding
(T.A.)
Legend
Mud-cracked argillite lithofacies
Transitional argillite lithofacies with annual, and some neap-spring cycles at base
Channeled quartzite lithofacies. Fine to medium grain size, normal grading
Coarse-grained channeled quartzite lithofacies facies, normal grading
Planar cross-bed sets, dashed where inferred
Rip-up clast and lags
B)
meters
Heterolithic tidal rhythmites (7-10 cm per neap-spring cycle). Laminae have truncations and/or have experienced soft-sediment deformation.
Channeled quartzite lithofacies. Normal grading.
Planar cross-bed sets, dashed where inferred
Rip-up clast and lags
Bank-collapse structure with heterolithic rhythmites
Stratigraphic offset 20 m east

FIG. 10.—Slump block (shown at arrow) with heterolithic rhythmites preserved in a tidal fluvial channel at the S-curve locality of Figure 1. Beds are contained in the north limb of an east-plunging anticline. Minor tectonic deformation of less competent argillite beds is on the order of 10 cm. Rotated channel scours and slump block are clear evidence of soft-sediment deformation. Photograph was taken looking towards the northeast.

are four thinning- and fining-upward sequences in the upper 300 m of the formation. (3) The channeled quartzite can also fine upwards into the laminated argillite. In this latter association, the channeled quartzites have scoured bases with rip-up clasts and then fine and thin upward into well-developed heterolithic rhythmites with neap–spring cycles (Fig. 9B). Other relationships of the channeled quartzite and laminated argillite association indicate more episodic shifts in facies. These feature include heterolithic rhythmite slump blocks encased within the channeled quartzite, which suggest bank collapse of the laterally adjacent laminated argillite into an active channel (Figs. 9B, 10), and abundant soft-sediment deformation (bent and contorted laminae) in laminated argillites overlying the channeled quartzites. These features imply channel migration and bank-margin slumping in an intertidal setting with tidal channels.

Quartzite Lateral Geometries

The channeled and sheet quartzite lithofacies differ from each other in their internal structure as well as their lateral geometries. The channeled quartzite (Fig. 11) typically has a lenticular geometry at a scale of tens of meters. Slump blocks in the channeled quartzite contain tidal rhythmites with 3 to 8 months of neap–spring cycles. Stacked channel quartzites have scoured bases and internal fining and thinning consistent with fluvial deposition.

The aspect ratios (height to length) of cross-bed sets within the channeled

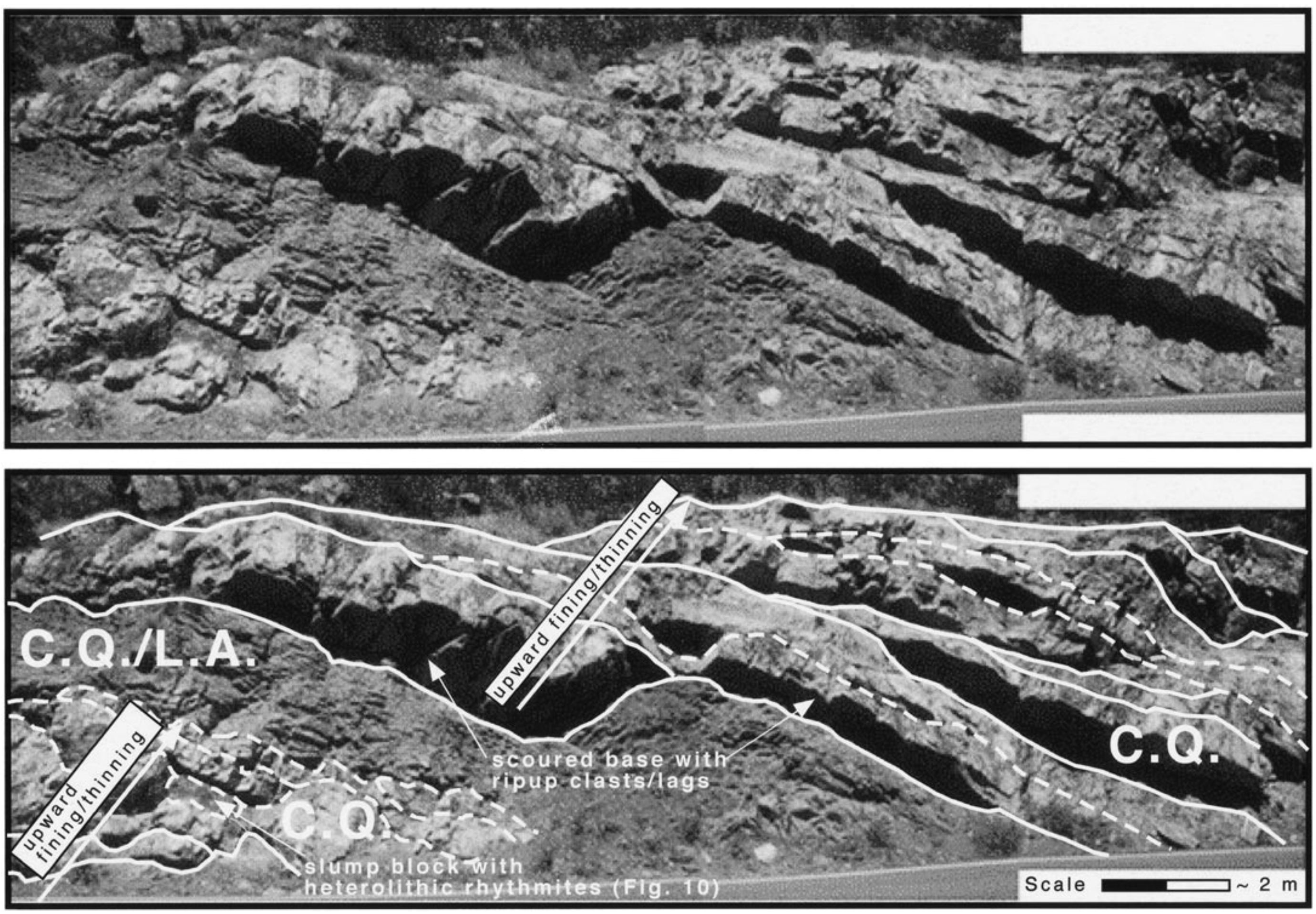


FIG. 11.—Photomosaic of channeled quartzite (C.Q.) geometries. White lines (dashed where inferred) indicate the boundary between cross-bed sets. Cross-bed sets thin upwards. S-curve locality of Figure 1. Beds are contained in the north limb of an east-plunging anticline. Minor tectonic deformation of less competent argillite beds is on the order of 10 cm. Rotated channel scours and slump block are clear evidence of soft-sediment deformation. Mosaic was assembled looking towards the northeast.

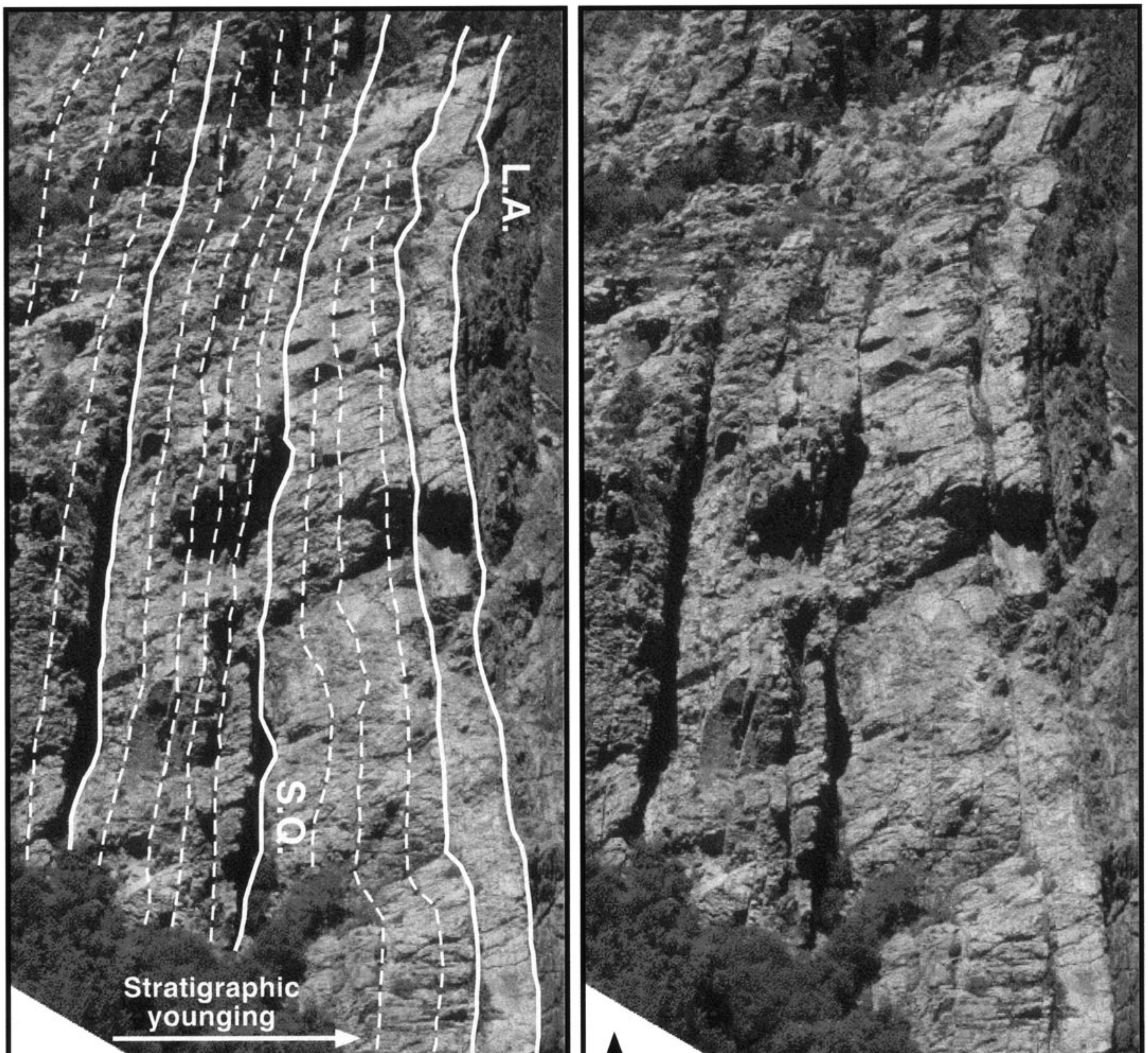


FIG. 12.—Vertically tilted sheet quartzite (S.Q.) geometries. Solid lines represent distinct boundaries between quartzite layers that are typically separated by 10+ cm of laminated argillite (dashed lines).

quartzite facies varies, although most cross-bed sets are 12 m in height and 20–50 m in width. These dimensions are consistent with aspect ratios documented for channeled facies in the Triassic of Central Spain and elsewhere in the Phanerozoic (Ramos et al. 1983; Collinson 1996, p. 64). The channeled quartzite facies extends laterally up to 12 km (the maximum extent of formation exposure) although individual beds can be traced for tens of meters.

The sheet quartzite lithofacies differs from the channeled quartzite in that beds generally lack internal structure (Fig. 7), are thicker, and are laterally continuous over hundreds of meters. Sheet quartzite geometries (Fig. 12) are separated by thin (~ 10–50 cm) shale interbeds at 20 m intervals (dashed lines in Figure 12) and are laterally continuous over the entire outcrop exposure (~ 600 m). Within the limit of visible outcrops there is no discernible lateral thinning.

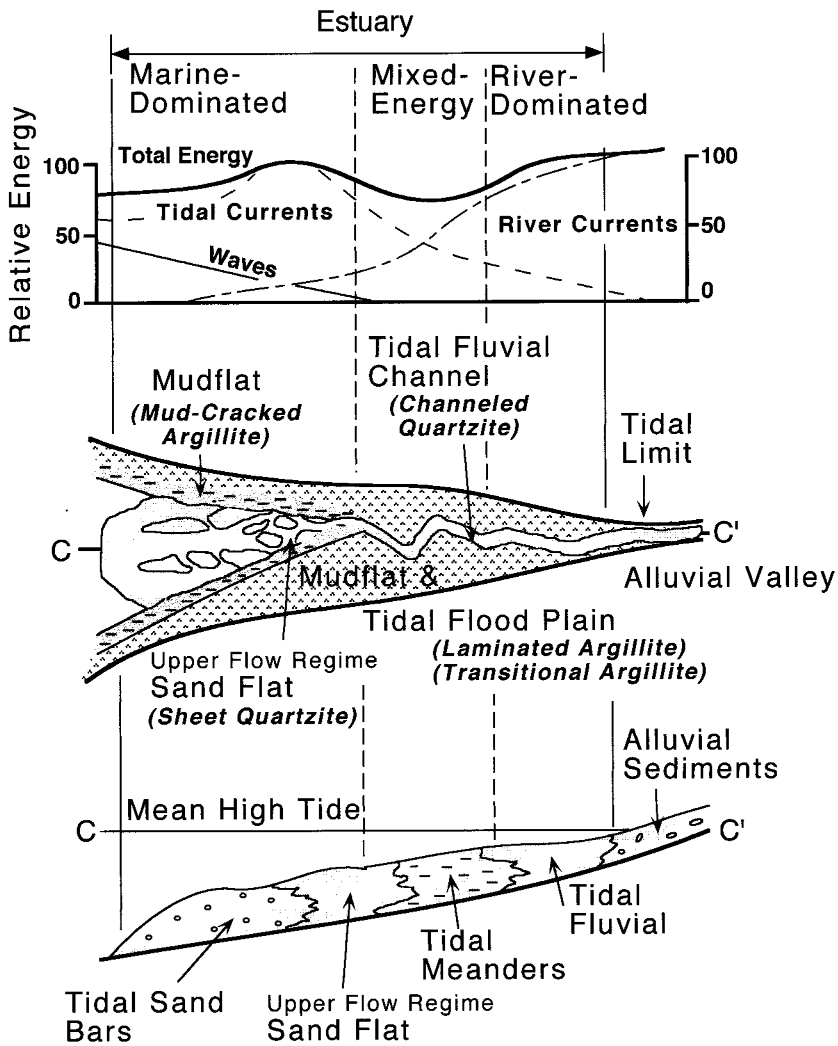


FIG. 13.—Estuarine depositional model for the Big Cottonwood Formation. Channeled quartzite facies and argillites with rhythmites were likely deposited in the mixed-energy setting. Sand-sheet facies (with wave ripples) occur at the marine end, near the mouth of the estuary. Modern depositional environments are labeled in the middle part of the figure, and Big Cottonwood Formation facies equivalents are in italics and parentheses. Modified from Dalrymple et al. (1992).

DISCUSSION

Estuarine Depositional Model

The Big Cottonwood Formation contains aspects of tidal, marine, and fluvial deposition. Diagnostic structures of heterolithic rhythmites with daily, semimonthly, and annual lunar periodicities, as well as sigmoidal bundles, current ripples with crests rounded by back flow, and clay-draped reactivation surfaces imply a tidal regime. The vertical and lateral association of quartzite and argillite lithofacies suggests a depositional system that incorporates tidal signatures, shallow-marine influence, and fluvial influence. The variety of structures and combination of facies in the Big Cottonwood Formation are accommodated in a tide-dominated estuarine model.

Classification of tidal environments can be problematic because tidal processes overlap into a number of clastic shoreline settings and confusion in nomenclature results from differences in scale and gradations between coastal systems (e.g., discussion in Reading and Collinson 1996, p. 182). Although tidal deltas or tide-dominated river deltas contain common transitional settings encompassing tidal and channel features, the diagnostic structures (respectively) of exchange across a barrier, or progradational lobes and the presence of a prodelta were not recognized in the Big Cottonwood Formation. Rather, the sedimentary structures and facies of the formation, as discussed below, resemble those of modern tide-dominated estuarine environments like the Bay of Fundy (Dalrymple et al. 1991; Dalrymple et al. 1992) and Mont-Saint-Michel (Tessier 1993).

Our interpretation for the Big Cottonwood facies is an estuary at a coastal embayment or a geomorphic reentrant with a drowned river valley. The estuary spans a broad range of geomorphic and environmental features, and allows for prominent tide-dominated structures (e.g., tidal channels, tidal sand bars, and tidal flats) and a paleogeographic tie to a major river system. Other studies of modern estuarine environments (e.g., Dalrymple et al. 1991; Dalrymple et al. 1992; Tessier 1993) illustrate the model of a tide-dominated estuary (Fig. 13), where the tidal limit typically extends up into the mouth of the alluvial valley.

Comparison with Modern Analogs

Modern estuaries provide a good analog to explain the observed sedimentary structures and lithofacies (Table 1) in the Big Cottonwood Formation. The vertically adjacent sheet quartzite and mud-cracked argillite facies (Fig. 3) are interpreted to form laterally adjacent to each other, similar to modern sandflat and mudflat facies toward the seaward end of an estuary (Fig. 13). Although few sedimentary structures are visible in the sheet quartzites, the relatively thick and tabular nature, presence of wave ripples, and weakly defined cross-bedding is consistent with modern sand sheet facies (Fig. 13) located near the mouths of modern estuaries (Dalrymple et al. 1991; Dalrymple et al. 1992; Tessier 1993). In both modern settings and in the Big Cottonwood example, the sand sheet facies are more laterally extensive than the fluvial channel facies.

The channeled quartzite may be similar to two types of tidal–fluvial channels found in the upper reaches of modern estuaries. Where the channeled quartzite is associated with the laminated argillite the quartzite facies may represent the ''main'' tidal–fluvial channel (Fig. 13). The bank-collapse structures in the channeled quartzite suggest deposition in the main tidal channel (with deep channel geometries) and a shifting, high-energy environment. The subtidal conditions of the main channel favor the formation of rhythmites, and could preserve reducing conditions (reflected in the dark-colored laminated argillite and diagenetic pyrite) near the base of the laminated argillite. Thin units (1–10 m) of laminated argillite in the upper half of the Big Cottonwood section (Fig. 3) probably flanked the main tidal channel in the subtidal zone or may have capped a channel sequence.

The channel quartzite is also overlain by the transitional argillite in other locales. In this association the channel quartzite may represent tidal–fluvial channels closer to the tidal limit in a more fluvially dominated regime where tidal influences are weaker. The transitional argillite lithofacies with annual-cycle rhythmites occurs at the top of the Formation (Figs. 3, 9A). In modern analogs, rhythmites with annual cycles form in zones with variable hydrologic conditions (high seasonal runoff, storm events) in the upper reaches of the estuary, near the tidal limit and removed from sedimentation associated with the main tidal channel (Tessier 1993). Thus, the transitional argillite was possibly deposited farther away from the main tidal channel and perhaps in the uppermost intertidal or supratidal zone. This facies is characteristically associated with the channeled quartzite as part of an upward-fining and -thinning sequence, suggesting shoaling with channel fill, and deposition along tributary tidal channels where thinner (more condensed) annual cycles might be preserved.

The mud-cracked argillite is thickest (> 20 m) in the lower part of the formation (Fig. 3) and thinner (< 20 m, Fig. 9A) near the top of the formation, where it is part of a upward fining channel succession. Thick successions of the mud-cracked argillite are interpreted to represent intertidal mudflats close to the mouth of the estuary (Fig. 13). In modern analogs, tidal mudflats are laterally extensive and continuous over several kilometers (Dalrymple 1992). Similarly, in the Big Cottonwood Formation, this facies is laterally continuous on the same scale. Thinner units of mud-cracked argillite appear to be part of fluvial upward-fining and -thinning sequences (Fig. 9A) deposited toward the landward end of the estuary where the channel floodplain lay adjacent to the tidal–fluvial channels.

The wide lateral extent of the channeled quartzite (up to 12 km) implies a broader fluvial deposystem than modern tidal–fluvial environments near the tidal limit (Dalrymple et al. 1991; Tessier 1993). The broad, shallow nature of the channels in the formation may be due to a lack of vegetation for bank stabilization in the Proterozoic. However, evaluation of potential microbial or algal-mat influence on bank stabilization warrants further investigation. Argillite facies are also more areally extensive (5–12 km in length) than most modern analogs. Silty facies in modern estuaries are generally continuous for 2–5 km along strike (Dalrymple et al. 1991; Tessier 1993). Thus, the Big Cottonwood Formation facies are more laterally extensive (by about twice or more) than modern equivalent estuaries.

In the Big Cottonwood Formation, rhythmites are observed in two depositional settings similar to modern examples in tide-dominated estuaries. (1) When associated with the transitional argillite the rhythmites were probably deposited adjacent to tidal channels on the mudflat as a type of ''overbank'' deposit in a tidal flat and/or floodplain in the upper reaches of the estuary. The sedimentary structures of the transitional argillite suggest intertidal deposition, and rhythmites contain a weakly defined annual cyclicity. A tidal flat/floodplain in the upper reaches of an estuary provides intertidal conditions for rhythmite formation and furthermore could sufficiently retard tidal influences so that annual cyclicities from storm events and/or seasonal deposition could be preserved. (2) Rhythmites associated with the laminated argillite facies would form at subtidal depths within the main tidal channel, where deposition occurs with every tide. This subtidal position of rhythmite deposition accounts for the bank-collapse structures with rhythmites preserved in the channeled quartzite of the formation and the association of diagenetic pyrite in the laminated argillite. Tessier (1993) notes two important conditions for preservation of modern rhythmites: a protected environment to limit erosion from wave action or highly energetic tidal currents, and high suspended-sediment concentrations so that thick heterolithic couples are deposited. Both these conditions are present at the upper end of modern estuaries within 5–15 km of the tidal limit or at subtidal depths within tidal–fluvial channels. In the Bay of Fundy and Mont-Saint-Michel Bay, rhythmites typically form adjacent to tidal–fluvial channels in subtidal to intertidal parts of tidal flats, or in abandoned tidal channels.

Macrotidal Deposition

The best examples of tidal rhythmites in the modern record come from macrotidal (> 4 m tidal range) systems. Rhythmites from these macrotidal systems are commonly described as heterolithic. The heterolithic nature of rhythmites can be well preserved because of the contrasting energies and velocities of alternating tides, and their ability to carry and deposit contrasting grain sizes. To date, there are no documented examples of tidal rhythmites in microtidal (< 2 m tidal range) settings. The documented mesotidal (2–4 m tidal range) rhythmites (Roep 1991) are not as well developed as the rhythmites from macrotidal settings. Correspondingly in these smaller tidal ranges, energy may be insufficient to transport and deposit contrasting grain sizes such that, even if rhythmites did develop, their fine-grained nature would make them difficult to recognize. The Big Cottonwood rhythmites with thick and well-developed neap–spring cycles suggest deposition in a macrotidal environment.

Macrotidal regimes result in formation of thick neap–spring cycles. The thickness varies according to tidal amplitude and the amount of sediment deposited. Thicknesses of neap–spring cycles in the Bay of Fundy range between approximately 15 and 37 cm (calculated from Dalrymple et al. 1991), and thicknesses from the Bay of Mont-Saint-Michel range from 2 to 5 cm (Tessier 1993). Big Cottonwood Formation cycle thicknesses range from several millimeters to 20 cm (e.g., see Fig. 4) and are generally within the range of the modern macrotidal cycles. The maximum tidal ranges in the Bay of Fundy and the Mont-Saint-Michel Bay are 15.6 m (Dalrymple et al. 1991) and 15.3 m (Tessier 1993), respectively. Unfortunately, no methodology has yet been developed for calculating tidal range from rhythmite thickness. Thus, macrotidal deposition in the Big Cottonwood Formation is largely inferred from comparison to modern analogs.

CONCLUSIONS

The variety of preserved structures and sequences in the Big Cottonwood Formation suggest tidal deposition in an estuarine setting. Paleocurrent measurements indicate dominant westward flow. Rounded detrital quartz grains indicate a mature sediment probably sourced from the Uinta Mountain Group to the east. Five distinct lithofacies (with respective interpretations) in the Big Cottonwood Formation include: fluvially dominated channeled quartzite (tidal channel); subtidal sheet quartzite (sand sheets at the estuary mouth); intertidal to supratidal mud-cracked argillite (probably gradational to a tidal-channel flood plain); subtidal to intertidal laminated argillite (inner part of the estuary where wave action is minimal); and an intertidal to supratidal transitional argillite (upper part of the estuary). These facies indicate estuarine deposition with river dominance in the upper reaches close to the tidal limit, to wave influence in sand sheets in the lower, subtidal reaches.

Comparisons with modern analogs of rhythmites suggest that the Big

Cottonwood Formation was deposited under macrotidal conditions. The presence of tidal deposits in the Big Cottonwood Formation necessitates a previously unrecognized connection of the depocenter with a westward ocean body capable of generating large (macrotidal?) amplitudes. Although previous work on the Big Cottonwood Formation had generalized the depositional setting as shallow marine, sedimentologic studies presented here emphasize the importance of tidal signatures and clarifies the relationships between lithofacies. Despite the lack of biota in Proterozoic deposits, physical structures are remarkably similar to those in estuarine models derived from modern analogs. Future studies of scattered Big Cottonwood Formation outcrops and other correlative strata to the west of the study area will refine an interpretation of the regional Proterozoic paleogeography.

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