BRIGHAM YOUNG UNIVERSITY

GEOLOGY

S T U D I E S

GEOLOGICAL SOCIETY OF AMERICA

FIELD TRIP GUIDE BOOK

1997 ANNUAL MEETING • SALT LAKE CITY, UTAH

PART 1 ONE

EDITED BY PAUL KARL LINK AND BART J. KOWALLIS

VOLUME 42 • 1997

PROTEROZOIC TO RECENT STRATIGRAPHY, TECTONICS, AND VOLCANOLOGY, UTAH, NEVADA, SOUTHERN IDAHO AND CENTRAL MEXICO

Edited by

Paul Karl Link and Bart J. Kowallis

BRIGHAM YOUNG UNIVERSITY GEOLOGY STUDIES

Volume 42, Part I, 1997

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A Publication of the
Department of Geology
Brigham Young University
Provo, Utah 84602

Brigham Young University Geology Studies is published by the Department of Geology. This publication consists of graduate student and faculty research within the department as well as papers submitted by outside contributors. Each article submitted is externally reviewed by at least two qualified persons.

Cover photos taken by Paul Karl Link.

Top: Upheaval Dome, southeastern Utah.

Middle: Lake Bonneville shorelines west of Brigham City, Utah.

Bottom: Bryce Canyon National Park, Utah.

ISSN 0068-1016
9-97 700 23348/24218

Preface

Guidebooks have been part of the exploration of the American West since Oregon Trail days. Geologic guidebooks with maps and photographs are an especially graphic tool for school teachers, University classes, and visiting geologists to become familiar with the territory, the geologic issues and the available references.

It was in this spirit that we set out to compile this two-volume set of field trip descriptions for the Annual Meeting of the Geological Society of America in Salt Lake City in October 1997. We were seeking to produce a quality product, with fully peer-reviewed papers, and user-friendly field trip logs. We found we were bucking a tide in our profession which de-emphasizes guidebooks and paper products. If this tide continues we wish to be on record as producing "The Last Best Geologic Guidebook."

We thank all the authors who met our strict deadlines and contributed this outstanding set of papers. We hope this work will stand for years to come as a lasting introduction to the complex geology of the Colorado Plateau, Basin and Range, Wasatch Front, and Snake River Plain in the vicinity of Salt Lake City. Index maps to the field trips contained in each volume are on the back covers.

Part 1 "Proterozoic to Recent Stratigraphy, Tectonics and Volcanology: Utah, Nevada, Southern Idaho and Central Mexico" contains a number of papers of exceptional interest for their geologic synthesis. Part 2 "Mesozoic to Recent Geology of Utah" concentrates on the Colorado Plateau and the Wasatch Front.

Paul Link read all the papers and coordinated the review process. Bart Kowallis copy edited the manuscripts and coordinated the publication via Brigham Young University Geology Studies. We would like to thank all the reviewers, who were generally prompt and helpful in meeting our tight schedule. These included: Lee Allison, Genevieve Atwood, Gary Axen, Jim Beget, Myron Best, David Bice, Phyllis Camilleri, Marjorie Chan, Nick Christie-Blick, Gary Christenson, Dan Chure, Mary Droser, Ernie Duebendorfer, Tony Ekdale, Todd Ehlers, Ben Everitt, Geoff Freethey, Hugh Hurlow, Jim Garrison, Denny Geist, Jeff Geslin, Ron Greeley, Gus Gustason, Bill Hackett, Kimm Harty, Grant Heiken, Lehi Hintze, Peter Huntoon, Peter Isaacson, Jeff Keaton, Keith Ketner, Guy King, Mel Kuntz, Tim Lawton, Spencer Lucas, Lon McCarley, Meghan Miller, Gautam Mitra, Kathy Nichols, Robert Q. Oaks, Susan Olig, Jack Oviatt, Bill Perry, Andy Pulham, Dick Robison, Rube Ross, Rich Schweickert, Peter Sheehan, Norm Silberling, Dick Smith, Barry Solomon, K.O. Stanley, Kevin Stewart, Wanda Taylor, Glenn Thackray and Adolph Yonkee. In addition, we wish to thank all the dedicated workers at Brigham Young University Print Services and in the Department of Geology who contributed many long hours of work to these volumes.

Paul Karl Link and Bart J. Kowallis, Editors

Proterozoic Tidal, Glacial, and Fluvial Sedimentation in Big Cottonwood Canyon, Utah

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ABSTRACT

Spectacular outcrops of Mesoproterozoic to Cambrian deposits illustrating a variety of depositional environments are exposed along the steep walls of Big Cottonwood Canyon of the central Wasatch Range. This field trip is designed to examine the unique aspects of tidal and estuarine deposition in the 4.8 km thick ~900 Ma Big Cottonwood Formation, which contains the oldest known examples of tidal rhythmites. The trip also includes stops illustrating Neoproterozoic glaciation in the Mineral Fork Formation, braided fluvial deposition in the Mutual Formation, and shallow marine deposition in the Tintic Quartzite.

INTRODUCTION

Big Cottonwood Canyon, just east of Salt Lake City, contains easily accessible outcrops of the Big Cottonwood Formation, Mineral Fork Formation, Mutual Formation, and Tintic Quartzite, which (with intervening unconformities) collectively span as much as 470 my of earth history from ~1000 to 530 Ma (Crittenden et al., 1952; Ojakangas and Matsch, 1980; Christie-Blick, 1983; Christie-Blick and Link, 1988) (Fig. 1 and 2). These Proterozoic formations fall within Precambrian successions B and C of western North America, as defined by Link et al. (1993) (Fig. 3).

The outcrops in Big Cottonwood Canyon lie structurally below the far-traveled thrust sheets of the Sevier orogenic belt. Though they do lie above thrust faults with small (few km) displacement, they are basically in place with respect to their underlying cratonic basement and their depositional site. They are thus parautochthonous, and were deposited tens of km to the east of the bulk of the Meso- and Neoproterozoic strata exposed along the western margin of North America, which is largely allochthonous (Young, 1979; Crittenden et al., 1983; Christie-Blick, 1983; Levy and Christie-Blick, 1989; 1991; Winston, 1991; Skipp and Link, 1992; Link et al., 1993; Rainbird et al., 1996).

The Big Cottonwood Formation has received little attention since the 1970s. However, despite mild metamorphic overprinting (greenschist facies), sedimentary features are well preserved. Renewed interest in the Big Cottonwood Formation has been sparked by the discovery of the oldest known examples of tidal rhythmites and related tidal structures (Chan et al., 1994; Archer, 1997; Kvale et al., 1997). These structures provide a new perspective on the tectonic setting and paleogeography of the unit (Ehlers and Chan, 1996a, 1996b), as well as insight into Proterozoic Earth-moon orbital mechanics (Sonett et al., 1996; Kvale et al., 1997).

The trip route traverses eastward and up section (Figs. 4 and 5) on Highway 190 (old Highway 152), from the Big Cottonwood Formation at the mouth of the canyon (stops 1–5; Fig. 2), to the Mineral Fork Formation at Mineral Fork (stop 6), the Mutual Formation (stop 7), and lastly the Tintic Quartzite (stop 8). The first portion of this trip will be run in conjunction with the companion three day Neoproterozoic trip led by Christie-Blick (1997).

HISTORICAL PERSPECTIVE

Big and Little Cottonwood Canyons are two prominent drainages that dissect the Wasatch Front (Fig. 1) and are well known for their scenery and recreational attractions. These two canyons also have a colorful mining history. Oligocene intrusive activity of the Little Cottonwood, Alta, and related stocks affected strata that had been folded and thrust faulted during Cretaceous and Paleocene time. The stocks generated hydrothermal systems, which produced skarns, veins and replacement deposits in deformed Paleozoic limestones stratigraphically above the Proterozoic rocks examined in this field trip. The Big and Little Cottonwood

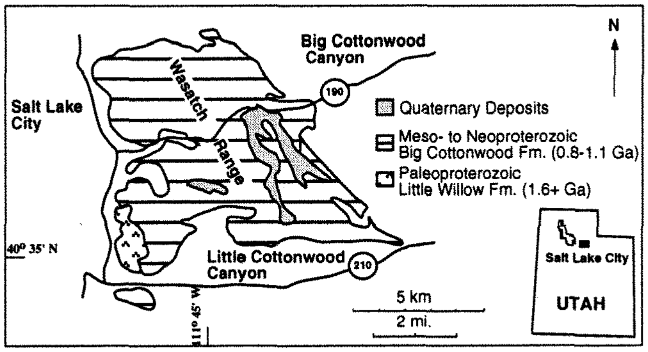

Figure 1. Generalized location map of Big Cottonwood Canyon, southeast of Salt Lake City.

mining districts produced over $34,000,000 from 1867 to 1940, from silver, lead and copper ores (Calkins and Butler, 1942; Crittenden et al., 1952; James, 1979). By the 1940s, mining activity had subsided, with the primary use of the canyon turning towards skiing and other recreational outlets.

GEOLOGIC SETTING

The Big Cottonwood Canyon area lies astride the Cordilleran hinge line (Wasatch Line) (Crittenden, 1976, p. 363), across which Neoproterozoic and Paleozoic passive-margin strata thicken drastically westward. An approximately 6 km thick composite stratigraphic section of Mesoproterozoic through Jurassic sedimentary rocks is exposed. The Mesoproterozoic through Cambrian rocks which will be examined on this field trip are exposed in the lower, western part of the canyon. The upper half of the canyon exposes late Paleozoic limestones (Fig. 5) with Mesozoic continental to shallow marine deposits comprising the highest canyon ridges (Crittenden, 1976; Stokes, 1986; Hintze, 1988).

In the Wasatch Range, Proterozoic through Mesozoic strata below the Absaroka, Willard and Charleston thrust faults of the Sevier orogenic belt are parautochthonous, but strata now located above these thrust faults have been transported tens of kilometers to the east with respect to the underlying craton (Crittenden, 1976; Bruhn et al., 1986; Levy and Christie-Blick, 1989; Cowan and Bruhn, 1992;

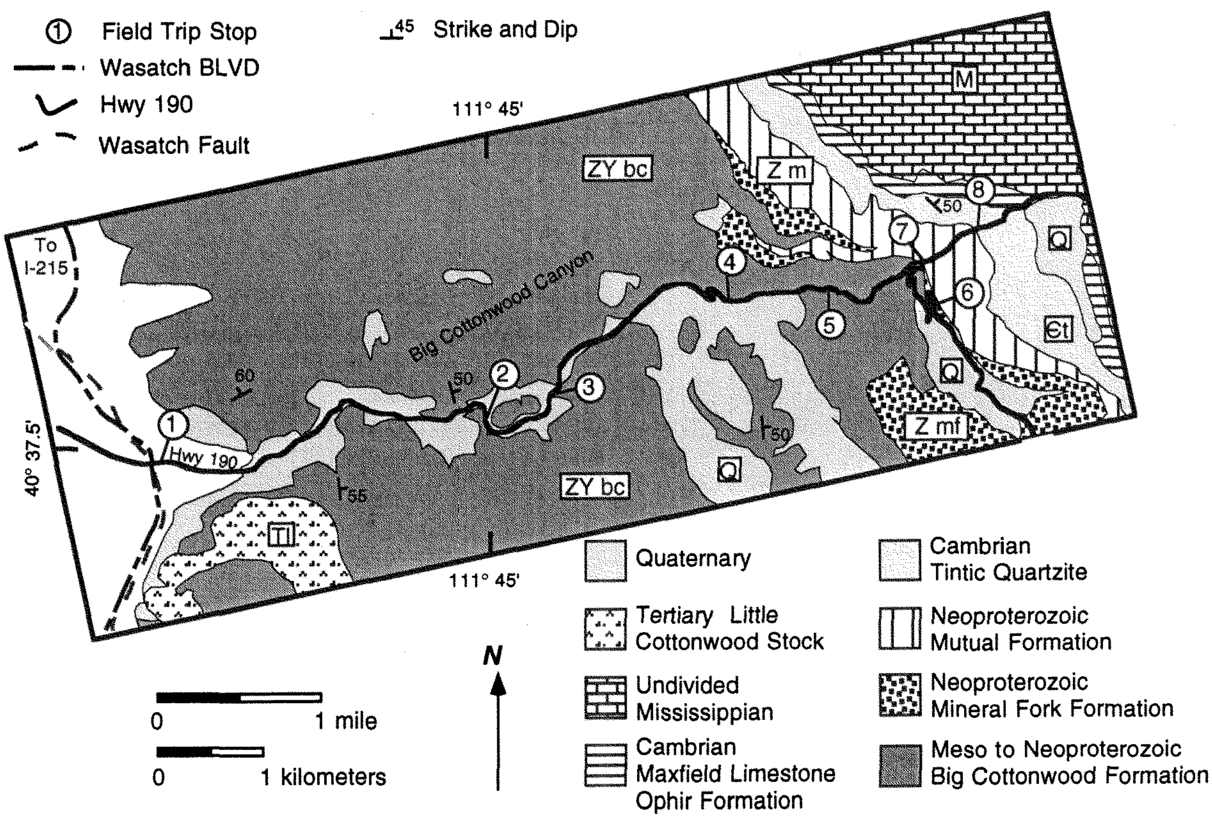

Figure 2. Location map of field trip stops and lithologies in the lower half of Big Cottonwood Canyon. Modified from James (1979).

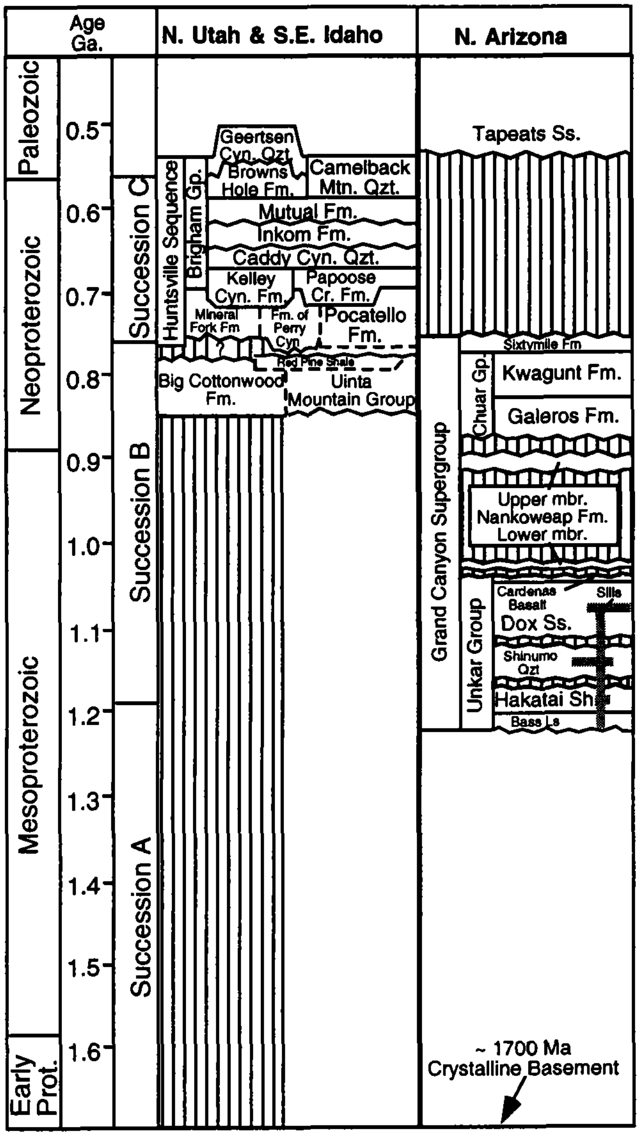

Figure 3. Stratigraphic correlation chart of Proterozoic succession B and C of western North America. White spaces represent missing record, or igneous rocks not shown on diagram. Modified from Link et al., 1993 (DNAG Precambrian volume).

Christie-Blick, 1997). Starting with the Late Cretaceous (Maastrichtian), the Wasatch Range experienced east-west compression (Sevier orogeny) followed by late Paleocene north-south compression (Laramide orogeny) which resulted in the formation of the east-trending Uinta Arch that extends westward through Big Cottonwood Canyon (Crittenden, 1976; Bruhn et al., 1983; 1986).

Following Oligocene plutonism (including emplacement of the Little Cottonwood and Alta Stocks), Basin and Range extension initiated along the Wasatch fault approximately 12–15 Ma (Zoback, 1983; Smith and Bruhn, 1984; Smith et al., 1989) and exhumed 11 km of rock near Little and Big Cottonwood Canyon to expose the rocks to their present position (Parry and Bruhn, 1987; Parry et al., 1988; Kowallis et al., 1990).

STRATIGRAPHY

Big Cottonwood Formation

Our understanding of the geologic relations in Big Cottonwood Canyon is based largely on the work of Max D. Crittenden, Jr., who worked in the northern Wasatch Range for the U.S. Geological Survey over a period of 30 years (Crittenden et al., 1952; Crittenden and Wallace, 1973; Crittenden, 1976). He defined mappable formations in the canyon and distinguished the prominent quartzite and shale lithologies within the Big Cottonwood Formation. James (1979) later summarized the geology and history of the Big Cottonwood mining district, with emphasis on the mineral deposits. The geology of the Big Cottonwood area is shown on the Mount Aire, Dromedary Peak, Sugar House, and Draper 7 1/2 minute geologic maps (Crittenden 1965a; 1965b, 1965c, 1965d). The most recent geologic compilation of the area is in Bryant (1990).

The thickest, and best preserved sequence of the Big Cottonwood Formation is exposed in Big Cottonwood Canyon (type area). Smaller sections (800 m or less) that have been mapped as Big Cottonwood Formation are exposed in Slate Canyon, East Tintic Mountains, Stansbury Island, and Carrington Island. These western sections show some lithologic similarities to a few of the facies in Big Cottonwood Canyon, but have not been studied recently. The present discussion focuses only on the thick and relatively continuous exposures present in Big Cottonwood Canyon.

The base of the Big Cottonwood Formation, where accessible, contains a thin conglomerate with clasts derived from the unconformably underlying Paleoproterozoic Little Willow Formation (Crittenden, 1976). The Big Cottonwood Formation is unconformably overlain by the Neoproterozoic Mineral Fork Formation where present, and the 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. 3) on the basis of paleomagnetic data (Elston, 1989; Link et al., 1993) and the commonalty of microfossils, including acritarchs, and *Melanocyrillium* (Hofmann, 1977; Knoll et al., 1981; Vidal and Ford, 1985). Crittenden and Wallace (1973, p. 117) made an initial Mesoproterozoic age assignment for the Big Cottonwood Formation and correlated it to the Uinta Mountain Group. Further, they made what is now thought to be an incorrect correlation of these strata with the Belt Supergroup, which fostered decades of misconception

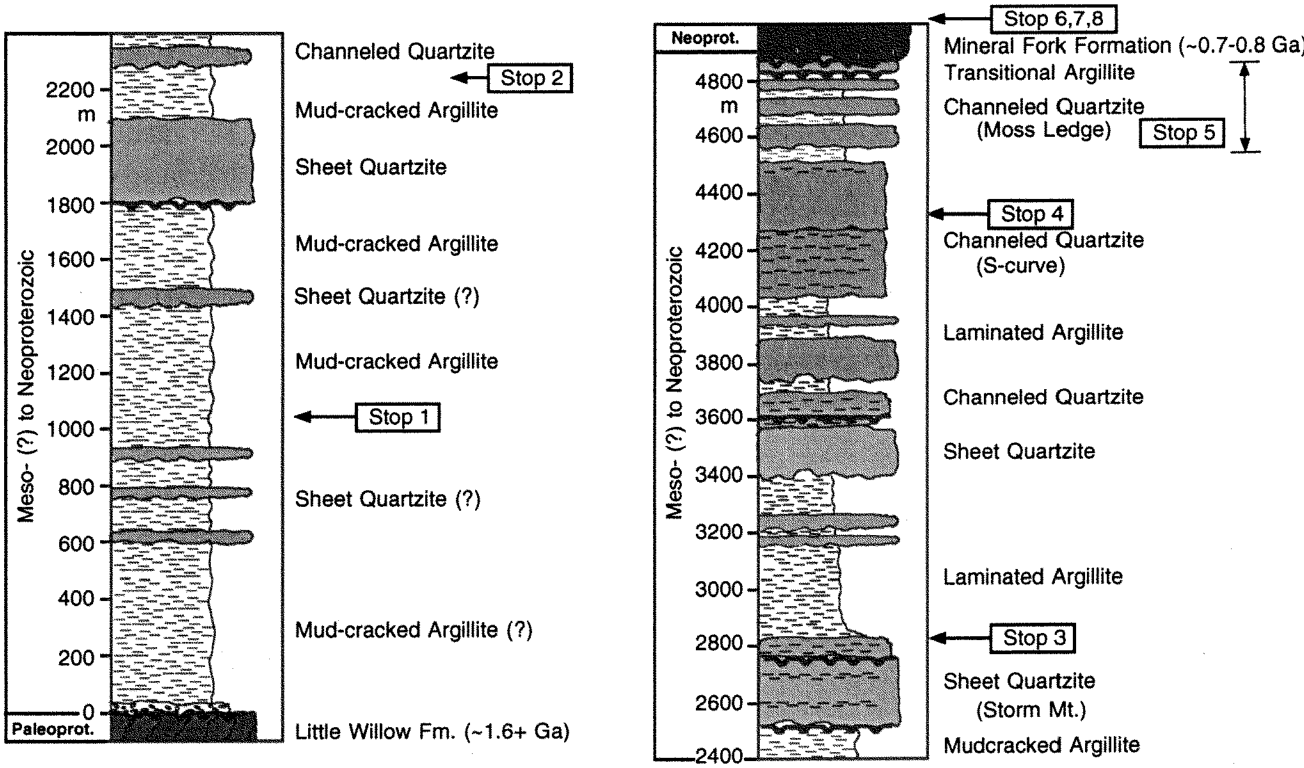

Figure 4. Generalized measured stratigraphic section of the Big Cottonwood Formation. Locations of stops (boxes) and lithofacies labels are shown to the right of each column. Erosional unconformities are shown with thick lines throughout the section.

about correlation of Mesoproterozoic strata of the western U.S. The Belt Supergroup is now thought to be older (1430–1200 Ma) than the Uinta Mountain Group (~1000 to ~800 Ma) (see discussion in Link et al., 1993). The Big Cottonwood Formation, Uinta Mountain Group and Chuar Group are collectively placed in the late Meso to early Neoproterozoic, although no reliable radiometric dates are available, except for the top of the Chuar Group (Sixty Mile Formation) where a K-Ar age between 855–790 (mean 823) Ma has been acquired (Elston and McKee, 1982).

Mineral Fork Formation

In Big Cottonwood Canyon, the Big Cottonwood Formation is overlain by up to 800 m of glaciogenic diamictite, siltstone, sandstone and conglomerate of the Mineral Fork Formation (Ojakangas and Matsch, 1980; Christie-Blick, 1983; Christie-Blick and Link, 1988). The name Mineral Fork Formation is used in parautochthonous settings in the Wasatch Range and in the Charleston thrust sheet to the south. The Mineral Fork correlates with much thicker glaciogenic deposits of the formation of Perry Canyon and Pocatello Formation in the Willard thrust sheet, and likely represents the global Sturtian glaciation at about 725 Ma (Crittenden et al., 1983; Link et al., 1994). The Mineral Fork Formation overlies the Big Cottonwood Formation in the field trip area, but to the north the Big Cottonwood Formation has been eroded and the Mineral Fork overlies the Archean and Paleoproterozoic Farmington Canyon Complex, as it does to the northwest at Antelope Island (Christie-Blick, 1983).

Mineral Fork strata now occupy west-trending, steep-walled (to 40 degrees) glacially scoured valleys up to 900 m deep. Their origin likely involved multiple episodes of incision, augmented by Neoproterozoic glacial deepening (Christie-Blick, 1983; Christie-Blick et al., 1989). Clasts in the Mineral Fork diamictites were likely glacially transported from eroded outcrops of the underlying Big Cottonwood Formation and other sources to the east. The Mineral Fork Formation contains carbonate clasts from an inferred post Big Cottonwood Formation carbonate deposit of intermediate thickness (Christie-Blick, 1997). The Mineral Fork was deposited in contact with glacial ice, in subaqueous environments. Christie-Blick (1997) further describes the details of sequence boundaries, and tectonostratigraphic relations of the Mineral Fork Formation.

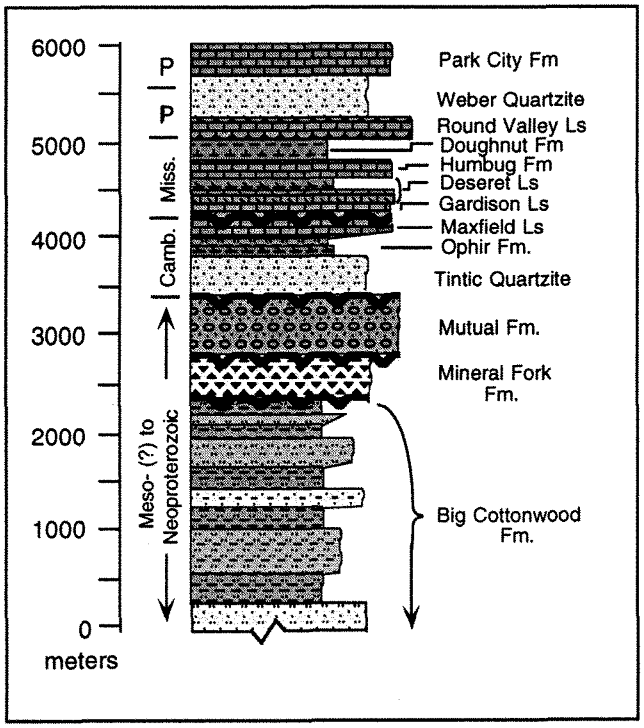

Figure 5. Generalized stratigraphic section of rocks exposed along Highway 190 in Big Cottonwood Canyon. Modified from Hintze (1988).

Mutual Formation

The Neoproterozoic Mutual Formation is up to 370 m thick in Big Cottonwood Canyon and unconformably overlies the Mineral Fork Formation, or where the Mineral Fork Formation is missing, the Big Cottonwood Formation. The Mutual Formation is overlain to the north (near Huntsville, Utah) by the Browns Hole Formation, which contains volcaniclastics and felsic volcanic rocks estimated to be 580 Ma by Ar-Ar dating (Crittenden et al., 1971; Christie-Blick et al., 1989; Link et al., 1993, p. 542).

The Mutual Formation is part of the Neoproterozoic and Cambrian Brigham Group, which contains thick quartzitic sandstones that lie above the Sturtian glacial deposits (Crittenden et al., 1971; Link et al., 1987). Levy and Christie-Blick (1991) summarize a sequence stratigraphic framework for the Brigham Group and correlative rocks, with four regionally recognizable Neoproterozoic sequence boundaries from southeastern Idaho to eastern Nevada.

The Mutual Formation is present in several thrust sheets in a large area of southeastern Idaho and northern Utah, but its thickness is generally less than 850 m. The Mutual Formation contains grayish red to red-purple, pebbly arkosic sandstone, with lenses of variegated red and green siltstone; lithology is quite consistent across the large area of exposure. Generally this formation is interpreted to represent a large braid-plain, locally occupying incised valleys, and representing a time of increased coarse clastic supply and relatively low sea level (Crittenden et al., 1971; Link et al., 1993). Discontinuous siltstone beds and pods suggest local flood plain or lake deposits.

The Mutual Formation contains two stratigraphic sequences, and sequence boundaries, in Big Cottonwood Canyon (Christie-Blick and Levy, 1989; Levy, 1991; Levy and Christie-Blick, 1991, p. 379). The lower part (30 m exposed between erosional contacts) correlates with the upper Caddy Canyon and Inkom Formations of southeast Idaho and west-central Utah. The upper portion is part of a relatively uniform blanket of braided fluvial Mutual Formation. This may represent highstand and transgressive systems tracts deposited during a period of lowered sea level during the late stages of the 610–580 Ma Varanger glaciation (Christie-Blick, 1997). The blanket geometry of the Mutual Formation suggests that accommodation space was controlled by late Varanger glacio-eustatic rise of sea level and not by differential thermal subsidence.

Tintic Quartzite

The Lower and Middle Cambrian Tintic Quartzite is about 240 m thick in Big Cottonwood Canyon, and consists of white to pink, texturally mature, cross-bedded coarse- to medium-grained quartz arenite with a local basal conglomerate. The formation passes upward to the fossiliferous Middle Cambrian Ophir Shale (Bryant, 1990).

The Tintic Quartzite in Big Cottonwood Canyon represents the stratigraphically youngest, eastern feather edge of a great latest Neoproterozoic to Middle Cambrian, westward-thickening (to over 2,000 m), shallow marine quartz sand wedge consisting of the upper Brigham Group (Camelback Mountain and Geertsen Canyon Quartzites) in Idaho and the northern Wasatch Range, and the Prospect Mountain and Tintic Quartzites in central and western Utah (Calkins and Butler, 1942; Stewart, 1972; Hintze, 1988; Levy and Christie-Blick, 1991; Link et al., 1993). The base Geertsen Canyon-Camelback Mountain Quartzite sequence boundary of the miogeocline is represented by the unconformable base of the Tintic Quartzite in Big Cottonwood Canyon, and the sequence boundary spans considerably more time in Big Cottonwood Canyon than in allochthonous locations, which were west of the Cordilleran hingeline (Levy and Christie-Blick, 1991).

Because the Tintic Quartzite is generally poorly fossiliferous, it has received much less attention than the overlying Cambrian Ophir Shale and Maxfield Limestone, and has not been described much since the work of Crittenden et al. (1952, 1971) and Crittenden (1976).

TIDAL CYCLES AND LUNAR PERIODICITIES

Oceanic tides produce deposits that are both significant and widespread in the geologic record. Our understanding of ancient clastic tidal deposits in the last decade has increased through important comparative studies on modern tidal processes and preserved structures and sequences. The recognition of diagnostic tidal structures and processes have useful application to interpretation of both outcrop and subsurface deposits as well as to exploration, basin analysis, and sequence stratigraphy. This section highlights portions of previous work to provide a background understanding of diagnostic structures such as tidal rhythmites (Fig. 6), and their lunar relationships (Fig. 7). For summaries of tidal depositional systems the reader is referred to Nio and Yang (1991), and Dalrymple (1992).

There are a variety of criteria that have traditionally been used to interpret tidal environments, such as the presence of sigmoidal bundles, tidal rhythmites, mud couplets or mud drapes, current ripples with crests rounded by back flow, reactivation surfaces, herringbone cross bedding, flaser bedding, mud cracks, and more. Two of these structures, sigmoidal bundles and tidal rhythmites (also referred to as cyclic rhythmites or small-scale tidal bundles), have cyclic variations in laminae thickness. Sigmoidal bundles occur as a series of laterally accreted, S-shaped, alternating sand and mud layers. They commonly occur in tidal channels. Tidal rhythmites commonly contain stacked sets of mud-draped ripples, or stacked sets of alternating flat laminae of mud and silt to sand. These stacked sets and laminations are organized into vertically accreted thickening and thinning tidal bundles/packages which contain periodic variations in thickness as a result of changing current velocities invoked by lunar cycles. The cyclicity in laminae thicknesses in sigmoidal bundles and tidal rhythmites is primarily a result of lunar orbital variations and the alignment of the Earth and Moon with respect to the Sun (Archer et al., 1991). Varying configurations in the position of the moon results in changes in the gravitational pull on the Earth's oceans, causing periodic oscillations in tidal amplitudes on short (less than a year) and long (1 to 10^4 years) time scales. Although longer lunar periods are not discussed here, summaries are presented in MacMillan (1966) and Nio and Yang (1989).

The shorter term lunar cycles of interest to this study are: 1) semidaily to daily tides, 2) semimonthly and monthly phase changes (neap-spring) of the moon; and 3) semiyearly periods from alignment of the sun and the major axis of the moon's orbit. The relationships of the main lunar periods affecting tidal amplitude are shown in Figure 7, and the affect of the lunar synodic month on

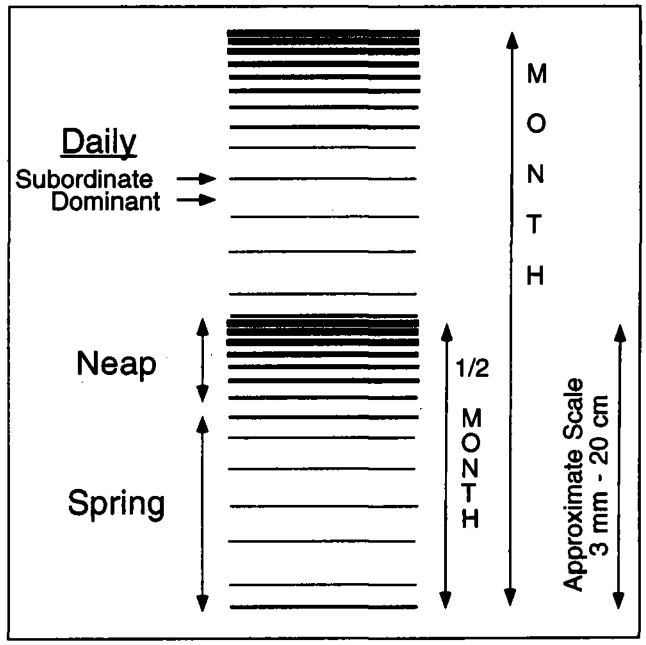

Figure 6. Idealized diagram of a heterolithic tidal rhythmite from a diurnal tidal regime (with no diurnal inequality). Two neap-spring cycles are shown in this figure where each cycle represents half a synodic month (modern length of 14.77 days). Relatively coarse grained layers are deposited during the dominant tide, and mud drapes from the subordinate tide. Neap-spring cycles in the Big Cottonwood Formation range between 0.3 to 20 cm. Similar examples of heterolithic rhythmites are at stop 3 of the trip.

rhythmite deposition in a diurnal tidal environment is given in Figure 6. These periodicities have been described from a number of both modern settings (e.g., Dalrymple et al., 1991; Tessier, 1993) and ancient settings (e.g., Sonett et al., 1988; Kvale et al., 1989, 1997; Tessier and Gigot, 1989; Williams, 1989; Archer et al., 1991; Archer and Feldman, 1994). Identification of tidal periodicities in a sequence of cyclic tidal deposits is accomplished with time series analysis using such methods as the Fourier transform to match cycles to known, diagnostic tidal lunar cycles (Schureman, 1958; Horne and Baliunas, 1986; Archer et al., 1991; Martino and Sanderson, 1993; Archer, 1994, 1996; Kvale et al., 1997).

Big Cottonwood Rhythmites

The Big Cottonwood Formation contains the oldest known (~900 Ma) example of tidal rhythmites (Chan et al., 1994). The tidal rhythmites in the Big Cottonwood Formation (e.g. see Fig. 8) are typically vertically stacked rhythmic alternations of light (silt/sand-rich) and dark (mud-drape) laminations. The smallest individual laminae

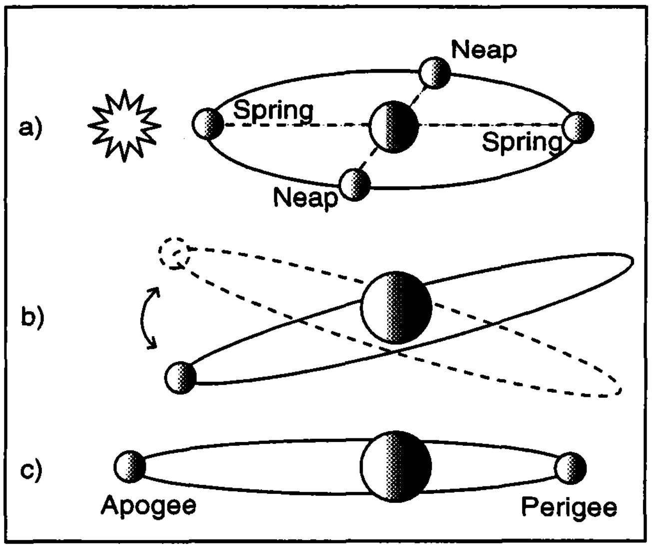

Figure 7. Primary lunar periodicities affecting tidal amplitudes. The synodic (a) half-month reflects lunar phases and has a modern half-period (time between new and full moon) of 14.77 days. The synodic half-month is visible in tidal rhythmites in the form of neap-spring cycles. The tropical half-month (b) reflects variations in lunar declination. The modern tropical half-month is 13.66 days, the time required to move from a northern to southern declination. The anomalistic month (c) represents variations in lunar distance from the Earth. The modern anomalistic month has a period (from perigee to perigee) of 27.55 days. Modified from Archer et al. (1991).

generally represent semidaily/daily tides with the silt/sand deposited by the dominant tide, and mud deposited by the subordinate tide (Fig. 6). The individual laminae are vertically organized into packages of thick and thin laminae. These smallest laminae can be counted and measured (much like counts of tree rings) with respect to laminae thickness. The packages of thick lamina (dominated by thicker silt/sand lamina) were created by stronger spring tides when the gravitational pull is greatest due to the straight alignment of the moon, Earth, and sun (Fig. 7). Spring tides occur during new and full moon cycles. The packages of thin lamina (dominated by thin mud lamina) were created by weaker neap tides when gravitational pull is slightly canceled out by the moon being out of phase with the Earth and sun. Neap tides occur during 1st and 3rd quarters. Thus the pair of a thin mud lamina package and thick sand lamina package comprises a neap-spring cycle, or a half month. Four packages of laminae (2 mud lamina packages and 2 sand lamina packages) comprise a full lunar month (synodic month). The counts and thickness spacing of the neap-spring bands literally allows the determination of the number of days in a month, how many months in a year, etc. Harmonic analyses are used to determine the tidal periodicities, and various smoothing and interpolation programs are used where some of the laminae may be truncated or difficult to distinguish.

Lamina and bundle counts from cores drilled through the Big Cottonwood tidal rhythmites have been used examine Proterozoic orbital parameters. The analysis indicates Proterozoic tides acted in a similar fashion to modern tides (Chan et al., 1994; Sonett et al., 1996). However, the Proterozoic Earth was spinning faster than it does now; the angular velocity has slowed over time. Thus, Proterozoic days were shorter (at ~ 18 hours/day vs. present 24 hours/day), and lunar months were also shorter (~ 25 days/month vs. present 29 days/month) (Sonett et al., 1996). Additionally, modern values of the lunar retreat rate away from the earth (based on NASA Apollo space research) are in the range of 3.8 cm/year, in contrast to Proterozoic lunar retreat rates of about 2 cm/year (Sonett et al., 1996).

BIG COTTONWOOD LITHOFACIES

Several major lithofacies are distinguished in the Big Cottonwood Formation. Thicknesses shown in the composite stratigraphic section (Fig. 4) are based on detailed measurements by Ehlers of the upper 2/3 of the section with a Jacobs staff. Lithofacies within the less accessible lower third of the formation were assigned thicknesses based on geologic map outcrop width (James, 1979) supplemented by observations and measurements collected at spotty outcrops. To augment this "one-dimensional" perspective of the Big Cottonwood Canyon exposures, lateral relationships, geometries, and variability of lithofacies were checked and verified by inspection of aerial photographs and reconnaissance studies along accessible trails to the high country (including Mount Olympus, Twin Peaks, Lake Blanche, and Mill B North Fork).

Description

The Big Cottonwood Formation is composed of alternating sequences of argillite and quartzite facies (Fig. 4) with relative abundance of about 50% each (Crittenden and Wallace, 1973). Argillites are more common in the lower half of the section. Five distinct lithofacies are further broken out of the basic quartzite and argillite lithologies: channeled quartzite, sheet quartzite, mud-cracked argillite, laminated argillite, and transitional argillite (Ehlers and Chan, 1996a, 1996b). The two quartzite facies (slightly metamorphosed quartz arenites) have lithologic and some internal structure similarities, but exhibit different lateral geometries. The three argillite facies are slightly metamorphosed mudstones to siltstones characterized by distinctly different internal structures. These three argillite types are typically notable in outcrop due to their difference in color. The characteristic stratigraphic position,

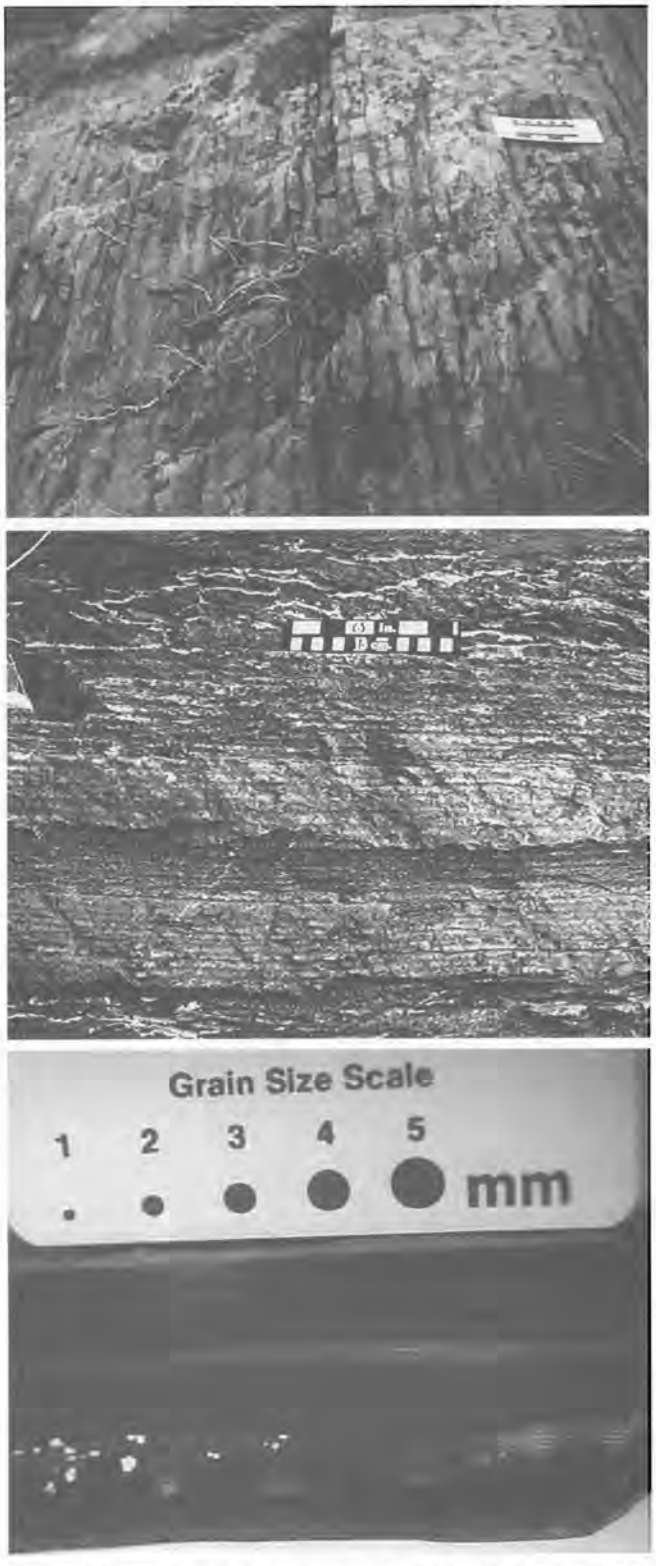

Figure 8. Examples of planar laminated rhythmites located in the Big Cottonwood Formation. Rhythmites like these are typically formed in zones of turbidity maximum in macro-tidal estuaries. Neap-spring cycle thicknesses average around 3–4 cm (a), and range from as much as 15 cm (b), to as little as several mm (c).

geometries, lithologies, and sedimentary structures for each facies are summarized in Table 1.

The channeled quartzite facies is largely distinguished by individual channels that are laterally extensive on the order of hundreds of meters, with a thickness on the order of tens of meters. The facies commonly exhibits a sharp scoured base that is lined with a coarse lag of quartz pebbles and/or argillite rip-up clasts. There is a general upward fining within this facies and a corresponding upward thinning of bed size. Internally, the channeled quartzite typically contains tabular and trough crossbedding, some soft sediment deformation, and current ripples.

The sheet quartzite facies exhibits a more tabular geometry that is laterally extensive on the order of hundreds of meters to several km, and hundreds of meters thick. Where exposed, the facies tends to be laterally traceable over several kilometers although it is difficult to trace individually stacked beds or sets any distance due to the terrain. The internal structure appears to be stacked cross bedding although outcrop weathering makes it difficult to distinguish. Wave ripples are present along some bedding plane outcrops.

The mud-cracked argillite is typically a weakly bedded, reddish purple mudstone to siltstone, with common mud crack structures. Where coarser (silt to sand size) fractions are present, associated features include mud-cracks, rain drop impressions, adhesion structures and wave ripples along bedding planes.

The laminated argillite is a black shale to siltstone with some thin sandstone beds. This argillite facies typically contains finely alternating mud- and sand-rich, mm-laminae herein termed rhythmites (e.g. Fig. 8, dark colored, mm scale rhythmites). The rhythmites range from being heterolithic, meaning a mix of grain sizes, or "unlike" lithologies (typically sand and mud) to those that have very little sand and therefore become more difficult to distinguish. Where the vertically organized heterolithic rhythmites occur, daily, semimonthly, and monthly cycles can be observed in both outcrop and in hand specimens. Syneresis cracks (possibly subaqueous shrinkage cracks?) are common along exposed bedding planes in the lower portions of the facies. Thin sandstone beds typically show small load casts and physical deformational features. Diagenetic pyrite is also common within the black laminated argillite. Some large and deformed blocks of the rhythmites occur in association with channeled quartzite.

The transitional argillite is green-gray in color and typically fines upwards into the reddish purple mud-cracked argillite. It is well bedded and also contains some rhythmites although not as finely developed as those that occur within the black laminated argillite. These rhythmites appear to represent annual cycles whose thickness can be verified with harmonic analyses and where daily and

Table 1. Summary of lithofacies observed in the Big Cottonwood Formation

Facies Name	Sedimentary Structures	Facies Association	Interpretation
Channelized Quartzite	• Channeled, upward fining successions 10s 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: 1–4 m thick by 10–200 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 quartzie or green-gray agrillite	• Inter- to possibly supratidal
Laminated Argillite	• Thinly laminated at base with heterolithic rhythmites • Diagenetic pyrite • Syneresis cracks	• Generally overlies channeled quartzite	• Sub- to intertidal
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	• Overlies channeled quartizite	• Intertidal at base to supratidal at top

monthly signals are not well preserved. This transitional facies contains small scour and truncations surfaces, small load structures, and climbing ripples.

Within the composite section through Big Cottonwood Canyon (Fig. 4), the mud-cracked argillite constitutes 40% of the section and is found mainly in the lower half of the section, whereas the laminated argillite constitutes 12% of the section and is found only in the upper half of the section. The transitional argillite is located in the upper 300 m of the section, and constitutes only 4% of the section. The channeled and sheet quartzite are interspersed throughout the section, and constitute 30% and 14% of the section, respectively. One hundred and fourteen paleocurrent measurements from crossbedding and current ripples in the upper 2/3 of the formation were evaluated. These measurements were corrected for two tectonic events to arrive at a dominant westward paleoflow direction.

Two important vertical relationships of facies and transitions are recognized: 1) The sand sheet quartzite generally has relatively straight, sharp contacts with adjacent argillite facies (e.g., stop 3). Although the contacts are sharp, there is little evidence of scouring (lags, rip-up clasts) at the base of the this facies. 2) The channeled quartzite characteristically has a scoured base with pebble size rip-up clasts and lags. The top of the channeled quartzite fines upward into overlying transitional argillite. The thinning and fining nature as well as some preservation of rhythmites between the underlying quartzite and overlying argillite suggests the gradual transition from a higher to relatively lower energy environment (e.g., stops 3, 4, and 5 of this trip).

Interpretation

Diagnostic structures of heterolithic rhythmites with daily, semi-monthly and annual lunar periodicities, as well as sigmoidal bundles, current ripples with crests rounded by back flow, and clay draped reactivation surfaces clearly indicate the strong tidal influence on the depositional setting. The association of quartzite and argillite lithofacies suggest a depositional system that incorporates aspects of a tidal signature along with river-like channels and some shallow marine influence. We argue that the Big Cottonwood facies of this area illustrate deposition in a tide-dominated estuary as discussed below.

The precise interpretation of tidal environments is somewhat problematic because tidal processes can overlap into a number of clastic shoreline settings. There is also confusion in nomenclature used to classify tidal deposits partly because of differences in scale and gradations between coastal systems (e.g., see discussion in Reading and Collinson, 1996, p. 182). The combination of both tidal and fluvial influence suggests a transitional environment in which both processes can operate. Tidal deltas are recognized as areas where constricted exchange through a barrier (e.g., barrier island) disperses sediment load on either side of the barrier as flood-tidal and ebb-tidal deltas. Nothing within the Big Cottonwood Formation indicates this kind of tidal delta setting.

Another transitional interpretation to be considered is a tide-dominated river delta. Shoreline deltas typically exhibit delta plain and delta front facies with well-developed, upward-coarsening sequences formed from delta lobe progradation and/or sea level change. However, no well-developed upward-coarsening successions were recognized within the Big Cottonwood Formation in Big Cottonwood Canyon.

An alternative interpretation we believe to be more appropriate to the Big Cottonwood facies is deposition in an estuary. An estuary spans a broader range of geomorphic and environmental features than most of the delta terminology, conveys a coastal embayment or geomorphic reentrant with a drowned river valley. This setting 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. Previous studies of modern estuarine environments (e.g., Dalrymple et al., 1991, 1992, and Tessier, 1993) provide a model (Fig. 9) that illustrates the facies of a tide-dominated estuary. The tidal limit typically extends up into the mouth of the alluvial valley. Modern analogs provide the conceptual basis for how we interpret the sedimentary structures and lithofacies summarized in Table 1.

The sheet quartzite lithofacies is located in the lower two thirds of the Big Cottonwood Formation section and ranges in thickness from 100–300 m. This facies shows little evidence of fluvial influence, and the presence of wave ripples is suggestive of marine processes. This facies is interpreted to represent subtidal sand waves and/or tidal sand bars (Fig. 9) which were deposited in the marine-dominated mouth of the estuary. Within the section, this facies is generally vertically adjacent with the mud-cracked argillite and interpreted to have formed laterally adjacent to the thick successions of mud-cracked argillite.

The channeled quartzite lithofacies with cross bedding and current ripples is most common in the upper half of the section and is vertically associated with the laminated and transitional argillite. The channeled quartzite may be similar to two types of tidal fluvial channels found in the upper reaches of modern estuaries. First, when associated with the laminated argillite, this facies may represent the "main" tidal fluvial channel (Fig. 9). Second, when associated with the transitional argillite, this facies may represent smaller tributary tidal channels which were oblique to sub-parallel to the main channel. A basis for a distinction between channels lies in the associated argillite facies.

The laminated argillite lithofacies with syneresis cracks, heterolithic rhythmites, and diagenetic pyrite likely formed in the sub- to intertidal zone. The dark color of the shale with diagenetic pyrite suggests reducing conditions and the presence of organic carbon that might have been best preserved at subtidal depths. Heterolithic rhythmites with daily lamina and neap-spring cycles suggests that depositional rates were relatively high and at a place where tidal currents were strong enough to deposit sand during the dominant tide. This facies occurs in both thick successions and thin units associated with channeled quartzite in the upper half of the section (Fig. 4). Where thin units (1–10 m scale) of laminated argillite flanked the main tidal channel in the subtidal zone, they may have capped a channeled sequence, or were flanking heterolithic rhythmites that were occasionally cut and collapsed along channel bank margins with shifting of the tidal channel (Figs. 17 and 18, and stops 4 and 5). Thick successions (100–300 m) of the laminated argillite are present in six locations largely in the lower half of the section (Fig. 4). At the base of the thick successions of laminated argillite, heterolithic rhythmites are also well preserved suggesting subtidal deposition adjacent to a tidal channel. However, the upper portion of the thick successions lack rhythmites and syneresis cracks and may therefore represent more intertidal mudflat deposition as the succession progressively shallows. Unfortunately, the upper portions of these thick succes-

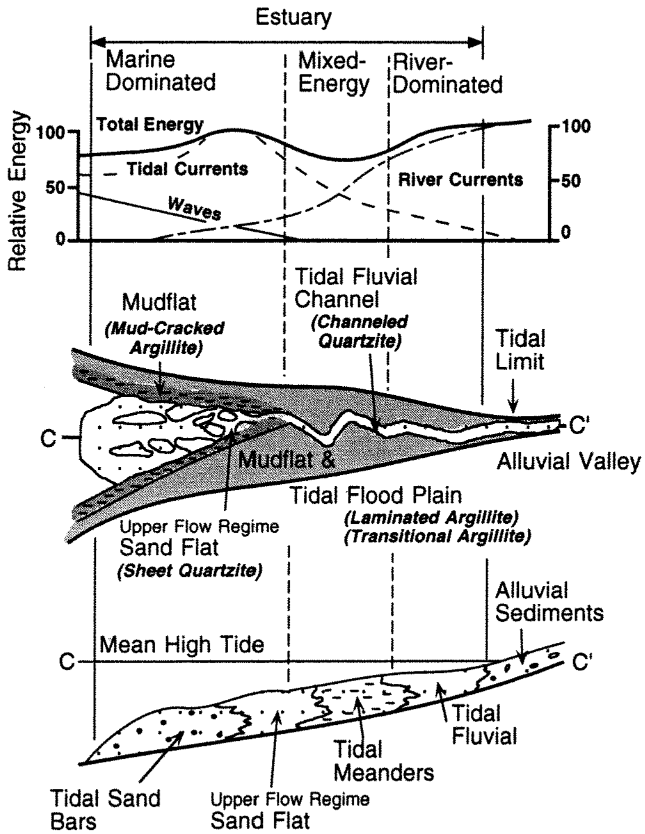

Figure 9. Estuarine depositional model for the Big Cottonwood Formation. Channeled quartzite facies, and argillites with heterolithic rhythmites were most likely deposited in the mixed energy environment where both fluvial and tidal sedimentation occurred. Sand sheet facies (with wave ripples) were most likely deposited near the mouth of the estuary where marine processes dominated. Modern depositional environments are labeled in the middle portion of the figure, and Big Cottonwood Formation facies equivalents are in italics and parenthesis. Modified from Dalrymple et al., (1992).

sions are generally fissile and sedimentary structures are not well preserved.

The transitional argillite lithofacies with annual cycle rhythmites, current ripples with crests round by backflow, and clay draped reactivation surfaces is located in the uppermost part of the section (Stop 5; Figs. 4 and 19). The presence of annual cycles in heterolithic rhythmites suggests that this facies was deposited farther away from the main tidal channel, perhaps in the uppermost intertidal, or supratidal zone and where only extreme hydrologic conditions (high seasonal runoff, storm events) caused sedimentation. This facies is characteristically associated with the channeled quartzite as part of an upward fining and thinning sequence, and suggestive of deposition along tributary tidal channels where thinner (more condensed) annual cycles might be preserved. Modern analogs indicate that hydrologic conditions required for episodic deposition of this facies are present in the upper reaches of the estuary, near the tidal limit, and removed from sedimentation associated with the main tidal channel.

The mud-cracked argillite lithofacies is most abundant in thick successions (100–500 m) in the lower half of the section, although thin layers (2–4 m) are found in the uppermost part of the section where it caps the transitional argillite (Figs. 4 and 19). We interpret the thick successions of this facies to represent intertidal mud-flats close to the mouth of the estuary (Fig. 9). In modern analogs, tidal mud-flats 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. The thick successions of the mud-cracked argillite in the Big Cottonwood Formation are vertically associated with the sheet quartzite facies (Fig. 4). The thinner units of mud-cracked argillite differ from the thick units in that they are part of a fluvial upward fining and thinning sequence (stop 5; Fig. 19). These thinner mud-cracked argillites were likely deposited towards the landward end of the estuary, adjacent to the tidal-fluvial channels as a hybrid tidal flat to flood plain deposit. In modern settings, this area in the landward end of the estuary is recognized as a salt marsh facies. However, in the Big Cottonwood setting with no plants, such a facies is not distinguishable.

Vertical facies associations in the Big Cottonwood Formation, and the location between facies in which rhythmites are found are also analogous to modern estuarine environments. Tessier (1993) notes two important conditions for the preservation of modern rhythmites: a protected environment is needed to limit erosion from wave action or highly energetic tidal currents; and suspended sediment concentrations must be high so that thick sand-mud couples are deposited. Both these conditions are found at the upper end of estuaries close to (within 5–15 km of) the tidal limit. In the Bay of Fundy and the Bay of Mont-Saint-Michel rhythmites typically form adjacent to tidal-fluvial channels in sub- to intertidal parts of tidal flats, or in abandoned tidal channels. In the former case, rhythmites form adjacent to tidal channels on the mud flat as a type of "overbank" deposit in a tidal flat/floodplain area where deposition occurs with every tide. The best preservation of the rhythmites is in the inner portion of the estuary where wave action is minimal and sedimentation rates are high. This location of rhythmite deposition accounts for the slump blocks (bank collapse structures) of rhythmites preserved in the channeled quartzite of the Big Cottonwood Formation. In the latter case where rhythmites form in abandoned tidal channels, modern analogs record a upward-fining succession with sands from the tidal channel at the base and then gradation into rhythmites and then silts.

Some differences exist between the lithofacies of the Big Cottonwood Formation and those found in the modern analogs. The most notable differences observed in the Big Cottonwood Formation include a broader and more sheet-like deposition of facies, particularly in the quartzite facies, and the lack of a salt marsh facies per se. We believe these differences are a result of the lack of vegetation in the Proterozoic. In modern estuaries, vegetation in salt marshes holds up steep (1–3 m high) banks which laterally constrain tidal currents to intertidal mudflats. The lack of vegetation in the Big Cottonwood Formation possibly resulted in more subdued topography and a broader, more laterally extensive distribution of facies. The lithofacies of the Big Cottonwood Formation are generally laterally extensive from 2–11 km, and are present over a greater lateral extent than similar facies of modern analogs. Because of the lack of vegetation in the Big Cottonwood Formation, we believe the Proterozoic equivalent of a salt marsh would be a tributary tidal channel flood plain. This ancient equivalent of a salt marsh would form in the uppermost intertidal zone, away from the main tidal fluvial channel, and would be blanketed by fine grained sediment during daily dominant tides.

This overall estuary interpretation also incorporates the landward (eastern) outcrops of the Uinta Mountain Group as a fluvial deposystem feeding the estuarine deposits of the Big Cottonwood Formation (Fig. 10). This scenario differs slightly from previous interpretations of the Big Cottonwood Formation and Uinta Mountain Group as deposited in shallow water, sand and mud flat, and possibly lacustrine environments (Crittenden and Wallace, 1973; Crittenden, 1976; Link et al., 1993).

Macro-Tidal Deposition

The best examples of tidal rhythmites from the modern record come from macrotidal (> 4 m tidal range) systems. Rhythmites from these systems are commonly described as heterolithic, meaning a mix of grain sizes. The heterolithic nature of rhythmites in these systems is 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 and convincing as the rhythmites from macrotidal settings. Correspondingly, in these smaller tidal ranges, energy may be insufficient to transport and deposit such contrasting grain sizes such that even if rhythmites did develop, their

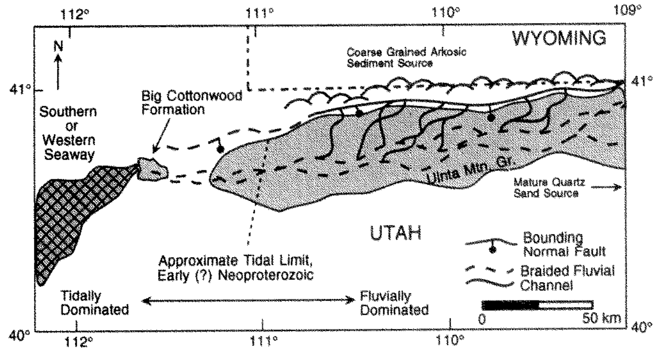

Figure 10. Paleogeography and tectonic setting of the Big Cottonwood Formation and Uinta Mountain Group. Location of the Big Cottonwood Formation and Uinta Mountain Group have been corrected for a 12 and 40 degree rotation, respectively, based on the paleomagnetic data of Elston et al. (in Link et al., 1993). This correction restores these units to their orientation at the time of deposition. The extent of the basin that encompassed these deposits is unknown, and the outcrop distribution in this figure is the same as their present day outcrops.

fine-grained nature would make them more difficult to recognize.

Interpretation of macrotidal deposition may be inferred on the basis of two criteria found in modern macrotidal analogs: 1) planar-laminated heterolithic rhythmites; and 2) thickness of both laminae and the neap-spring cycles. Analysis of modern macrotidal analogs include the diurnal Bay of Fundy (Dalrymple et al., 1991, 1992), and the semidiurnal Bay of Mont-St.-Michel (Tessier, 1993). Within these modern macrotidal systems, heterolithic, planar-laminated rhythmites generally form in the uppermost portion of the tidal regime, and typically in zones of turbidity maximum in estuaries (Archer, 1997). The macrotidal system typically has heterolithic lithologies (due to the contrast of dominant and subordinate tides) and is able to generate planar rhythmite lamina (due to the high energy). Planar laminated rhythmites in the Big Cottonwood Formation (Fig. 8), and the thick (3 mm to 20 cm) heterolithic nature of the rhythmites, are used to infer a high-energy, macro-tidal regime (Ehlers and Chan, 1996a, 1996b).

Larger (macro tidal) tidal regimes also result in the formation of thicker neap-spring cycles. The thickness of neap-spring cycles varies according to tidal amplitude and the amount of sediment deposited. Neap-spring cycle thickness 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 2–5 cm (Tessier, 1993). For the Big Cottonwood Formation, cycle thicknesses range from several mm to 20 cm (e.g., see Fig. 8). In general, neap-spring cycles of the Big Cottonwood Formation are within the range of the modern macro-tidal cycles, although slightly thinner than those found in the Bay of Fundy, and thinner to thicker than those observed in the Bay of Mont-Saint-Michel.

Variation between Big Cottonwood Formation rhythmite thicknesses and the observed modern analogs is probably due to differing tidal ranges within the macrotidal regime and/or variations in the sampling location within the depositional basin. The maximum tidal ranges in the Bay of Fundy and Bay of Mont-Saint-Michel are 15.6 m and 15.3 m, respectively. Unfortunately, no proxy for calculating a precise tidal range from rhythmites is known so we are unable to speculate on the magnitude of the paleomacrotidal range of the Big Cottonwood Formation and can only draw reference from modern analogs. Rhythmite thicknesses in both modern settings vary depending on the sample location within the estuary. In the cited modern settings, rhythmite thickness increases (several to tens of cm) landward, where thicker and relatively more heterolithic rhythmites form generally within 5 km or less of the tidal limit in the zone of maximum turbidity. The presence of well developed rhythmites of comparable thicknesses to modern analogs suggests a macrotidal regime for the Big Cottonwood Formation.

One assumption in the comparison of rhythmites from modern analogs and the Big Cottonwood Formation that remains an unknown is the effect of vegetation (lacking in the Precambrian) as a bank stabilizer, and whether or not it influences tidal amplitudes. Tidal amplitudes depend on the latitude, basin geometry, and the size of the body of water in which the tides occur. Vegetation could influence the basin geometry by causing low relief along banks and perhaps affecting basin hydrodynamics. It is difficult to quantify this aspect of Big Cottonwood sedimentation.

Sequence Stratigraphy

The general lateral relationships of facies within the Big Cottonwood Formation were studied and mapped from aerial photos and some outcrops. However, steep topography, dense vegetation, and time constraints inhibit a more thorough tracing of lateral facies relationships. Five prominent, laterally continuous channeled quartzite bodies are present and overlie erosional unconformities in the upper half of the section. The channeled quartzite facies are 100–300 m thick and laterally extensive (8–12 km) over the entire study area. These unconformities are interpreted to represent sequence boundaries overlain by channeled quartzites. Because the accessible outcrop exposures are limited to several km, it is unlikely that these unconformities can be regionally correlated. However, other Proterozoic incised valley deposits in younger formations (Christie-Blick et al., 1988; Levy et al., 1994; Link et al., 1993; Christie-Blick, 1997) have proven useful for some regional stratigraphic correlations.

BIG COTTONWOOD PALEOGEOGRAPHY AND TECTONICS

Previous interpretations of the tectonic setting of the Big Cottonwood Formation and correlative Uinta Mountain Group concluded that these strata were deposited in a shallow water intracratonic basin fed by a braided fluvial system located to the east where the present-day Uinta Mountain Group is exposed in the Uinta Mountains (Wallace and Crittenden, 1969; Wallace, 1972; Crittenden, 1976; Sanderson, 1978, 1984; Link et al., 1993). These generalizations predate the discovery of tidal signatures and macro-tidal interpretations for the Big Cottonwood Formation which necessitate a western ocean body to generate tides. Recent studies (Ehlers and Chan, 1996b) also indicate minor tidal influence in portions of the Uinta Mountain Group. It is likely that the braided fluvial deposits of the Uinta Mountain Group fed westward into the Big Cottonwood system and occasionally preserved a tidal influence in the uppermost reaches of the estuary, probably close to the tidal limit. In modern estuarine settings, it is not uncommon for the tidal limit to extend some forty to several hundred kilometers inland (e.g., Dalrymple et al., 1991, 1992; Dalrymple, 1992; Tessier, 1993).

The lower half or more of the eastern Uinta Mountain Group was deposited along the southern flank of an east-west trending normal fault (Sears et al., 1982; Bruhn et al., 1983) (Fig. 10) that is believed synchronous with deposition of the Uinta Mountain Group (Bruhn et al., 1986; Link et al., 1993; Ehlers and Chan, 1996b). Evidence for synchronous deposition stems from the conglomeratic Jesse Ewing Canyon Formation (located at the base of the eastern Uinta Mountain Group) which lies adjacent to the fault and abruptly grades laterally (over 1 km) to a siltite (Hansen, 1965; Link et al., 1993). The abrupt lateral gradation suggests a rapid subsidence of the hanging wall. The amount of offset on this fault is unknown, but the Jesse Ewing Canyon conglomerate is approximately 800 m thick so that the north-south extension associated with formation of the half graben was most likely of moderate proportions.

The base of the Big Cottonwood Formation contains cobbles and angular debris of the underlying schistose Paleoproterozoic Little Willow Formation. The bounding normal fault on the north side of the Uinta Mountain Group (Fig. 10) may extend westward to the Big Cottonwood Formation and could have caused deposition of the thin basal conglomerate there. However, this westward continuation of the fault is uncertain. Only a small portion (100 km^2) of the Big Cottonwood Formation is exposed along the Wasatch Front, and the fault can not be traced westward to the Big Cottonwood Formation. The dominant westward paleoflow direction of the Big Cottonwood Formation does not suggest southward transport of material from the inferred footwall to the hanging wall.

We suggest that the Big Cottonwood Formation was rapidly deposited in a macro-tidal estuarine environment, possibly in an east-trending half-graben. The age of the formation is only broadly to constrained to a 200 my period indicating a minimum, time averaged accumulation rate of ~2.5 cm/ka. Sedimentation rates in estuarine environments are generally high due to sediment sources from both fluvial and marine ends of the estuary. Modern estuaries have sedimentation rates between 100–780 cm/ka (Fairbridge and Bourgeois, 1978, p. 689) which are two orders of magnitude higher than the conservative average rate for the Big Cottonwood Formation. If we assume an average modern estuarine sedimentation rate of 440 cm/ka for the Big Cottonwood Formation, then deposition of the entire preserved formation (4.8 km, not including decompaction of sediments) would have occurred in approximately 1.1 m.y. Moreover, sedimentation rates in the Big Cottonwood Formation estuary were possibly higher than modern estuaries due to a lack of vegetation for bank stabilization in the Proterozoic, suggesting deposition could have occurred in less than 1 m.y. However, periods of non deposition, erosion surfaces, and unconformities in the Big Cottonwood Formation may also account for a significant amount of time that cannot be evaluated. The primary point of interest here is that deposition of the Big Cottonwood Formation most likely occurred in a significantly shorter period of time than required by stratigraphic constraints.

The Big Cottonwood Formation is inferred to have been connected to an oceanic body of major proportions, with the appropriate basin geometry to generate macro-tidal amplitudes and thus heterolithic rhythmites. Modern macrotidal environments are located in basins connected to either the Atlantic or Pacific ocean and by analogy suggest that the Big Cottonwood was similarly connected to a large paleooceanic body. Even the Mediterranean Sea, which is considered a large enclosed sea, only generates microtidal amplitudes of 10–30 cm (Reading and Collinson, 1996, p. 164). Modern analogs also indicate that macrotidal ranges exist in areas connected to open oceans and localities where the tidal bulge encounters shallow water, converging shores, and/or is funneled into estuaries (Dalrymple et al., 1991; Dalrymple, 1992; Tessier, 1993; Reading and Collinson, 1996, p. 164; Archer, 1997).

Paleocurrent measurements from the Big Cottonwood Formation and Uinta Mountain Group indicate westward transport, suggesting that other Big Cottonwood Formation deposits may exist west of the Wasatch Range. However, westward outcrops of the Big Cottonwood Formation are sparse, and are more than 4 kilometers thinner than in Big Cottonwood Canyon. We have not yet studied westward outcrops in detail, although some constraints exist on the extent of the Big Cottonwood Formation basin from regional stratigraphic studies in western Utah. Mesoproterozoic rocks are not present in subsurface wells in the San Rafael Swell to the south, suggesting that the Big Cottonwood Formation–Uinta Mountain Group basin did not extend far southward. Mesoproterozoic rocks are also not present to the west on Antelope Island in the Great Salt Lake, nor in the allochthonous Raft River and Albion Ranges in northwestern Utah and southern Idaho. The lack of widespread correlative Proterozoic deposition suggests that either deposition to the west occurred but was not preserved, or that westward deposition was limited to a narrow seaway which connected to an ocean.

This half-graben which contains the Uinta Mountain Group, and possibly the Big Cottonwood Formation, may have formed close to 800 Ma as a precursor to the rifting associated with the Bannock Volcanics (ca 750 Ma) (Link et al., 1993). This correlation and tectonic setting are very similar to the uppermost rocks of the Grand Canyon area (Sixtymile Formation, deposited into half-grabens during the Grand Canyon orogeny, around 780 Ma; Link et al., 1993). Thus the tectonic setting of the Big Cottonwood and Uinta Mountain Groups could be more closely associated with succeeding Neoproterozoic rifting and mafic volcanism than previously thought.

The magnitude of rifting associated deposition of the Uinta Mountain Group and Big Cottonwood Formation is believed of moderate proportions due to the coherence of the craton underlying these strata and the limited thickness (~800 m) of the Jesse Ewing Canyon Formation in the eastern Uinta Mountain Group. The Paleoproterozoic (1.8–1.6 Ga) Cheyenne Belt underlies the Big Cottonwood Formation and Uinta Mountain Group and extends continuously due west to approximately Ely, Nevada (Bryant, 1988; Hoffman, 1988, 1989; Link et al., 1993) where it terminates and marks the edge of the Proterozoic craton. To the south of the Big Cottonwood Formation, the underlying craton is composed of the Paleoproterozoic Yavapai and Mazatzal provinces which extend to southern Arizona (Hoffman, 1988, 1989). Although Basin and Range extension has increased the distance of the Big Cottonwood Formation to the southern edge of the Proterozoic craton (the closest distance to a Mesoproterozoic ocean body), tidal amplitudes would still have to be transmitted approximately 200–400 km into the craton to cause deposition in the Big Cottonwood Formation. These distances seem large, but tidal currents associated with rhythmite deposition in modern tide-dominated estuaries can extend several hundred kilometers inland (Dalrymple, 1992).

NEOPROTEROZOIC TECTONIC SYNTHESIS AND WORKING HYPOTHESES

A reasonable Neoproterozoic tectonic synthesis is as follows (Levy and Christie-Blick, 1991; Link et al., 1993; Christie-Blick, 1997). The Mineral Fork Formation and Pocatello Formation represent the Sturtian glaciation (750–700 Ma), with synchronous continental rifting and bimodal volcanic activity. Above the last glacial lowstand, strata deposited during the post-glacial transgression and subsequent thermal subsidence of the incompletely rifted continental margin are represented by the upper Pocatello and lower Brigham Group strata up to the lower part of the Caddy Canyon Quartzite. The Mutual Formation in Big Cottonwood Canyon contains both the upper Caddy Canyon-Inkom sequence and the Mutual sequence, which may have been deposited during transgressive and highstand phases of glacio-eustatic cycles during the Varanger glaciation (610–580 Ma). The Geertsen Canyon-Camelback Mountain-Tintic sequence represents thermal subsidence of the Cambrian Cordilleran passive margin.

The problem arises in terms of how to fit the early Neoproterozoic macrotidal Big Cottonwood Formation into the previous tectonic scenario, which suggests a tectonically quiet intracratonic setting prior to rifting associated with the Mineral Fork Formation. We offer speculation as to how the Big Cottonwood Formation and Uinta Mountain Group might relate to regional paleotectonics and the Rodinia Supercontinent (Dalziel, 1991; Moores, 1991; Unrug, 1997). The proposed scenarios are based on: macrotidal deposition in the Big Cottonwood Formation; a normal bounding fault synchronous with deposition in the Uinta Mountain Group and possibly the Big Cottonwood Formation; and westward paleocurrent flow in the Big Cottonwood Formation and a majority of the Uinta Mountain Group.

One hypothesis is that the Big Cottonwood Formation and Uinta Mountain Group were deposited prior to the ~750 Ma breakup of western Rodinia between southwestern Laurentia and East Antarctica along the SWEAT connection (Dalziel, 1991; Moores, 1991; Powell et al., 1993; Torsvik et al., 1996; Dalziel, 1997). If deposition occurred at this time then macrotidal amplitudes in the Big Cottonwood Formation would have been generated through a ~300–400 km connection of this unit to a southern ocean body.

A second hypothesis is that deposition is associated with the breakup of Rodinia allowing for a shorter (~200 km) western connection of the Big Cottonwood Formation to ocean waters that inundated between western Laurentia and East Antarctica (Dalziel, 1997).

For both of these cases, macrotidal amplitudes could have been transmitted into the craton by two different mechanisms. The connection to this ocean body could be by means of a narrow seaway that focused tidal energy into the craton, somewhat analogous to the Bay of Fundy. Connection to an ocean by a narrow seaway would leave little evidence of its presence, and therefore making it difficult to find in the geologic record. A second mechanism could be that western Laurentia was relatively low, and sea level high; meaning that a tide-dominated shelf environment over southwestern Laurentia transmitted tidal energy to the Big Cottonwood Formation estuary. This second mechanism is similar to the modern tide-dominated shelf environment of the North Sea which locally has macrotidal amplitudes. A tide-dominated shelf environment would presumably cause some deposition across western Laurentia, for which no evidence has yet been found. However, evidence of a post-Big Cottonwood Formation carbonate platform is preserved in clasts of the Neoproterozoic Mineral Fork Formation. If a marine shelf environment did provide macrotidal amplitudes for the Big Cottonwood Formation, then the post-Big Cottonwood Formation carbonates preserved in the Mineral Fork Formation might represent a subsequent period of marine sedimentation over southwestern Laurentia.

In the companion field guide on Neoproterozoic sedimentation and tectonics of west-central Utah, Christie-Blick (1997) suggests that sedimentation in the Big Cottonwood Formation is a result of Late Mesoproterozoic to Early Neoproterozoic (~1.1–0.8 Ga) crustal extension followed by thermally driven subsidence and deposition of the overlying carbonate unit, which was removed by glaciation (~750 Ma) subsequent to lithification. The main distinction between our tectonic hypothesis and that of Christie-Blick lies in the time of rifting and deposition. Christie-Blick suggests deposition was unrelated to the breakup of Rodinia (~750 Ma), and is the result of a separate rifting event of moderate magnitude that occurred in southwestern Laurentia while western Rodinia was still assembled. Both hypotheses are plausible. However, at this time they require further development including an examination of Big Cottonwood Formation deposits west of the Wasatch Range. A goal would be calculation of predicted tectonic extension and thermal subsidence amounts using McKenzie (1978) type stretching models, though lack of geochronometric data will probably preclude all but the most general models. If predicted Big Cottonwood Formation extension amounts are large, then perhaps deposition was associated with the breakup of Rodinia since no other evidence of large magnitude extension has been documented in the Late Mesoproterozoic to Early Neoproterozoic of southwestern Laurentia. Future work in the Big Cottonwood Formation will focus on the sparse western outcrops located in Slate Canyon, the East Tintic Mountains, Stansbury Island, and Carrington Island.

SUMMARY

Several Proterozoic formations exposed in Big Cottonwood Canyon illustrate a range of clastic depositional systems from contrasting paleogeographic and tectonic regimes. Within the thick, Big Cottonwood Formation there is remarkable preservation of sedimentary structures which suggest tidal deposition in an estuarine setting. Paleocurrent measurements indicate a dominant westward direction of flow, fed by the easterly fluvial systems of the Uinta Mountain Group. Five distinct lithofacies in the Big Cottonwood Formation include: fluvial-dominated channeled quartzite (tidal channel); subtidal sheet quartzite (sand sheets at mouth of estuary); inter- to supratidal mud-cracked argillite (probably gradational to a tidal channel flood plain); sub- to intertidal laminated argillite (in the inner portion of the estuary where wave action is minimal); and a inter- to supratidal transitional argillite (toward the upper portion of the estuary). These facies suggest deposition in an estuarine setting with river dominance in the upper reaches (tidal limit), to wave influence in tidal sand bars in the lower reaches (subtidal). Comparisons with modern estuarine environments are used to infer that the Big Cottonwood experienced macro-tidal amplitudes in a diurnal tidal regime. Harmonic analysis of tidal rhythmites indicate that the Proterozoic tides acted in a similar fashion to modern tides and record daily, semimonthly, monthly, and annual cycles.

The relatively younger Neoproterozoic Mineral Fork Formation and Mutual Formation, and the Cambrian Tintic Quartzite indicate a shift in depositional and tectonic styles from that of the Big Cottonwood Formation. The Mineral Fork Formation suggests deposition in temperate glacial-marine glacially sculpted fjord. The Mutual Formation records deposition in a braided fluvial environment and contains a regional stratigraphic sequence boundary. Deposition in the Cambrian Tintic Quartzite suggests marine passive-margin sedimentation.

DESCRIPTION OF STOPS

The mileage of all the stops is measured from the mouth of Big Cottonwood Canyon at the parking lot. The green mile markers along Highway 190 do not represent the mileage from the mouth of the canyon.

Stop 1: Overview of the Wasatch Range (mile 0)

Location: Parking lot at the mouth of Big Cottonwood Canyon.

Description: This stop provides an overview of the Wasatch Front. Oligocene magmatism resulted in the emplacement of plutons such as the quartz monzonite visible high on the south side of the canyon across from the parking lot. The rocks in the central Wasatch range (at this stop) were exhumed approximately 11 km (Parry et al., 1988; Parry and Bruhn, 1987) as a result of Basin and Range extension. The seismically active Wasatch fault (a normal fault at the eastern boundary of the Basin and Range province) crosses the highway just east of the parking lot and is capable of generating M 7.0–7.5 earthquakes (Arabasz et al., 1990). From this location, the road ascends rapidly into the rugged topography of Big Cottonwood Canyon.

Stop 2: Remnants of an ancient sea sign—Big Cottonwood Formation (mile 2.3, 3.8 km)

Location. Pull out is located long the south side of Highway 190, at the National Forest Sign reading "Remnants of an Ancient Sea."

Description: This stop is located about 1/3 of the way up the stratigraphic section of the Big Cottonwood Formation (Figs. 2 and 4) at an outcrop of the purple-colored, mud-cracked argillite facies. This facies typically overlies the channeled quartzite or transitional argillite facies, and is hundreds to several meters thick. The lateral extent of the mud-cracked argillite is generally 1 km or more. Several distinct structures are preserved in this weakly bedded facies (particularly along the bedding plane exposures) including mud cracks, rain drop impressions, adhesion structures, and wave ripples.

Green-colored beds indicate more permeable fine-grained sandstone and siltstone. Fluids resulting from emplacement of the Little Cottonwood Stock (~30 Ma) moved along the zone of the Wasatch Fault to produce hydrothermal alteration (including white vein quartz with hematite and pyrite) in the fine-grained beds.

Interpretation: The mud-cracked argillite is interpreted to have formed in intertidal to possibly supratidal flat area within the tidal limit of the estuarine system. This facies is vertically associated with the sheet quartzites, interpreted to be subtidal sand bars, suggesting that the mud-cracked argillite facies was a mud flat located towards the mouth of the estuary. This facies could also have been transitional to tidal channel flood plain deposits. The presence of mud cracks and rain drop impressions indicates subaerial exposure. The small wave ripples superimposed on the mud-cracked bedding planes imply shallow water and oscillatory flow. It is difficult to determine whether other parts of the facies might be supratidal due to lack of any paleosols (correlated with a lack of vegetation in the Precambrian).

Stop 3: Storm Mountain quartzite sign—Big Cottonwood Formation (mile 2.9, 4.8 km)

Location: Located just past the Storm Mountain picnic area and amphitheater. Pull off along the south side of the

Figure 11. Photograph of mud cracked argillite (stop 2).

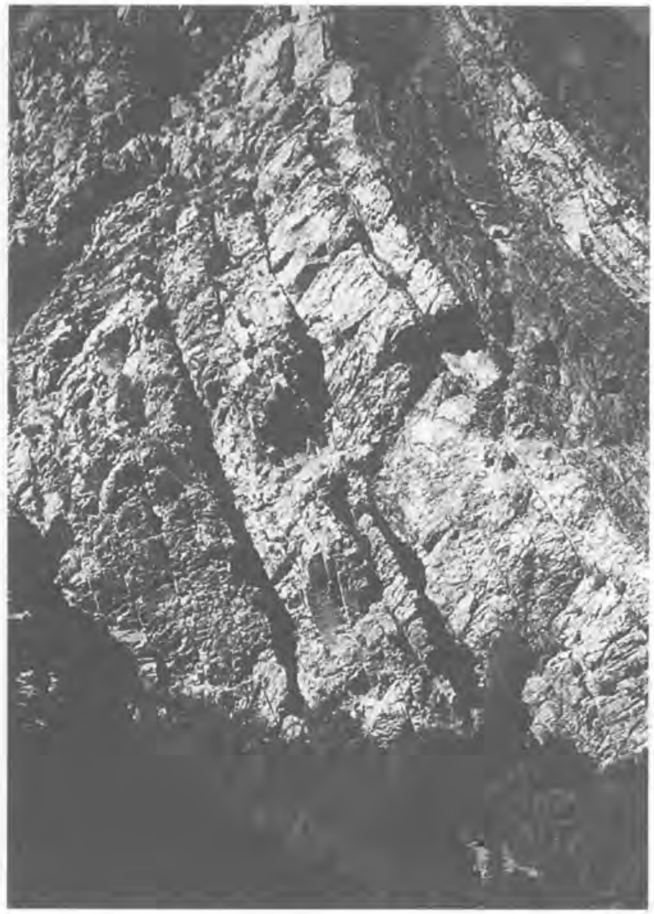

Figure 12. Sand sheet quartzites located behind Storm Mountain amphitheater (looking northwest from stop 3). Approximate distance across the bottom of the figure is 300 m.

road at the "Storm Mountain Quartzite" sign. The second part of this stop will involve walking to an outcrop of well developed rhythmites on the north side of the Storm Mountain Reservoir (on the north side of Highway 190).

Description: Laminated argillite and channeled quartzite facies are exposed just north of the reservoir where lenticular geometries are visible. Numerous, stacked sheet quartzite bodies form Storm Mountain to the southwest, and the steep quartzite outcrops by the amphitheater (Fig. 12). The black, laminated argillite crops out immediately to the northeast of the pullout. Syneresis (subaqueous shrinkage?) cracks (Fig. 13) are common along bedding plane exposures, and diagenetic pyrite is present within some of these laminated argillites. Immediately to the east, over the knoll, an example of heterolithic rhythmites (with daily and semi-monthly cycles) deposited over about 8 months can be seen in the gradational contact between the underlying channeled quartzite and black argillite.

At the top of the knoll, there are blocks of channeled quartzite facies which contain coarse-grained lags and cross bedding (Fig. 14) . One area at the top of the slippery talus slope shows an example of soft sediment deformation and truncation within the laminated argillite facies.

Interpretation: The preservation of the rhythmites (Fig. 8 and 15), the finely laminated structures, and diagenetic pyrite within the black argillite suggest a reducing sub- to intertidal environment with the presence of organic carbon. Although little/no carbon is currently left in this black argillite, correlative units such as the Chuar Group of Arizona are currently being explored as Precambrian source rocks (e.g., Summons et al., 1988; Elston, 1989; Chidsey et al., 1990; Uphoff, 1997).

The laminated argillite facies at this stop is traceable to the south up Broads Fork, all the way to the top of Twin Peaks (elevation: 11,328 ft.). Along Broads Fork, the laminated argillite contains similar sedimentary structures (rhythmites, syneresis cracks and diagenetic pyrite) to those seen at this stop. Although tidal rhythmites are visible in this facies near the top of Twin Peaks, the neap-spring cycles are generally not as well developed.

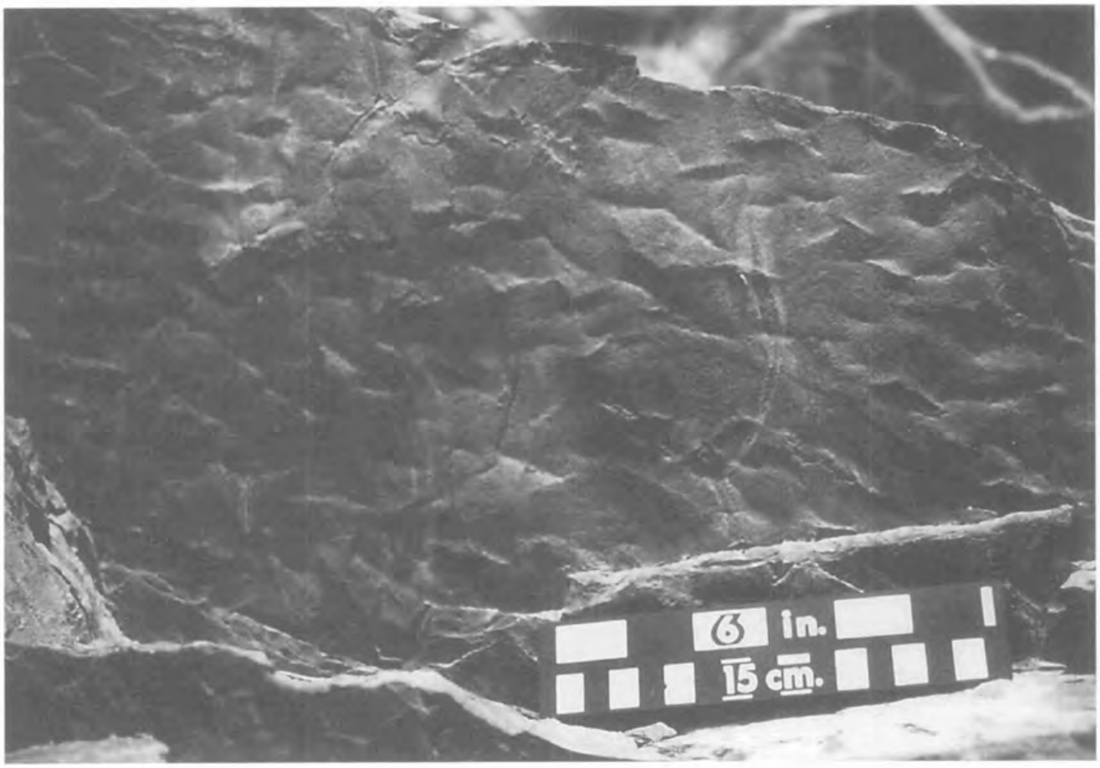

Figure 13. Syneresis cracks of the laminated argillite (stop 3).

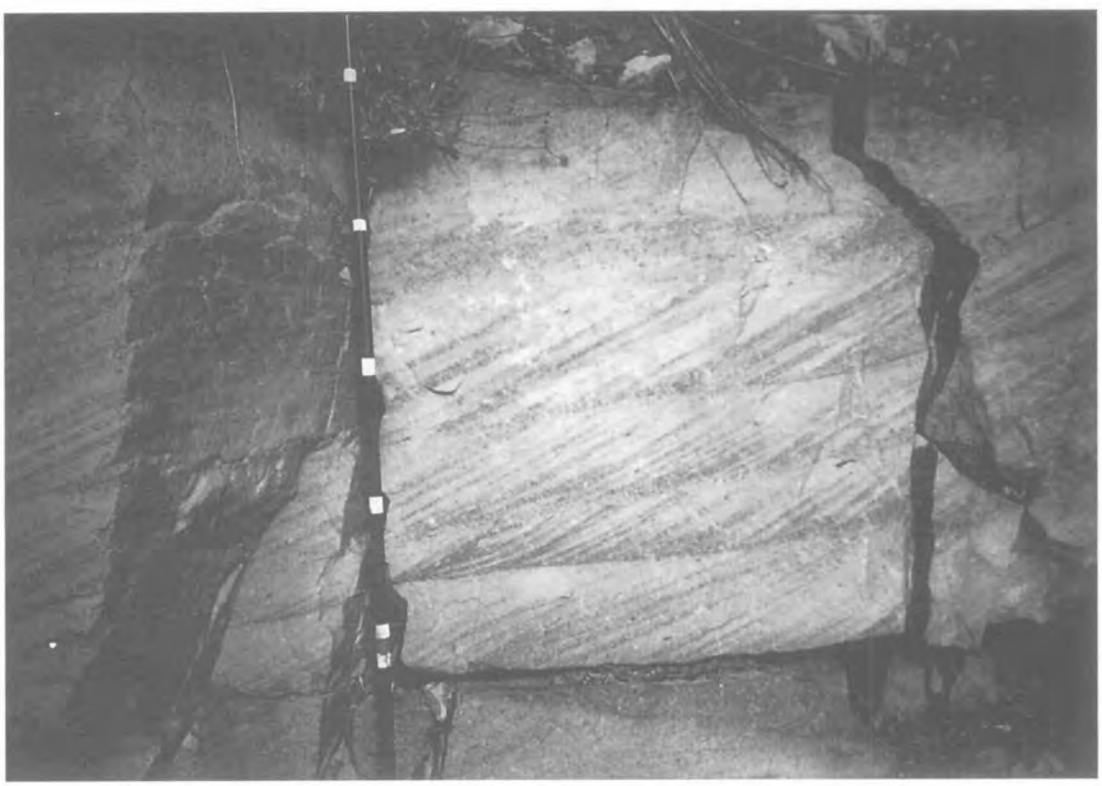

Figure 14. Cross beds of the channeled quartzite facies (stop 3). White marks on scale are at 10 cm intervals.

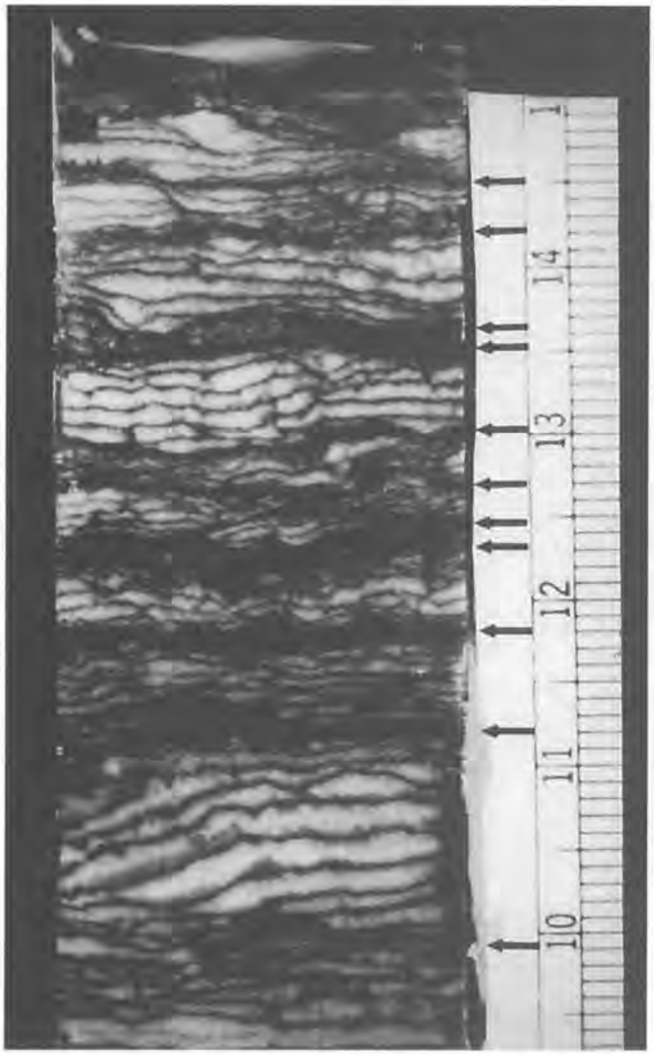

Figure 15. Tidal rhythmites with climbing ripples collected from core. Dark arrows represent the location of neap cycles. This core sample was collected near stop 3.

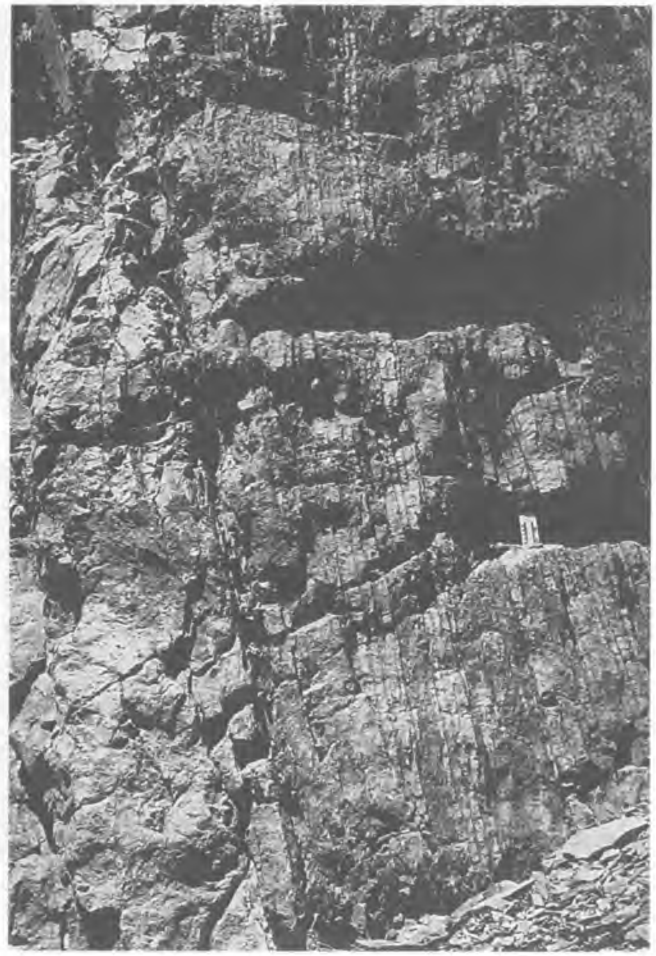

Figure 16. Tidal rhythmites by the Storm Mountain reservoir. These rhythmites are located in a transition zone between the channeled quartzite (left) and laminated argillite (right, 3 m off edge of photograph) lithofacies (stop 3).

The channeled quartzite with lags is interpreted to represent tidal channel deposits. The one deformed block (with soft sediment deformation) is interpreted to be a tidal fluvial channel bank collapse structure. The channeled quartzite is also visited in more detail at the next two stops. Figure 8 shows examples of tidal rhythmites collected from this area.

North Side of Storm Mountain Reservoir

For the second half of this stop, walk down the talus slope to the road on the east side of the knoll. Continue walking up the road (~30 m) across the bridge over Big Cottonwood Creek. After the bridge, turn left (west) by the chain link fence and walk along the creek past the outcrop of laminated argillite on your right. Turn right (north) at the edge of the outcrop and follow it across the flat, grassy meadow to the outcrop where channeled quartzite grades into laminated argillite.

The outcrop provides a view of over 2 m of heterolithic rhythmites (Fig. 16). This outcrop also demonstrates the typical vertical facies arrangement in which rhythmites form. The left (west) side of the outcrop is composed of channeled quartzite facies. This facies grades into well-developed planar laminated tidal rhythmites which contain visible daily, semi-monthly, and monthly cycles. To the right (east) of the rhythmites, the section progressively fines upward into ~300 m of laminated argillite. A similar rhythmite outcrop to this one is also located at mile 3.1 along the north side of the road (50 m up the steep hill slope just south of the large boulder next to the road). This locality at mile 3.3 also contains well developed neap-spring cycles in the laminated argillite. A 1.5 m core

Figure 17. Slump block with heterolithic rhythmites preserved in a tidal fluvial channel at the S-curves (stop 4).

of these neap-spring cycles has been collected, and contains approximately 10 years of continuous deposition.

Stop 4: S-curve channeled quartzite—Big Cottonwood Formation (mile 4.7, 7.8 km)

Location: Outcrop located about 0.1 mi. past the second hair pin "S-curve." Use the pullout about 0.2 mi. from the second curve and walk west (back down the canyon) to the outcrop along the north side of the road across from the concrete rail, east of Hidden Falls. Please watch carefully for cars.

Description: This stop includes a good lateral and vertical view of the channeled quartzite facies including a large rotated block, containing about 18 months of tidal rhythmites. The geometries can be viewed from the south side of the road. This is one of the localities of drilled core used in analysis of tidal rhythmites (Chan et al., 1994; Sonett et al., 1996). Quartzite structures observed here include west-dipping crossbed sets, scoured basal contacts, and current ripples. Daily rhythms and neap-spring cycles are well developed in these heterolithic rhythmites (distinct white sand laminae alternating with dark, thin clay drape laminae). Some of the daily rhythms are also preserved in climbing ripples.

Interpretation: The sedimentary structures within the channeled quartzite suggest a current-dominated tidal fluvial channel. The block of rhythmites (originally deposited adjacent to or near channel margins) (Fig. 17) is interpreted as a channel bank collapse structure adjacent to the fluvial-tidal channel. Figure 18 is a photomosaic of the channeled quartzite geometries. The white lines in this figure outline the channel geometries and the crossbed sets which internally thin upwards. Also note the scoured bases with lags.

Stop 5: Moss Ledge picnic area—Big Cottonwood Formation (mile 5.1, 8.5 km)

Location: Park along the north side of the road at the Moss Ledge picnic area parking lot.

Description: This stop highlights upward thinning and

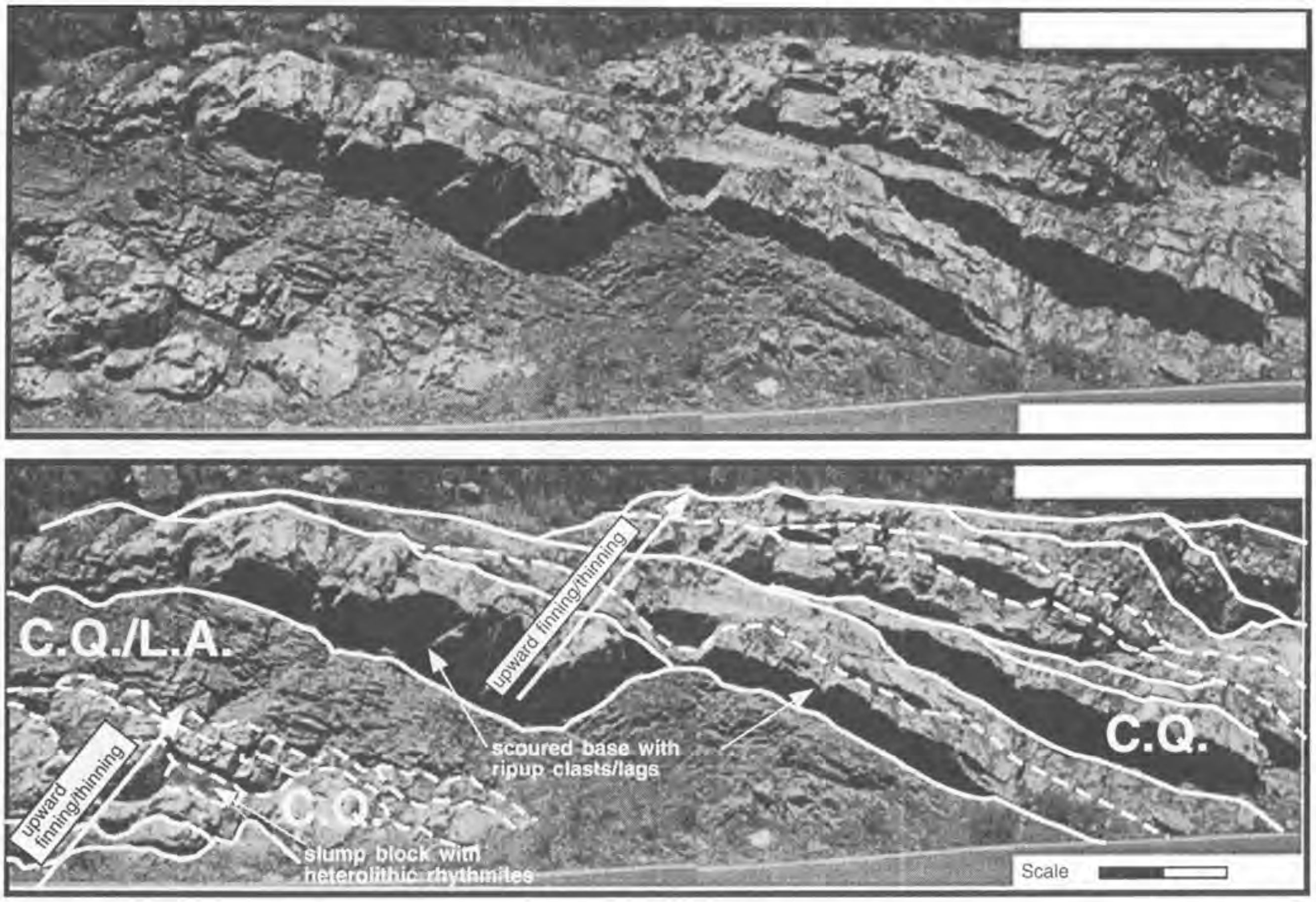

Figure 18. Photomosaic of the S-curve channel geometries. White lines (dashed where inferred) indicate the boundary between cross-bed sets, which fine and thin upwards. Other noteworthy sedimentary features are labeled (stop 4).

fining successions of the channeled quartzite, and the green-gray transitional and purple mud-cracked argillite facies. There are four stacked facies successions (channeled quartzite to transitional argillite) similar to the generalized succession shown in Figure 19. The top of the Big Cottonwood Formation is truncated at the top of the ridge by the Mineral Fork Formation. Sigmoidal bundles are present in the quartzite from along the road (just west of the parking area). In the channeled quartzite above the picnic area, there is a good exposure of the scoured basal contact with coarse grained rip-up clasts, overlain by distinct crossbed sets that thin upwards. The green-gray transitional argillite facies (exposed to the west of the picnic table) contains sand-mud couplets with yearly periodicities (Fig. 20, determined from spectral analysis; Erik Kvale, pers. commun., 1996), current ripples with crests rounded by back flow, some load and soft-sediment deformational structures, and clay-draped reactivation surfaces. Inferred tidal rhythms as well as sedimentary structures in this facies are significantly different from those in the black laminated argillite. A thin (2–4 m) layer of purple mud-cracked argillite (similar to the argillite seen at stop 2) overlies the transitional argillite and caps the upward-fining sequence. The mud-cracked argillite is in turn overlain by the channeled quartzite followed by more stacked fining-upward successions (Fig. 19).

Interpretation: This facies is interpreted to represent a fluvial channel with intermittent tidal influence, probably in the upper reaches of the estuary close to the tidal limit. The scoured base, and internal upward thinning and fining of bed size and grain size respectively suggest channel infilling and shallowing (Fig. 19). The annual cycles in the sand-mud couplets suggest tidal deposition in the upper end of the estuary during episodes of annually high sedimentation (high seasonal water levels, storm events). Only one of the channeled quartzites at this Moss Ledge locality is aerially extensive over the entire outcrop area north and south of Big Cottonwood Canyon, and appears to be correlative to the quartzite near the top of Mount Olympus (9,026 ft) about 9 km to the northwest.

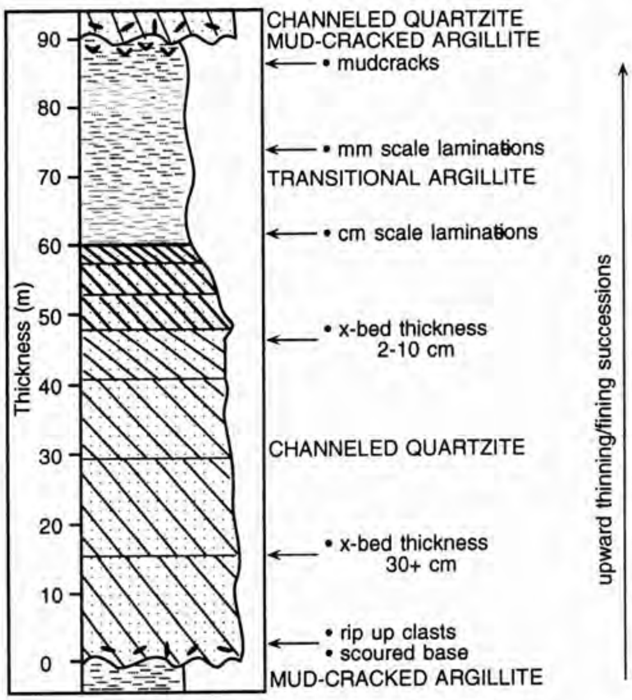

Figure 19. Typical stratigraphic succession of the Moss Ledge Picnic area (stop 5). About 4 of these channeled quartzite and transitional argillite successions are stacked close to the top of the Big Cottonwood Formation. Successions are typically 60–90 m in thickness.

Figure 20. Heterolithic rhythmites of the transitional argillite with annual lunar periodicities (stop 5).

Stop 6: Mineral Fork Formation (mile 5.9, 9.9 km)

Location: Continue east, up the canyon from the Moss Ledge picnic area approximately 0.8 miles. A pullout for Mineral Fork is located along the south side of the road immediately after the brown sign that reads "No Dogs Allowed." A narrow dirt road continues south past the iron gate.

Description: We will stop at the mouth of the Mineral Fork canyon and walk up the trail for about twenty minutes just past the fourth switchback to the first outcrop of poorly sorted, black pebble diamictite (Fig. 21). Boulders of the Mineral Fork Formation with mm-cm scale angular clasts are visible along the hike up the trail. The diamictite is in distinct contrast to the other siliciclastic rocks present in Big Cottonwood Canyon since it is poorly sorted, high in clay matrix, and was deposited and lithified under reducing conditions which preserved its black color. Other distinctive diamictite and laminated sandstone and siltstone lithologies are evident in the talus and alluvium.

Interpretation: The Mineral Fork Formation represents the complex deposits of a sub-glacial fjord carved into the flat-lying subjacent Big Cottonwood Formation (Christie-Blick, 1983; Christie-Blick and Link, 1988; Link et al., 1994). Note the variety of clasts in the diamictite (including orthoquartzite, carbonate, fine-grained sedimentary rocks, and sparse granite and gneiss), which suggests that the source terrane which supplied coarse sediment to the Mineral Fork lobe of Neoproterozoic Sturtian (750–700 Ma) glaciers contained quartzite and carbonate rocks with little basement contribution (Crittenden et al., 1952; Varney, 1976; Ojakangas and Matsch, 1980; Christie-Blick, 1983).

Deposition was in a temperate glacial-marine environment, relatively close to the grounding line of a partially buoyant ice sheet (Christie-Blick, 1983; 1997; Christie-Blick and Link; 1988; Christie-Blick et al., 1989; Link et al., 1994). The Mineral Fork Formation is dominated by proximal facies, but lacks major internal erosional surfaces. This suggests that it represents an overall retreat of the ice sheet, with minor oscillations in the ice margin .

Stop 7: Mutual Formation across from Mineral Fork (mile 5.9+, 9.9+ km)

Location: The outcrop of the Mutual Formation is located

Figure 21. Large boulder (1.5 m diameter) of Mineral Fork Formation located along the trail to the outcrop (stop 6). This boulder contains mm-cm scale angular clasts within a black, silty matrix.

about 0.1 mi up canyon and across the road from the pullout for Mineral Fork. Walk up the canyon to the first outcrop of purple quartzite, adjacent to the green sign that reads "mile 8."

Description: The Mutual Formation here contains purple to pinkish gray, medium- to coarse-grained sedimentary litharenite (quartzite), and interbedded argillite (Fig. 22 and 23). The sandstone is medium-bedded, with a general upward-fining succession from left to right. Some of the fine-sand beds contain current ripples on bedding planes. One internal contact is channelized into the underlying dark-colored argillite. The basal bed of the channel fill contains pebble conglomerate and mudstone rip-up clasts.

The type section of the Mutual Formation is located at the old Mutual Mine here in Big Cottonwood Canyon. Although not shown on geologic maps of this area, the Alta thrust repeats the Mutual Formation type section on both sides of Big Cottonwood Canyon.

Interpretation: The depositional environment of this outcrop was likely a high-energy stream system, with local erosive channels and areas of lower regime flow over a fine-grained substrate. Regionally the Mutual Formation contains less than 850 m of trough cross-bedded pebbly sandstone with local and variable pods of siltstone (Christie-Blick, 1982). It was deposited as a stratigraphic blanket, in a braided stream system with local lakes and flood basins (Link et al., 1987; Levy and Christie-Blick, 1991). Accommodation space was apparently controlled by late Varanger post-glacial sea level rise rather than by differential thermal subsidence (Christie-Blick, 1997).

Stop 8: Cambrian Tintic Quartzite (mile 6.7, 11.0 km)

Location: Continue up the canyon approximately 0.5 miles from Mineral Fork. Field trip participants can easily walk up the canyon. There is a parking area on the south side of the road where the shoulder widens. The best outcrops of tan quartzite are on the north side of the road, adjacent to a thicket and across about 10 m of field grass. Immediately down the canyon is a more continuous, stratigraphically lower, roadside exposure (Fig. 24).

Description: The Tintic Quartzite in the thicket (Fig. 25) is coarse- to very coarse-grained, planar cross-bedded sandstone. It is texturally more mature than the Mutual Formation, suggesting its interpretation as a shallow marine sandstone.

Interpretation: The Middle Cambrian Tintic Quartzite represents the immediate post-rift shallow-marine phase of development of the Cordilleran passive continental margin, which had entered the carbonate platform phase by Early Cambrian time. The Tintic here represents the parautochthonous, uppermost eastern feather edge of the regional, west-thickening wedge of shallow marine sandstone represented by the Geertsen Canyon, Camelback Mountain and Prospect Mountain quartzites. This wedge is overlain by fossiliferous Lower and Middle Cambrian mudrock, and was deposited in accommodation space created by thermal subsidence of the Neoproterozoic and Paleozoic Cordilleran miogeocline (Christie-Blick, 1982; Christie-Blick et al., 1989; Christie-Blick and Levy, 1991; Link et al., 1993).

OTHER OPTIONAL STOPS

The eastward continuation of Highway 190 up Big Cottonwood Canyon traverses through Late Paleozoic limestones (Mile 7.0 at "Mississippian Marble" sign) and passes the lowest point that Pleistocene glaciers extended down the canyon (Mile 8.6 at "Meeting of the Glaciers" sign). The Highway ends in a loop at the Brighton Ski Resort.

Figure 22. Outcrop of Mutual Formation located about 0.1 mi. up the road from Mineral Fork. Alternating layers of quartzite and argillite have normal grading from left to right. The quartzite layer on the right hand side of the figure has a scoured base that cuts down into the underlying argillite. Also visible on the left are current ripples along the bedding plane of the quartzite (stop 6).

ACKNOWLEDGMENTS

The research presented here is a result of funding by NSF grant EAR 9315937 (to Chan), and GSA research grant 5813-96 (to Ehlers for Uinta Mountain Group work). Thoughtful discussions and rhythmite core interpretation by Al Archer and Erik Kvale contributed greatly to this work. We acknowledge a most helpful review of the manuscript by Nicholas Christie-Blick.

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Figure 23. Contact between the quartzite and argillite facies of the Mutual Formation. The quartzite facies has scoured the underlying argillite and contains pebble size ripup clasts (stop 7).

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