SEDIMENTOLOGY OF THE PRECAMBRIAN BIG COTTONWOOD FORMATION, BIG COTTONWOOD CANYON, CENTRAL UTAH

by

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CONTENTS

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ABSTRACT

Spectacular outcrops of Precambrian quartzites and shales (4880 m) of the Big Cottonwood Formation are exposed in the lower gorge of Big Cottonwood Canyon, along the Wasatch Front. This study represents a preliminary investigation of the sedimentology and interpretations of depositional environments, and Proterozoic sedimentation in the Uinta trough.

Past depositional environment interpretations for the Big Cottonwood Formation have been largely generalized as shallow marine, based on the presence of well-preserved ripple marks, cross-bedding, intraformational conglomerates, mudcracks, and some rain-drop impressions. Observations in this study suggest that the quartzites are subtidal nearshore sand bodies produced by migrating subaqueous dunes. Modification of the dunes by flow reversals produced rippled and reactivation surfaces within the cross-bedded sandstones. Additionally, prominent rhythmic laminations (couplets of interlaminated sandstone and mudstone) and cyclic bundles within some of the dark variegated shale intervals of the Big Cottonwood Formation have never been previously described, and may be the one of the most diagnostic structures in interpreting a tide-dominated depositional environment. Rhythmites, variable couplet thicknesses, and organized vertical cycles suggest a tidal origin with neap-spring tide fluctuations (related to the phases of the moon). The variety of structures and preservation of rhythmite cycles imply mostly subtidal conditions, with some periods of exposure in an intertidal setting.

Vertical successions (cycles/bundles) of thickening and thinning rhythmic laminae are examined, although counting laminations (to determine the number of days within a lunar cycle) proved difficult in these preliminary studies. More detailed counting approaches and time series and power spectra analysis would be necessary to understand the evolution of climate, sun-moon-earth relationships and orbital parameters in Proterozoic time.

INTRODUCTION

Excellent exposures of Proterozoic quartzites and shales of the Big Cottonwood Formation are displayed in the lower gorge of Big Cottonwood Canyon, along the Wasatch Front of central Utah. Despite the age and the tectonic overprints within the Formation, sedimentary structures are still well preserved, and can yield a wealth of information about the depositional setting. Surprisingly little has been reported on the Big Cottonwood Formation, except for some basic description of the unit (Crittenden, 1964, 1976; James, 1979) and some mapping (Crittenden and others, 1978; James, 1979; and Bryant, 1990). Although other portions of the Precambrian in the Western U.S. have been studied with respect to the sedimentology and sequence stratigraphy (e.g., Christie-Blick and Levy, 1989 a and b), the Proterozoic sections along the Wasatch Front have been relatively untouched.

The purpose of this report is to document sedimentary aspects of Big Cottonwood Formation in Big Cottonwood Canyon, with particular emphasis on aspects of the shale lithologies. Rhythmic and cyclic sedimentary structures, previously undocumented, are especially useful in interpreting a tidal depositional environment. This study is significant in that the oldest examples of Precambrian tidal rhythmites in the literature are from the Upper Proterozoic deposits of Australia, and are dated at 650-800 million years old (Williams, 1989, 1991). The Big Cottonwood rocks and tidal rhythmites of this study are approximately Middle to Late Proterozoic at 850 million to 1.0 billion years old (e.g., Hintze, 1988), and thus may represent the oldest tidal rhythmites known. Counts of tidal laminae are planned for future study, and can have enormous implication for understanding the Earth - moon relationships in the geologic past.

In addition, there has been considerable interest in the petroleum source rock potential for Precambrian rocks (e.g., Chidsey and others, 1990). Sedimentologic studies of Precambrian examples (such as this study of the Big Cottonwood Formation) can greatly contribute to understanding the distribution of the potential resources and deposits, as well as their origins.

GEOLOGIC SETTING

The Big Cottonwood rocks are exposed in the central Wasatch Mountains, and were deformed during both the Sevier and Laramide orogenies. The Big Cottonwood Formation is considered to be correlative with both Belt rocks to the north and Uinta Mountain strata to the east (Frazier and Schwimmer, 1987). The paleogeographic and paleotectonic settings for the Big Cottonwood deposits are not well constrained. The age of the Big Cottonwood Formation (about Middle to Late Proterozoic) implies that deposition probably occurred in the Uintah trough or aulacogen. During the Late Proterozoic, a western part of proto-North America split off and left western Utah and eastern Nevada as the hot trailing edge of the broken plate. Loss of heat from the raw trailing edge caused it to slowly subside and permitted the accumulation of thousands of feet of shallow water sediments in a miogeoclinal basin (Frazier and Schwimmer, 1987). This subsidence of the miogeocline might have been at the very latest Proterozoic (~ 600 mya) (e.g., Armin and Mayer, 1983), after much of the Big Cottonwood deposition.

Structural and tectonic aspects of the Wasatch Mountains are complex (Bruhn and others, 1986 and Bradley and Bruhn, 1988). In the Big Cottonwood area, the dominant structure is a large NNE plunging fold that probably formed during Cretaceous thrust faulting, and was subsequently refolded during uplift of the Uinta Mountains in the Early Tertiary (Bruhn and others, 1986; Bruhn 1992, pers. comm.). This fold was exhumed during uplift and northeast tilting of the Wasatch Mountains, following formation of the Wasatch normal fault zone. The NNE plunging fold is presumably cored by a blind thrust fault in crystalline basement, implying that the entire Cottonwood area is at least parautochthonous, although the amount of translation is yet to be determined (Bruhn 1992, pers. comm.).

LOCALITY

This study area largely concentrates on the lower gorge section of Big Cottonwood Canyon (just southeast of Salt Lake City, UT), utilizing the road cuts particularly around Storm Mountain picnic ground (figure 1 and Appendix A). In the scope of this study, it would be impossible to fully examine the entire 4880 m section of the Big Cottonwood Formation. Hence, efforts concentrate largely on the sedimentology of shales (and the quartzites to a lesser extent), with several measured sections along Highway 152.

Field studies were used to distinguish lithofacies, with samples taken at localities shown on figure 1 (also see Appendix B). Thin sections from representative lithologies are described petrographically in Appendix C and related to the defined lithofacies. Three partial stratigraphic sections (Appendix D) give detailed description of lithologic characteristics. Sections are generally faulted and difficult to correlate. Beds vary in true thickness in part due to tectonism.

In general, the stratigraphic up direction is very difficult to determine and structures are often ambiguous. Criteria used for the stratigraphic top direction includes: mud-chip lags at channel bases, a few graded beds, and ripple and cross-bedding structures. A few isolated beds in the localities on the west flank of the anticline in the study area (e.g., 91-20 and 91-16, see figure 1), seemed to indicate that the beds could be overturned. However, the same types of structures within the same outcrop intervals also seem to show stratigraphic up towards the northeast (e.g., 91-13). These interpretations as well as the alternations of normal and overturned beds on published geologic maps, suggest that the structure is very complex. For this study, it is assumed that the beds are not overturned, as mapped by Bryant (1990).

PREVIOUS WORK

James (1979) summarized much of the previous work in the Big Cottonwood Canyon area, with emphasis on aspects of the mining district. The Big Cottonwood Formation is estimated to be 4880 m (16,000 feet) in thickness (James, 1979), and consists of various light-colored quartzites, and dark colored shales and siltstones. This Formation is underlain by the Precambrian Little Willow Formation (metamorphic rocks) and unconformably overlain by the Mineral Fork Tillite (dark colored tillite, quartzite and conglomerate) (figure 2). Much of the Big Cottonwood Formation is steeply dipping exposures, with a generally simple north-northwesterly strike and a steep northeasterly dip, comprising the north flank of a broad uplift/anticlinal arch (James, 1979). Most of the rocks have undergone slight metamorphism, but the preservation of structures is still good.

Past depositional environment interpretations for the Big Cottonwood Formation (e.g., Crittenden, 1964, 1976; James, 1979; and Hintze, 1988) were largely generalized as shallow marine, based on the presence of well-preserved ripple marks, cross-bedding, intraformational conglomerates, and some rain-drop impressions. New observations of sedimentary structures in this study are presented to further amplify and clarify interpretations of tide-dominated conditions within the Big Cottonwood Formation.

TIDES

Because many of the interpretations in this study are based on an understanding of tides, a brief summary of concepts is presented here. Many general texts also describe more details about tides and tidal systems. An excellent recent summary and reference is Dalrymple (1992). He presented an annotated bibliography of basic sources of information on tidal systems, and further elucidated on the status and future directions of study in tidal deposits.

Daily tides are produced due to gravitational pull of the moon and the orbital motion of the Earth and moon. Semidiurnal tides (2 high and 2 low tides per day) predominate in low to intermediate latitudes, and diurnal tides (1 high and 1 low tide per day) predominate in high and some lower latitudes (Allen, 1982) or where the semidiurnal tide is damped out by destructive interference (Dalrymple, 1992). Within a lunar cycle, the relative positions of the earth, moon, and sun produce predictable differences in the range of tidal fluctuations, with the periodicity of a lunar month (figure 3). During new and full moon conditions, when the 3 bodies are aligned, there is an additive effect, and the tidal range is the greatest for a lunar month. These are called spring tides and occur every 2 weeks (during first and last lunar quarters). The intermediate positions of the moon at right angles with the sun and the moon, results in minimal tidal fluctuation because forces counteract each other. This produces the neap tides which occur every 2 weeks during new and full moons (figure 3). For semidiurnal tides, the neap-spring cycle has a period of 14.77 days and contains 28 cycles (Dalrymple, 1992). In contrast, the diurnal tides produce neap-spring periods of 13.66 days and contain 14 cycles (Dalrymple, 1992). Tidal deposits which preserve these neap-spring periodicities may be used to determine whether ancient lunar cycles were different from those of the present. Further discussion of tidal systems is given in later sections of this paper.

FACIES

Geologic mapping by previous workers (Crittenden, 1965; Crittenden and others 1978; James, 1979; and Bryant, 1990) separated mappable quartzite and shale lithologies of the Big Cottonwood Formation. However, there is considerable variation in these lithologies not only in color, but in texture, composition, structure, and origin. Each of these aspects is discussed below, with some further subdivisions of lithologies recognized around the study area in Big Cottonwood Canyon.

Quartzites

Two quartzite lithofacies are discussed, based largely on visible color in the outcrop exposures, and corresponding mineral composition differences detected in thin section. Stokes (1986, p. 43) also noted some of the differences in the quartzites. These quartzite lithofacies may represent end members with some variation in between. Both quartzite facies have similar outcrop characteristics, which are discussed and interpreted together following the sections describing compositional differences.

White Quartzite Facies

Both white and pink quartzites occur throughout much of lower exposures of the Big Cottonwood Formation. Color variation seems to be largely a function of varying degrees of weathering and iron oxide content staining the quartzite. In thin section, these are relatively clean quartz arenites or quartzites with less than a few percent of grains other than quartz (with overgrowths), and little to no matrix (see Appendix C). These quartzites are commonly associated with and separate portions of the black shale facies. Grain sizes vary from fine-grained quartz arenites/quartzites to coarse-grained quartz arenites/quartzites. This quartzite facies commonly exhibits a sugary texture in outcrop.

Some ichnofabrics are present in this quartzite facies (T. Ekdale, 1992 pers. comm.). In many cases, there are a variety of physical features (?) noted in this study (both in quartzites and shales) that seem to resemble burrow traces.

Green Quartzite Facies

A greenish colored quartzite facies is similar to the white quartzite facies, but is more common in upper exposures of the Big Cottonwood Formation, east of Storm Mountain picnic area and up towards Mineral Fork (figure 1). The green quartzites range from being fine-grained to coarse-grained. The light greenish color appears to be a function of the amount of matrix and altered grains/sericite (on the order of 5-10+% of the total rock, see Appendix C). Quartz cement and overgrowths are common, with pseudomatrix (from squashed altered grains and/or rock fragments) and probable epimatrix (clays derived from the altered grains), comprising the remaining groundmass.

Quartzite Structures

In both quartzite facies, the dominant sedimentary feature is cross-stratification (figures 4 - 6). Cross-bedding ranges from small scale (centimeters to decimeters) to medium-scale (meters). Dip angles range from several degrees up to about 25 degrees. Reactivation surfaces are present in some compound cross-stratified exposures of the quartzites, showing truncation of underlying topset laminae (figure 4). Some small tabular planar sets exhibit a strong unidirectional transport direction (figure 6), although the stratigraphic up/top direction is ambiguous at times. Other tabular quartzite beds appear to exhibit sigmoidal-shaped sets (figure 5). Mud rip-up conglomerates at the bases of some quartzite beds contain clasts averaging a few centimeters in diameter, with moderately rounded edges (figure 7). Wave ripples commonly occur along broken bedding plane surfaces.

Tectonic overprinting makes it difficult to determine some of the quartzite geometries, although there is notable pinch and swelling of quartzite beds. Cross-bedding in the quartzites is strongly unidirectional towards the NW. Some of the paleocurrent data is given in Appendix E.

Interpretation of Quartzite Facies

The evidence of : wave ripples, compound cross-bedding, abundant reactivation surfaces, and a few sigmoidal bundles, support an overall interpretation of a sandy subtidal setting (Nio and Yang, 1991). Cross-bedded quartzites of this study are largely interpreted to represent small dunes or mega-ripples, that are tidally produced bedforms. Sets contain reactivation surfaces, formed when the top of a large, angle-of-repose bedform is modified, commonly during falling tides. Many of these reactivations surfaces were probably formed by dominant flows (De Mowbary and Visser, 1984; Nio and Yang, 1991). Larger sets may indicate small sand waves or composite dunes (Dalrymple, 1992). In deeper subtidal settings, the modification may be due to wave erosion of the bedform crest during neap periods of lower sediment transport rates, upstream of the bedform crest.

Tidal bundles are the deposits of a single dominant tide, whether the bundles are bounded by reactivations surfaces or mud drapes (Dalrymple, 1992). However, these bundles may not be evident when there are smaller superimposed dunes on the larger forms (Dalrymple, 1992). Regularly spaced mud drapes and neap-spring bundles did not appear to be common, although a more comprehensive study may show it to be an abundant structure. In some instances, subordinate-flow mud drapes may have been eroded and removed by ensuing tidal currents, with mud clasts being picked up and redeposited. Mud rip-up conglomerates at the bases of some quartzite beds imply periods of high energy influx, that incorporated preexisting lithologies.

A summary in Walker (1985) discussed very thick late-Precambrian/Cambrian quartzites, as a significant category of ancient tidal sand bodies. In many of these examples, paleoflow directions appear to be dominantly unidirectional. Unidirectional cross-bedding directions in the Big Cottonwood quartzites imply that the dominant flow direction was to the NW. However, it is not clear whether the dominant flow is an ebb or a flood direction.

Shales

Notable variations within the shale intervals indicate two major shale facies with different depositional conditions. Shales intervals commonly separate quartzite lithologies, providing mappable units within the Big Cottonwood Formation. Shales largely in the lower mouth of Big Cottonwood Canyon along Road 152 (just west of Storm Mountain picnic ground) largely comprise the purple shale facies. At the Storm Mountain area and towards the northeast, much of the exposed shale consists of the black shale facies with distinctive rhythmites. This black shale facies also extends southward towards Twin Peaks (figure 1).

Purple Shale Facies

A generally weakly bedded to massive to purple shale facies occurs within some of the lower reaches of Big Cottonwood gorge west of Storm Mountain picnic ground, and particularly around the exposures close to the Birches picnic ground, and by the "Ancient Sea" sign (figure 8). This purplish shale is largely silty. For much of the lower gorge section, the shale seems relatively massive and featureless (e.g., localities 91-22 and 91-23 of figure 1), with poorly developed bedding. However, at the "Ancient Sea" sign (locality 91-20, of figures 1 and 8) continuous networks of polygonal mudcracks and a few raindrop impressions (?) are visible on northeast exposed bedding plane surfaces (figure 9). Polygons are on the order of several centimeters to a few tens of centimeters in diameter, with crack diameter infills up to about 2 cm thick. It is commonly difficult to trace the vertical crack depths. A few subtle small wave ripples ($\lambda = 3 - 5$ cm and h = < 0.5 cm) are superimposed on the bedding planes containing mudcracks.

Some flaser bedding and thin ripple bedding of "pin-stripe" laminations (thin, mm alternations of white sand and dark mud) are present. Symmetrical interference ripples are preserved on the bedding plane exposures and indicate two flow directions. Additionally, some symmetrical ripples have smaller ladder ripples in the troughs of the main ripple set. These ladder ripples can be attributed to late-stage wave action during emergence (Collinson and Thompson, 1982, p. 61).

This purple shale facies is also contains a green shale which is actually a silty shale to a very fine-grained sandstone, colored by reduced iron. Intervals of the green shale beds average about 1 m in thickness with beds themselves ranging on the order of a few centimeters or more. The 1 m thick green shale intervals are separated and/or spaced by 4 - 6 m thick intervals of the purple shale. Internally, the green shales (in particular at locality 91-20, figure 1) contain thin laminations, and ripple lamination; much more lamination than is present in the "hosting" purple shale.

Thin, irregular white secondary veins (< 1 cm) commonly cut across the shale lithologies. In thin section, the thin, white-colored veins within the shale facies reveal mineral assemblages of chlorite rims (with crystal growth perpendicular to the fracture surface), and contemporaneous intergrowth of pore-filling quartz and hematite. Typically, the chlorite, hematite and quartz veins may also occur with chlorite, pyrophyllite, and quartz veins (W. T. Parry, pers. comm. 1992). Papers of Parry and Bruhn (1986, 1987, 1990) and Parry and others (1988) indicated that vein fillings such as those of the study area are related to progressive displacement along the footwall of the active Wasatch normal fault. Fluid inclusion and pore fluid chemistry data (W. T. Parry, unpublished data) indicate that Big Cottonwood shales experienced metamorphism of the greenschist facies, and within the pyrophyllite stability window of 270-350^{o}C. The illite crystallinity within the shales is also consistent with the estimate of a 300^{o}C temperature.

Interpretation of Purple Shale Facies

The purple shale facies is largely interpreted to represent subtidal to intertidal beds that experienced periodic exposure (desiccation). The presence of wave ripples, flaser bedding, mud cracks, and raindrop impressions is consistent with tidal flats that may have been periodically dried. The silty green shales containing "pin-stripe" laminations and ripples may indicate slightly deeper water conditions, and/or episodic periods of coarser influx onto the tidal flat. Where the bedding appears more massive, it is possible that secondary alteration (perhaps associated with the veins) has obscured some of the original structures.

Black Shale Facies

This shale facies largely consists of dark grey to black shale (slightly metamorphosed to almost a slate), and is generally bedded, with parts that are very well-laminated. Bedding is more distinct in this facies (than in the purple shale facies), with a variety of structures (figures 10-12) not found in the purple shale facies. This black shale facies is exposed right around and east of the Storm Mountain picnic site. Portions of the shale contain small (mm-sized) disseminated and scattered pyrite cubes. Laminated portions (figure 12) of the black shale facies contain a variety of wave ripples and interference ripples. The ripples are commonly draped by mud, producing a variety of forms of flaser bedding and lenticular bedding (figures 10 and 11). Shrinkage/desiccation cracks ("syneresis cracks") are present along some bedding plane exposures and show incomplete crack networks and/or incomplete polygons. The lenticular cracks (figure 13) vary in scale ranging on the order of 2 - 5 cm in length and have relief up to about 1 cm. Some smaller crack networks also appear superimposed on or in between larger cracks.

A diagnostic and abundant structure in the black shale facies is sand-mud couplets consisting of a light sand lamina/layer and a darker mud lamina/layer (figures 14-17). These thin interlayered beds are herein referred to as rhythmites where the layers consists of the couplets (two repeatedly alternating phases). The rhythms themselves (light or dark beds) may be variable on the scale of millimeters to a few centimeters. In hand specimen, thin rhythmic couplet laminations may show a finely detailed, alternating light and dark bands which produce a pin-striping effect (figure 14). These thin "pin-stripe" laminations range from being flat-bedded (figure 12) to rippled (figure 11), with ripple foresets accentuated by the alternating colors. Some climbing ripple lamination appear to have symmetrical wave forms. Small reactivation surfaces within the facies can also truncate some of the ripples. Lamination couplets are also distinguished by grain size and grain composition alternations in thin section. White laminations appear to be slightly thicker (may range up to 3 mm), slightly coarser (very fine-grained sandstone) and more quartz rich, than the dark, clay-rich laminations (siltstone to mudstone).

Internally (particularly within the light-colored sand layers), very fine, "pin-stripe" laminations may be present. Other layers appear to show internal grading in thin section (see Sample 91-10a, Appendix C). In some of the thickest layers or laminae of this facies (where the layer maybe be close to 3 cm), the layer may internally show flat lamination changing to ripple lamination at the top of the bed. In some of the light layers, there also appears to have a very thin dark lamination dividing the band nearly in the middle, or unequal thicknesses of the "thick couplets" (Nio and Yang, 1991). This variation of unequal thickness in the thick couplets may represent diurnal inequality, which is discussed later in the interpretations.

Portions of the rhythmites commonly show vertical organization or/and vertical bundles or cycles. These cycles are generally on the order of on the order of a few centimeters, ranging up to about 20 cm or so in thickness. Rhythmites within the cycle tend to show fining and thinning upward, i.e., laminae and grain size thin in the upward direction. Counts of the rhythmites in the shale facies is difficult in part due to exposure and in part due to the fine/thin nature of the rhythmite layers. A few general counts of larger/thicker rhythmites seem to indicate approximately 25+ rhythms (e.g., 25 light laminae alternating with 25 dark laminae) within one cycle. Of these 25+ rhythms, about half (12 or so) are thicker (towards the base) and half (12 or so) are thinner (towards the top). There is admittedly difficulty in counting laminae with the naked eye once the laminae become smaller (thinner) towards the top of the bundle/cycle, and tend to blur into a dark shaley interval.

Interpretation of Black Shale Facies

The variety of structure in the black shale facies, as well as the association of the quartzite facies, all imply a tidal setting. Common symmetrical, wave ripples may also have been produced in a shallow tidal setting, with reactivations surfaces and drapes occurring with changing flow conditions. Some thin beds indicate deposition under decelerating flow conditions, with lower parallel laminated portions deposited in upper flow regime conditions and upper rippled tops indicating transition to the lower flow regime conditions. Small ripple forms (e.g., $\lambda = 4.5 - 7$ cm and h = 1.5 cm), flaser bedding, and the presence of shrinkage/desiccation cracks suggest shallow water depths. Irregular shapes and propagation of shrinkage/desiccation cracks may be related to lithology (e.g., clay content) and/or the influence of evaporite minerals such as gypsum casts, which were subsequently dissolved. It is not clear that all the shrinkage-type cracks in this study are subaerial, but a thorough discussion of subaerial vs. subaqueous interpretations appeared in Astin and Rogers (1991).

The rhythmites are the most diagnostic of all the structures, and are interpreted as tidal rhythmites. Good preservation of the tidal rhythmites in fairly complete cycles implies that the black shale facies was largely subtidal, with some parts that may have been intertidal. Three important orders of cyclicities in the tidal rhythmites are present: 1) On a small scale, individual sand-mud couplets indicate tidal cyclicity. The light sand lamina implies peak flow deposition (including deposition by currents), with the dark mud lamina representing stillstand deposition. These tidal rhythmites preserve variations in the tidal current speed. 2) On a slightly larger scale (about double that of number 1) above), there are unequal thicknesses in pairs of couplets. This indicates that there is diurnal inequality. This would further imply that the tides were semi-diurnal (two high tides and two low tides per day), such that, for example, the strongest high tide of the day would produce the thicker sand lamina, then the weaker high tide would produce a thinner sand lamina. 3) The cyclic vertical organization of the rhythmites shows neap-spring cycles, indicative of a lunar month within the Proterozoic. Thicker layers in the bundle indicate maximum spring tides, with thinnest portions indicating the minimum neap tide (figures 14-17). The counts of 25+ rhythmites in one of the vertical neap-spring cycles also implies semi-diurnal tides, with 12+ days in one cycle. Additional counts planned for future study may help resolve the monthly and perhaps some yearly cycles, where successive neap-spring cycles are stacked (e.g., figure 16).

Paleocurrent Data

Paleocurrent measurements on cross-bedding, ripple crests, and ripple foresets were measured within the steeply dipping bedding planes. Specific measurements and data summaries are given in Appendix E. Corrected data points (after two correction rotations: one for the plunge of the anticline, and the second to bring the limbs of the fold to horizontal) show there is about a 30^{o} difference between uncorrected and corrected paleocurrent data. In the data of this study, the numbers of data points are small, and may not be significant. Measurements were subdivided into two categories: unidirectional measurements from cross-bedding and ripple foresets, and bidirectional measurements from flow perpendicular to ripple crests. Unidirectional data (Appendix E) show a large scatter from about 190-350^{o}, a mean flow of 284^{o}, and the largest petal (33%) between 340-350^{o}. Bidirectional flow (Appendix E) shows a wider degree of scatter, with the mean at 290^{o}, and the largest petal between 330-340^{o}. The combination of this preliminary data suggests a strong and dominant preservational flow direction to the northwest, with a secondary, nearly perpendicular set towards the southwest.

DISCUSSION

Facies Model

A wealth of literature exists on examples of Precambrian tidal deposits, indicating their abundance in the early parts of earth history. Thus, it is not surprising to see that the Big Cottonwood Formation contains similar features. Recent studies of tidal rhythmites and bundles (e.g., Kriesa and Moiola, 1986; Kvale and others, 1989; Brown and others, 1990; Demko, 1990; Dalrymple and others, 1991; Williams, 1989, 1991) generated much enthusiasm for documenting tidal environments and tidal cycles. An exhaustive discussion of tidal deposits in the stratigraphic record is not presented here, but the reader is referred to reviews in Ginsburg (1975); DeRaff and Boersma (1971); Klein (1977); Terwindt (1981, 1988); and papers in de Boer and others (1988) and Smith and others (1991). Excellent summaries of tidal depositional systems are given in Nio and Yang (1991) and Dalrymple (1992).

Areas affected by tides may cover a broad scope of environments, and there may be considerable variations where the relative intensity of sedimentary processes may determine more of the character of deposits, even over the geomorphic setting (Dalrymple, 1992). Thus it is difficult to precisely determine what kind of tidal environment existed for the deposition of the entire Big Cottonwood Formation. The Big Cottonwood rocks appear to be strongly tide-dominated (versus tide-influenced), based on the interpretations of the tidal sand bodies in the quartzite facies and the tidal rhythmites in the shale facies. The quartzites were likely deposited in a sandy subtidal setting (relatively deep offshore), with largely unidirectional flow. Channelized deposits may indicate inshore portions of an estuary or tidal embayment. The shales probably represent shallower subtidal to intertidal conditions (possibly close to the shoreline), perhaps from distal deltas and/or tidal flats. The black shale facies probably represents overall deeper water conditions than the purple shale facies, which shows more evidence of desiccation and exposure.

Implications for Earth - Moon Relationships

Counting rhythms and laminae in the shales proved to be difficult, particularly where the laminations thin to millimeter thicknesses and less. Other methods that might be employed (planned for future study but not available for this preliminary study), include using a gas-powered rock coring device in the field to core through blocks of the shale, then slabbing the core, polishing, and finally counting laminae and measuring laminae thicknesses using a binocular microscope. Additional methods of counting, similar to equipment used for counting tree rings might prove useful at the scale of the shale laminae for more accurate determinations of cyclicity and numbers.

Well-developed tidal rhythmites in the Precambrian Elatina Formation (~650-800 Ma) of South Australia show aspects of the lunar orbits, as documented by Williams (1989, 1991) and discussed by Sonnet and others (1988). Williams (1989, 1991) interpreted and counted the rhythmite distal ebb-flood deposits to show 13.1 (+0.5) lunar months, and c. 400 (+20) days, and a lunar month of 30.5 (+1.5) days. Precambrian rhythmites such as these may reveal important history and implications on the lunar rates in the geologic past. The Precambrian Big Cottonwood rhythmites show marked similarities, and with future counts of the rhythmites, it may be possible to verify proposed rates of lunar recession for the Late Proterozoic and/or possibly propose new rates for the Middle Proterozoic.

Eustatic Effects

Sequence stratigraphy examines genetically related facies within a framework of chronostratigraphic surfaces (i.e., unconformities or their correlative conformities) (e.g., Van Wagoner and others, 1988; Van Wagoner and others, 1990). One original objective of this study was to determine the feasibility of applying sequence stratigraphic concepts to the Big Cottonwood Formation. Sequence stratigraphy could establish an important framework for correlation within the Big Cottonwood Formation. However, the sequence stratigraphy of tide-dominated systems is not as established as sequence stratigraphic concepts primarily developed in wave-dominated settings (Dalrymple, 1992). Several workers suggested that tidal deposition is favored by transgression (Dalrymple, 1992), and that concept may be useful in interpreting eustatic change.

Many late Precambrian tidal shelf deposits are not easily divisible into transgressive and regressive intervals because the units may contain hundreds of meters of cross-bedded sandstone (Dalrymple, 1992). However, in the Big Cottonwood Formation, there are shale intervals that separate the quartzites, and the lithologic contacts may be significant boundaries. Although sequences were not established in this preliminary study, additional studies may be able to discern and interpret sequences.

Eriksson and Simpson (1990) recognized meter-scale cyclicity in Proterozoic siliciclastic tidal deposits of Australia which they attributed to a eustatic origin, utilizing

Fischer plots. Although the Big Cottonwood deposits of this study show some similar features (and more variable thicknesses of "parasequences"), there is little time control and probably too many assumptions to be made in order to successfully use Fischer plots.

SUMMARY

The Proterozoic Big Cottonwood Formation of central Utah is a thick deposit of quartzite and shale. Despite its age and the tectonic overprints, there are abundant, well-preserved sedimentary structures that indicate deposition in a tide-dominated setting(s) like an estuary, tidal embayment, tidal flat, and/or tidal delta. Quartzites contain reactivation surfaces and compound cross-bed sets indicative of tidal dunes and sand waves. Shales can be divided into two facies: purple shale, and black shale. The purple shale shows mud polygons and other evidence of subaerial exposure that might be expected in tidal flats or intertidal deposits subjected to periodic desiccation. The black shale facies shows three orders of tidal rhythmites and cyclicities. The tidal rhythmites are an important and diagnostic structure of a tide-dominated environment and imply subtidal to intertidal conditions. Where rhythmite cycles are relatively complete, this suggests subtidal conditions where the preservation potential of structures would be greater. There is great potential for using tidal rhythmites to interpret lunar recession rates in the ancient geologic past, and these aspects of rhythmite counts are planned for future studies. These interpretations of a tide-dominated depositional environment for the Big Cottonwood Formation are new, and represent a significant contribution with the recognition of tidal rhythmites and cycles.

ACKNOWLEDGEMENTS

I extend special thanks to Med Bennett who originally brought some of the tidal features within the Big Cottonwood Formation to my attention. I thank Ron Bruhn for his assistance with structural aspects of the study, and stereonet corrections for paleocurrent data. John and Mark Middleton were my able and willing field assistants.

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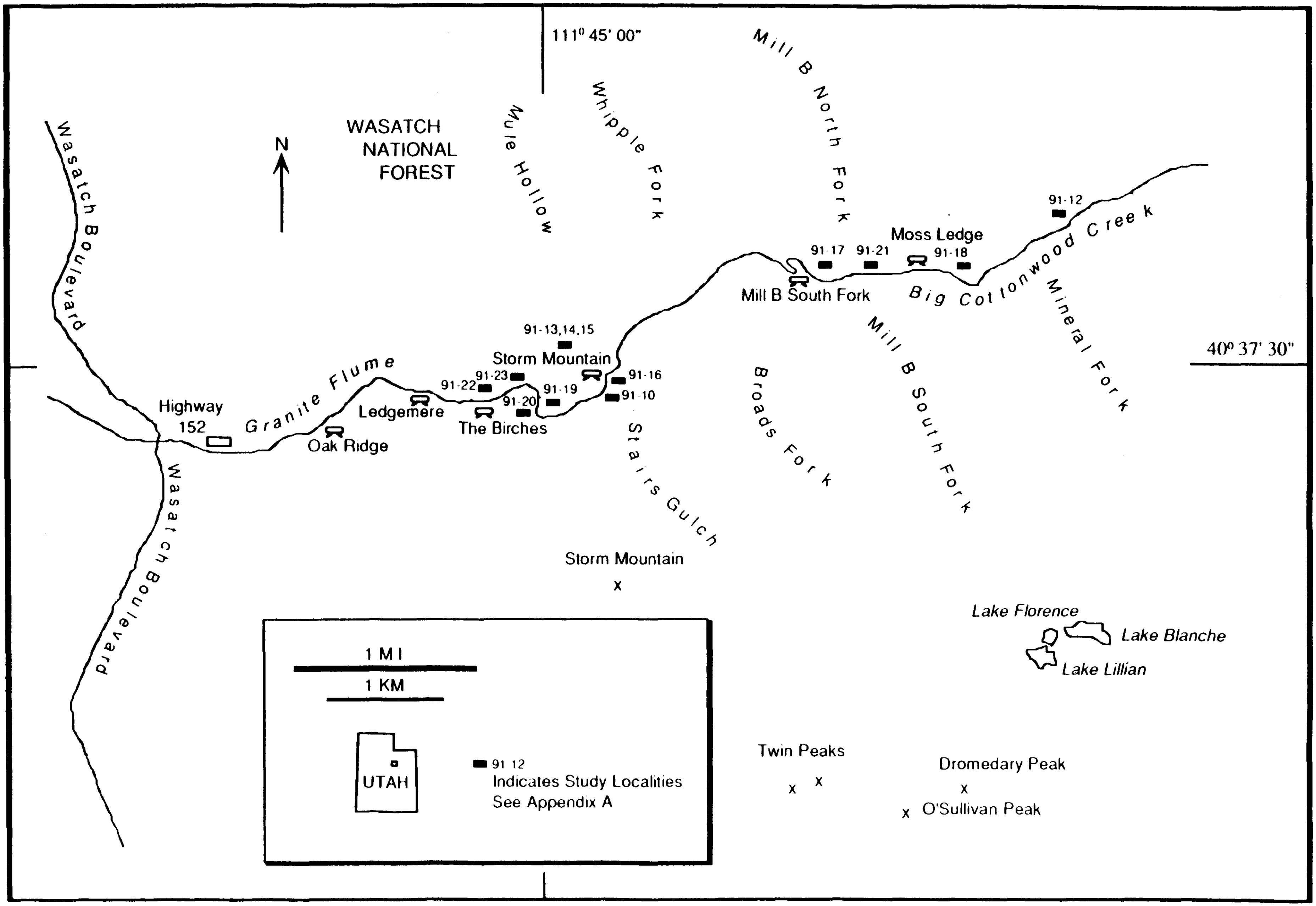


Figure 1. Study area of Big Cottonwood Formation, Big Cottonwood Canyon, Wasatch Front, Utah.

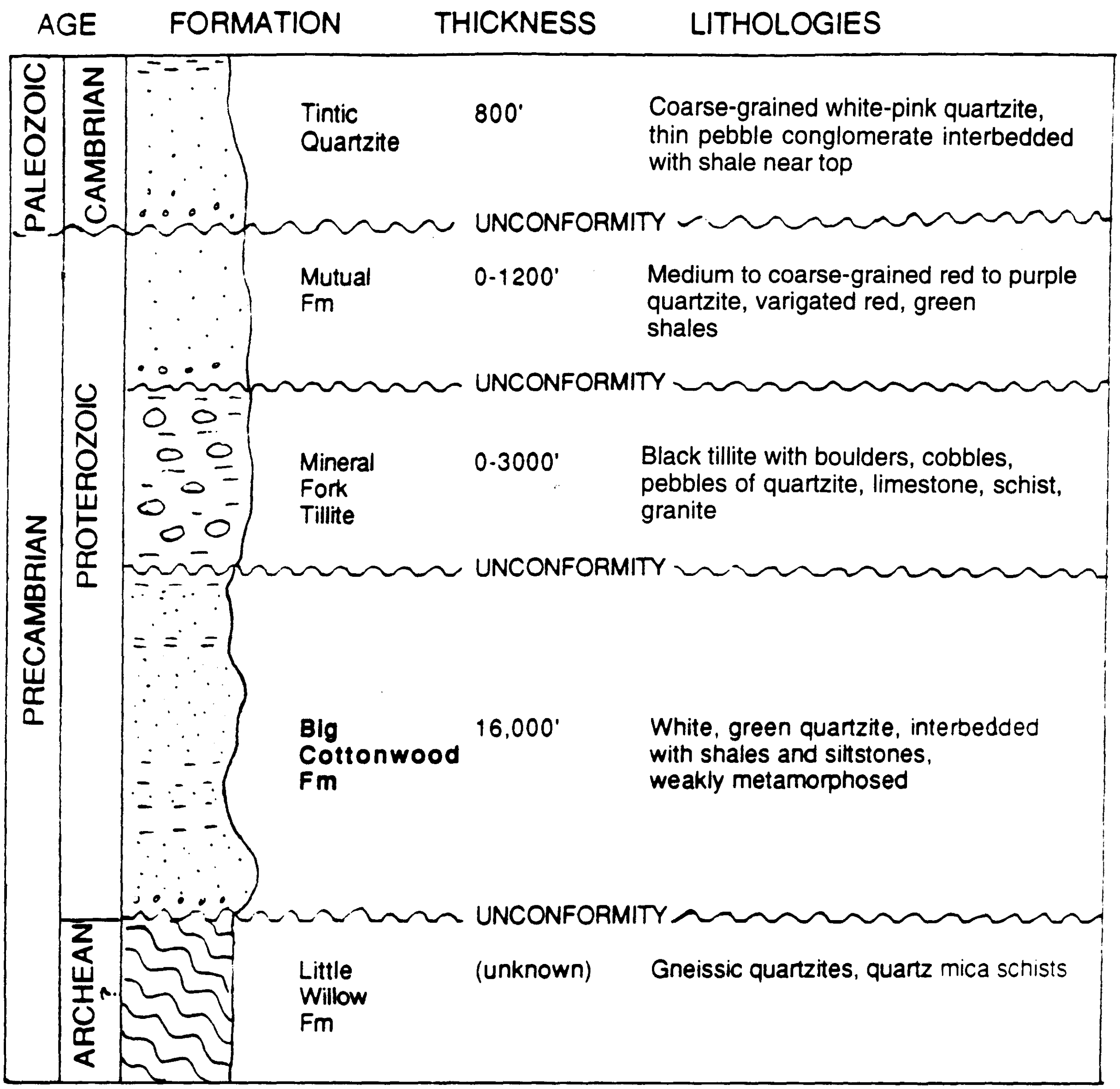


Figure 2. Partial stratigraphy of Big Cottonwood area, modified after James (1979), and Hintze (1988).

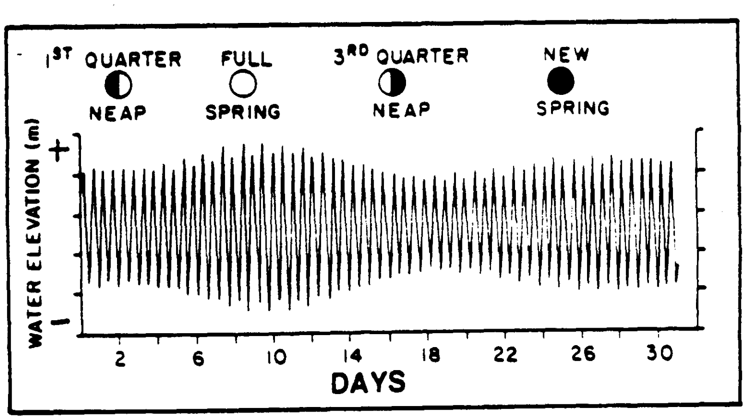


Figure 3. General tidal cyclicity of present-day neap-spring tides in a lunar month (modified from Dalrymple, 1992). Tidal fluctuations show greatest tides during the spring cycle(s), and smallest tides during the neap cycle(s).

Figure 4. Reactivation surfaces in cross-bedded quartzite, as shown by arrows. Stratigraphic top (?) to the right (northeast). Location: 91-13, north side of Storm Mountain Dam Site.

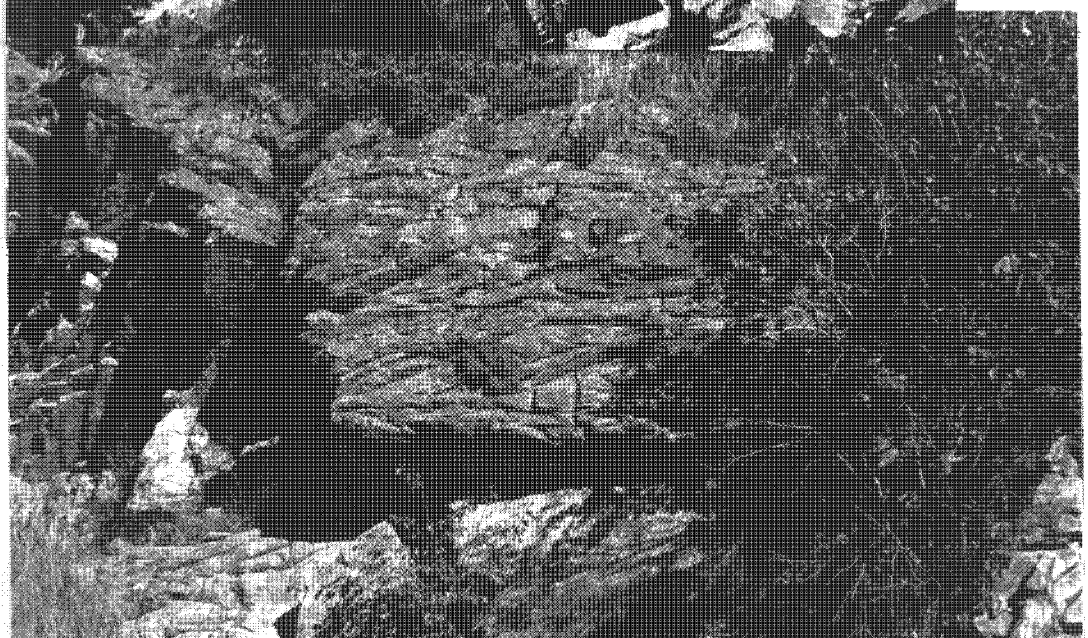


Figure 5. Sigmoidal shaped tidal bundles (?) in cross-bedded quartzite, as shown by arrows. Figure/ picture height represents about 3 m. Location: 91-13, north side of Storm Mountain Dam Site.

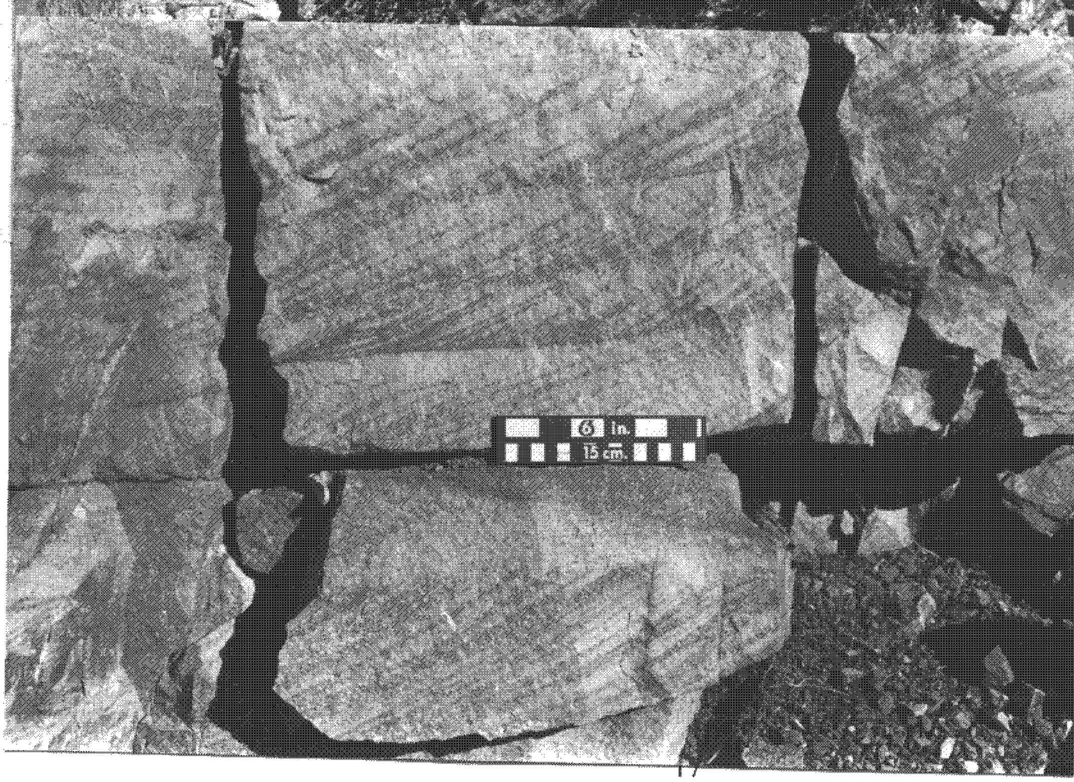


Figure 6. Small tabular cross-bed sets in quartzite. Dominant transport direction to the NNW. Location: 91-17, "S-curve" near Mill B South Fork.

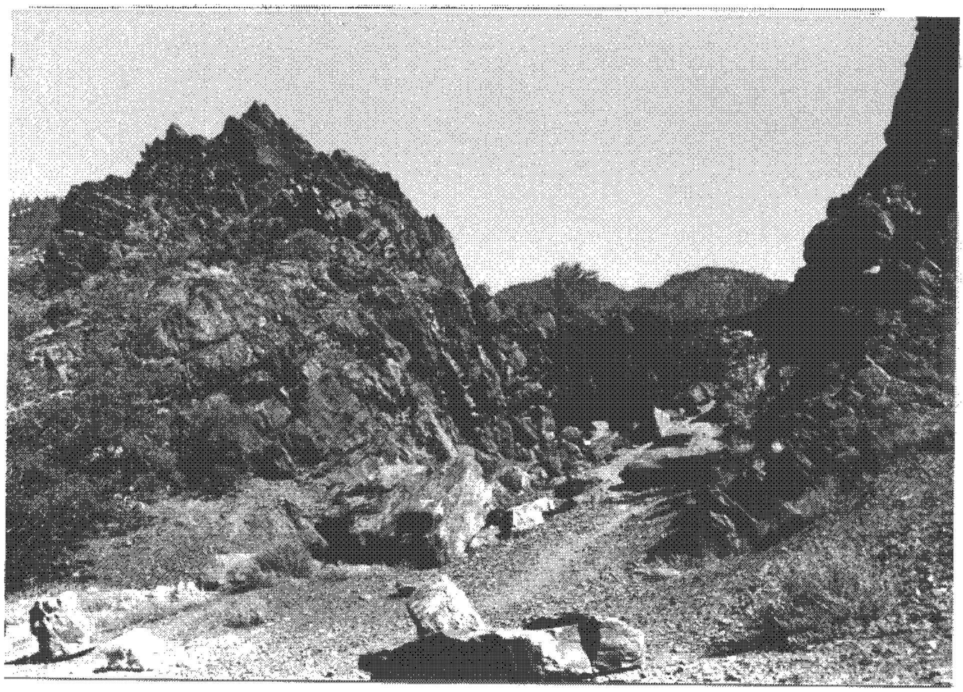


Figure 7a. Black shale facies containing rhythmic beds, with white quartzite facies float blocks in foreground (arrows) at "Storm Mountain Quartzite" sign. Beds are steeply dipping to the east (right). Location: 91-16 at "Storm Mountain Quartzite" sign.

Figure 7b. Mud rip-up clasts shown by arrows. Clasts occur along a channel or scoured base in white quartzite facies float block of figure 7a above. Location: 91-16 at "Storm Mountain Quartzite" sign.

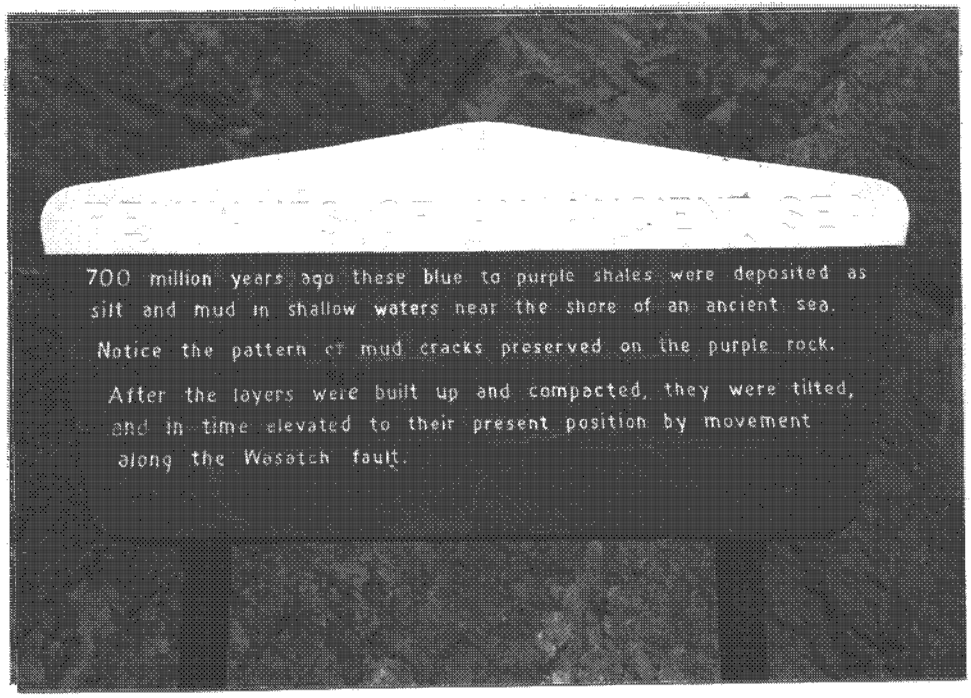


Figure 8. "Remnants of An Ancient Sea" sign, describing shale (purple shale facies) and uplift. Location: 91-20.

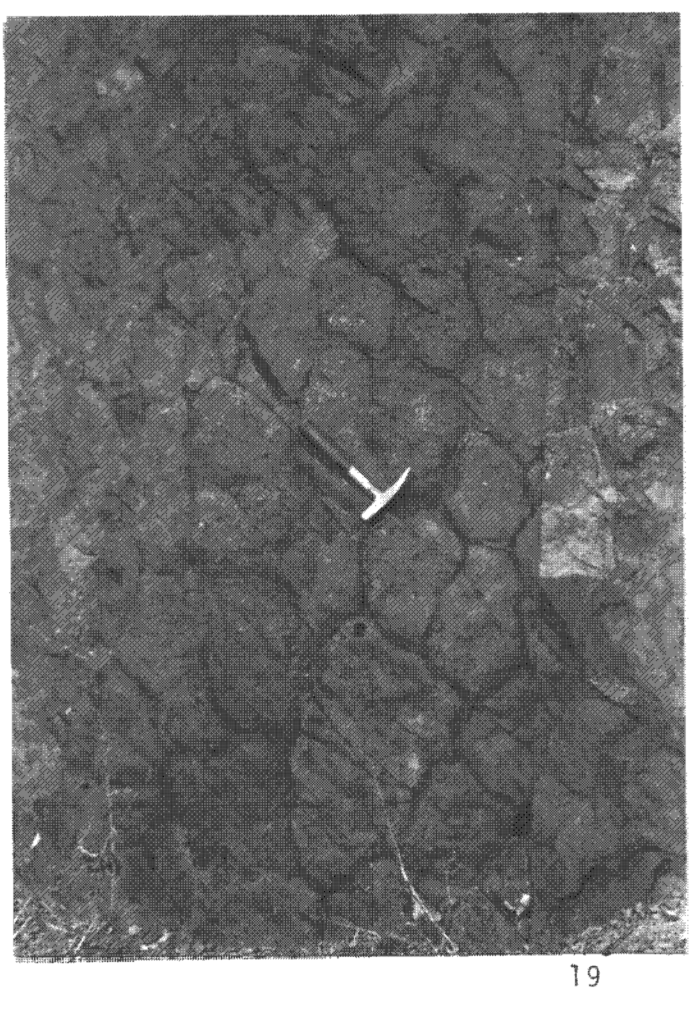


Figure 9. Polygonal mudcracks along tilted bedding plane surface. Hammer length = 28 cm. Location: 91-20 at "Remnants of An Ancient Sea" sign.

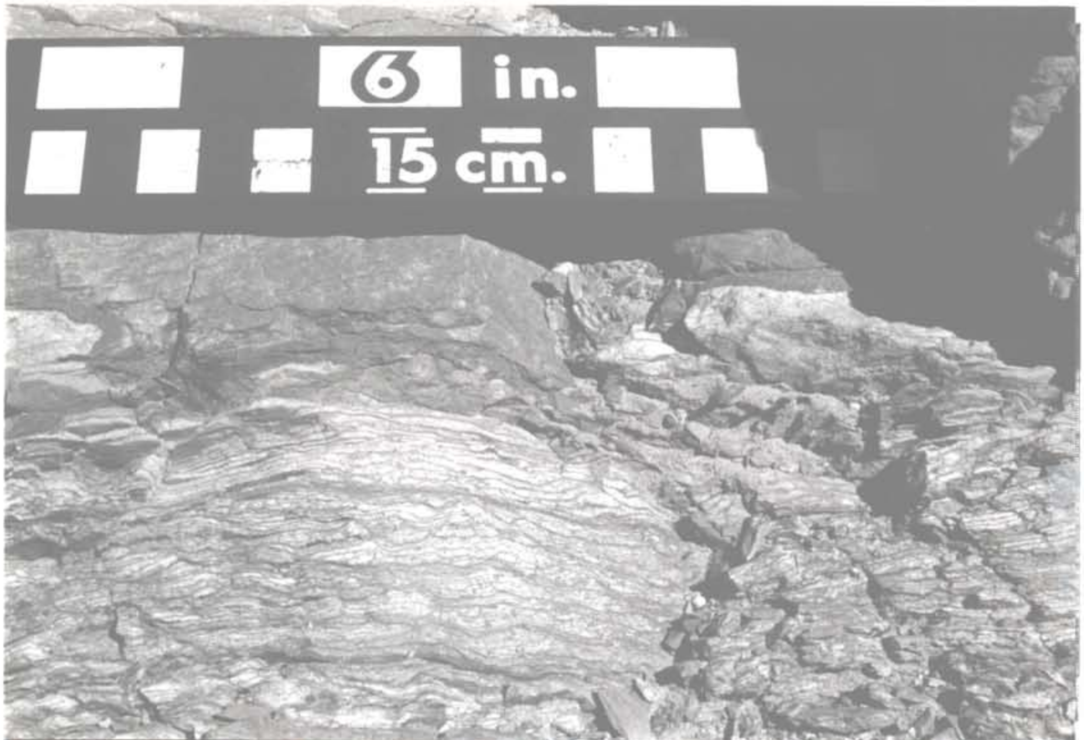


Figure 10. Flaser bedding showing alternating white (sand) and dark (mud) laminae. Location: 91-17, "S-curve" by Mill Fork B South Fork.

Figure 11. "Pin-stripe" ripple laminations of white (sand) and dark (slack-water mud). Location: 91-10 south of Storm Mountain picnic entrance.

Figure 12. Extremely fine "pin-stripe" laminations in a polished slab. Location: 91-10, south of Storm Mountain picnic entrance.

Figure 13a. Shrinkage or desiccation (?) cracks in float block of black shale facies. Location: 91-13, north side of Storm Mountain Dam Site.

Figure 13b. Positive relief shrinkage or desiccation (?) cracks (few centimeters in length) along bedding plane base in black shale facies. Location: 91-16 at "Storm Mountain Quartzite" sign.

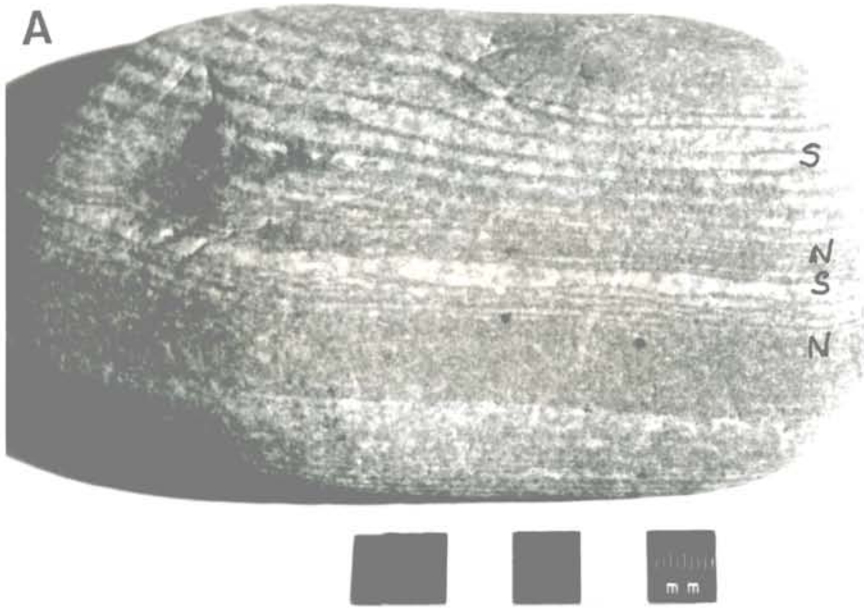


Figure 14a. Fine tidal rhythmites showing sand (white) and mud (dark) couplets in black shale facies. Note variations in rhythmite thicknesses of a spring-neap tidal cycle. Thicker rhythmites represent spring (S) tide, and thin rhythmites represent neap tide (N). Float cobble from Big Cottonwood Creek.

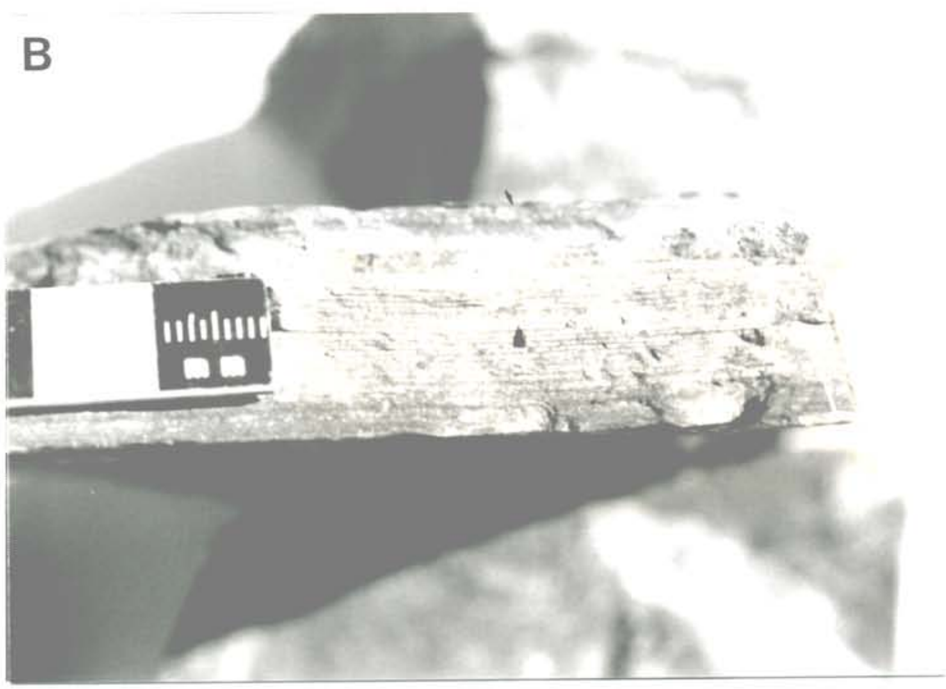


Figure 14b. Fine tidal rhythmites showing sand (white) and mud (dark) couplets in black shale facies. Location: 91-10 , south of Storm Mountain picnic entrance.

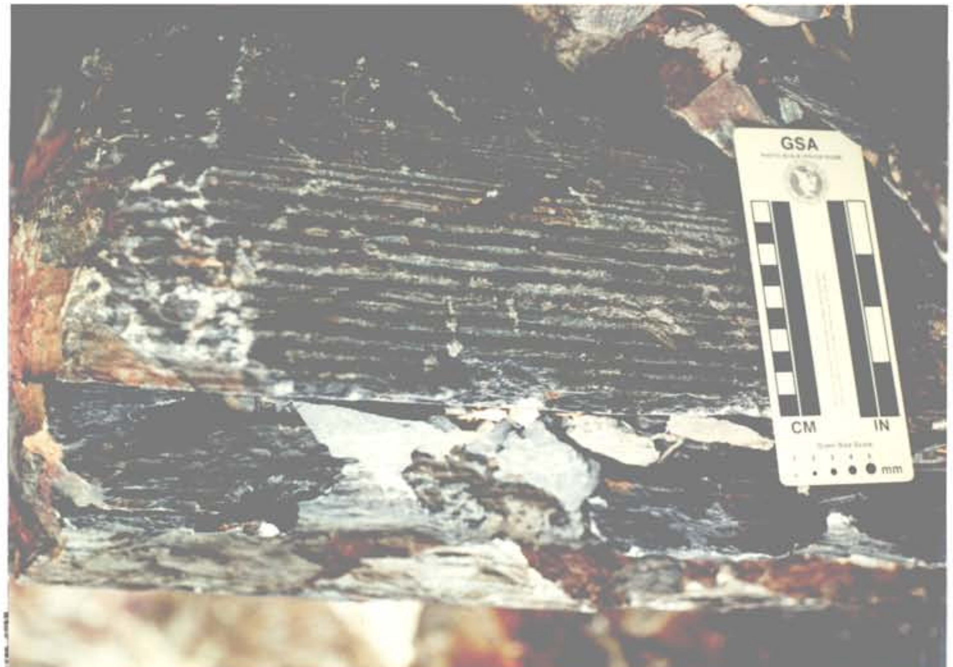


Figure 15. Vertically stacked tidal rhythmites showing sand (white) and mud (dark) couplets in black shale facies. Note variations in rhythmite thicknesses of a spring-neap tidal cycle. Thicker rhythmites represent spring (S) tide, and thin rhythmites represent neap tide (N). Location: 91-10 , S of Storm Mountain picnic entrance.

Figure 16. Two spring-neap tidal cycles comprising a 30+ cm thick monthly cycle, within the black shale facies. Arrows show spring (S) - neap (N) cycles. Location: Trail up to Twin Peaks.

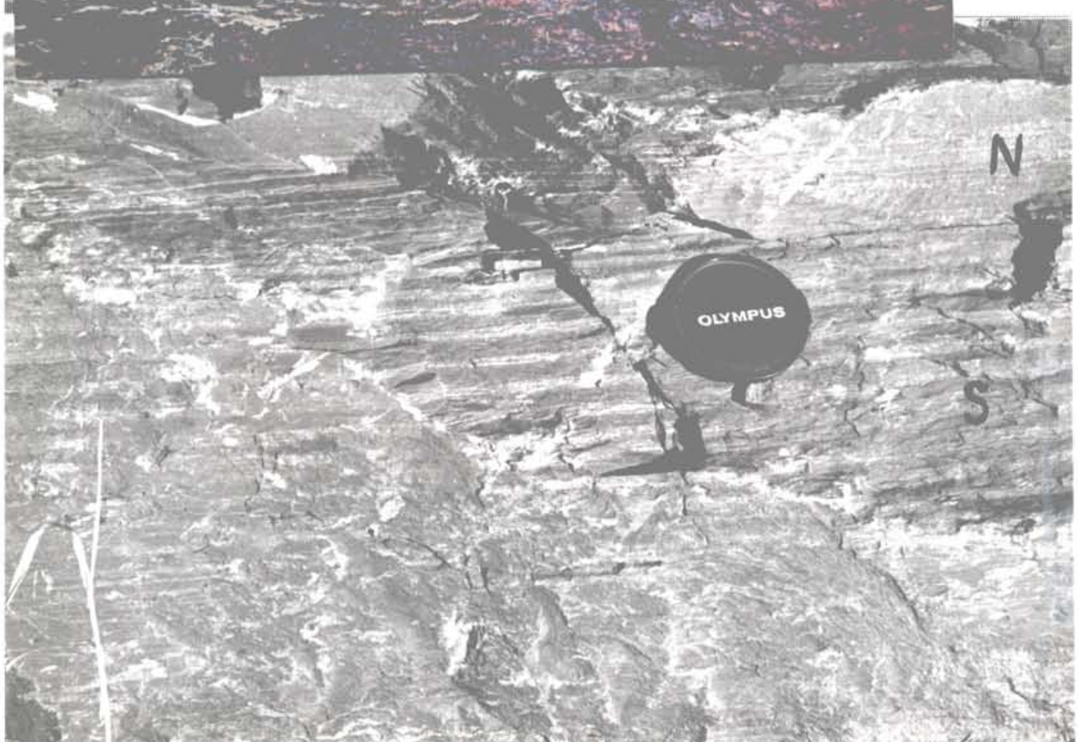


Figure 17. Group of thick rhythmites represent spring (S) tides, alternating with a group of thin rhythmites that represent neap (N) tides. Location: 91-10 , south of Storm Mountain picnic entrance.

APPENDIX A STUDY LOCALITIES

Stop Localities of study along Highway 152 up Big Cottonwood Canyon.
All stop localities in T2S R2E, Salt Lake County, Utah. (See figure 1)

STOP	LOCALITY DESCRIPTION
91-10	SE 1/4 of Sec. 20, Almost directly opposite (south) of Storm Mountain picnic ground entrance where there is an abandoned cement pad, and a large talus pile with float blocks showing packets of vertical tidal rhythmites.
91-11	Streambed up from Storm Mountain.
91-12	SW 1/4 of Sec. 14, 0.2 mi up (east) from Mineral Fork, Exposure on north side of road.
91-13	SE 1/4 of Sec. 20, At the Utah Power + Light dam site on north side of creek. Started measuring stratigraphic section right at the northward continuation of cement dam, then going up section (northeast).
91-14	SE 1/4 of Sec. 20, Continuation of 91-13.
91-15	SE 1/4 of Sec. 20, Continuation of 91-14, above fault. Section becomes more faulted in shale interval.
91-16	SE 1/4 of Sec. 20, south side of road by "Storm Mountain Quartzite" sign (opposite picnic area) at turnout. Measure section up through small saddle, and continuing northeastward until on to private property and Maxfield Lodge area.
91-17	NE 1/4 of Sec. 21, Towards top of "S-curve" near Mill B South Fork, beds appear to be right side up.
91-18	NE 1/4 of Sec. 22, Above (east) of Moss Ledge, located 0.6 mi west (downhill) from Mineral Fork Trail Head.
91-19	SW 1/4 of Sec. 20, In creek bed just west of Storm Mountain picnic area, opposite sign "Remnants of an Ancient Sea". Stratigraphic up to the east? based on tangential toes of cross bed sets.
91-20	SW 1/4 of Sec. 20, At sign "Remnants of an Ancient Sea" on south side of road.
91-21	NW 1/4 of Sec. 22, 100 m down (west) from Moss Ledge picnic pullout, north side of road.
91-22	SW 1/4 of Sec. 20, Just above water treatment plant, opposite Birches picnic turnout.
91-23	SW 1/4 of Sec. 20, Just opposite power plant, by water aqueduct.

APPENDIX B SAMPLING
(Localities in Appendix A)

Sample #	ts, ps	Description	Facies
91-10a	ts, ps	banded (1 cm bands) grey shale	black shale
91-10b	ts, ps	pinstripe black & white qtzite	black shale
91-10c	ts, ps	pinstripe black & white qtzite	black shale
91-10d	ts	banded pink qtzite	white quartzite
91-10e	ts	pinstripe black & white sltst-v.f. ss	black (rhythmic) shale
91-10f	ts	greenish qtzite	green quartzite
91-10g	ts, ps	greenish qtzite	green quartzite
91-10h	ts	white + pink weather (Fe) qtzite	white quartzite
91-10i	ts	white + pink weather (Fe) qtzite	white quartzite
91-10j	ts	white + pink weather (Fe) qtzite	white quartzite
91-10k	ts	white qtzite	white quartzite
91-10m	ts	white qtzite	white quartzite
91-11a	ts, ps	stream cobble w/ f. gr.	
91-11b	ts, ps	stream cobble, disrupted laminations??	
91-12a	ts	MF- purple cgl- v. crse ss w/ mud rip-ups	
91-12b	ts	MF- purple cgl- v. crse ss w/ mud rip-ups	
91-12c	ts	MF- purple cgl- v. crse ss, mud rip-ups + kfsp?	
91-13a	ts, ps	f. gr. greenish gray qtzite	green quartzite
91-17a	ts	m. gr. greenish qtzite	green quartzite
91-18b	ts, ps	green crse ss w/ kfsp? (pink) + green grs.	green quartzite
91-20a	ts	purple sh	purple shale
91-20b	ts	purple sh	purple shale
91-20c	ts	greenish sh	purple shale
91-20d	ts	sh vein fill?	purple shale
91-21a	ts	tan v. crse ss w/ green grs.?	green quartzite
91-21b	ts	white-tan m. gr. qtzite	white quartzite

Abbreviations:

ts= thin section
ps=polished slab
MF= Mineral Fork Tillite

sh=shale, sltst=siltstone, ss=sandstone, qtzite=quartzite
v. = very, f.=fine, m.=medium, crse= coarse, gr.=grain
kfsp=K-feldspar, w/=with, weather=weathered

Descriptions of select thin sections follow in Appendix C.

APPENDIX C SELECTED THIN SECTION DESCRIPTIONS

(See Appendix A for all localities, and Appendix B for description of sampling)

Quartzite and Shale Samples

Sample #: 91-10a Rock Name: quartzite
Other description: "pinstriped" fine-grained quartzite
Grain size: very fine- to fine-grained sand (.07-.15 mm)
Textures: alternation of grain sizes, "pinstriping" due to alternations and varying amounts of clay, organic content, appears to have some grading of shale to siltstone to very fine and fine-grained sandstone over about 1 cm.
Interpretation: black shale facies (rhythmites)

Sample #: 91-10b, 91-10c Rock Name: quartzite
Other description: "pinstriped" fine-grained quartzite
Grain size: very fine- to fine-grained sand (.07-.15 mm)
Textures: alternation of grain sizes, "pinstriping" due to alternations and varying amounts of clay, organic content
Interpretation: black shale facies (rhythmites)

Sample #: 91-10d Rock Name: quartzite (quartz arenite)
Other description: banded quartzite
Grain size: fine-grained sand (0.12-0.4 mm)
Textures: subangular to subrounded grains
Mineralogy:

Grains	~ 80-98%	quartz and overgrowths (minor)
	<20%	altered grains/sericite (cryptocrystalline quartz- volcanic? rock fragments)
	<1%	muscovite
Matrix	<5%	clay/sericite

Interpretation: white quartzite facies

Sample #: 91-10e Rock Name: quartzite (quartz arenite)
Other description: banded, siltstone + very fine-grained sandstone layers, some pyrite cubes with alteration haloes
Grain size: very fine-grained sand (0.10-0.15 mm)
Textures: subrounded quartz grains
Mineralogy: quartz rich
Interpretation: black shale facies

Sample #: 91-10f Rock Name: siltstone
Grain size: silt
Textures: subrounded quartz grains
Mineralogy: quartz rich
Interpretation: black shale facies

Sample #: 91-10g Rock Name: quartzite (quartz arenite)
Grain size: medium- to coarse-grained sand (0.25-0.8 mm)
Textures: subrounded to rounded grains
Mineralogy:

Grains	~ 90%	quartz and overgrowths (minor)
	<5%	altered grains/sericite (cryptocrystalline quartz- volcanic? rock fragments)
Matrix	<2%	clay/sericite (some epimatrix to pseudomatrix)

Cement/Diagenesis: <10% Quartz overgrowths, alteration to epimatrix and pseudomatrix
Interpretation: green quartzite facies

Sample #: 91-10h, and 91-10m Rock Name: quartzite (quartz arenite)
Grain size: medium-grained sand (0.3-0.6 mm)
Textures: rounded to well rounded grains
Mineralogy:

Grains	~ 98%	quartz and overgrowths (minor)	
	<2%	altered grains/sericite (cryptocrystalline quartz- volcanic? rock fragments)	
Matrix	none?		

Cement/Diagenesis: iron stains around grain contacts
Interpretation: white quartzite facies

Sample #: 91-10i Rock Name: quartzite (quartz arenite)
Other description: some rutilated quartz grains
Grain size: medium-grained sand (0.15-0.5 mm)
Textures: well-rounded quartz grains with overgrowths
Mineralogy:

Grains	~ 90%	quartz and overgrowths
	<2%	muscovite + altered grains/sericite
Matrix	<10%	clay/sericite (pseudomatrix from squashed rock fragments)

Interpretation: white quartzite facies

Sample #: 91-10k Rock Name: quartzite (Quartz arenite)
Grain size: fine-grained sand (0.2-0.4 mm)
Textures: subangular to subrounded grains
Mineralogy:

Grains	~ 95%	quartz and overgrowths (minor)
	~2%	plagioclase
	<2%	muscovite
	<1%	rounded biotite
	<2%	altered grains/sericite (cryptocrystalline quartz- volcanic? rock fragments)

Cement/Diagenesis: quartz overgrowths
Interpretation: white quartzite facies

Sample #: 91-13a Rock Name: quartz wacke
Grain size: very fine- to fine-grained sand (0.08-0.2 mm)
Textures: subangular to rounded grains, long to concavo-convex contacts
Mineralogy:

Grains	<80%	quartz and overgrowths (minor)
	<5%	plagioclase
	<10%	altered grains/sericite (cryptocrystalline quartz- volcanic? rock fragments)
Matrix	10-15% illite?/clays (high birefringence, coats most of grains)	

Cement/Diagenesis <2% calcite and dolomite rhombs?
Interpretation: green quartzite facies ("dirty sandstone", with fair amount of pseudomatrix)

Sample #: 91-17a Rock Name: quartzite (quartz arenite)
Grain size: medium-grained sand (0.15-0.5 mm)
Textures: well-rounded quartz grains with overgrowths
Mineralogy:

Grains	~ 98%	quartz (88+%) and overgrowths (<10%)
	<1%	muscovite
	<2%	altered grains/sericite (cryptocrystalline quartz- volcanic? rock fragments)
Matrix	<1%	clay/sericite

Cement/Diagenesis: some chloritized grains?
Interpretation: green quartzite facies

Sample #: **91-18b** Rock Name: quartzite (quartz arenite)
Grain size: medium- to coarse-grained sand (0.4-0.8 mm)
Textures: subrounded to rounded grains
Mineralogy:

Grains	~ 90%	quartz and overgrowths, some rutilated quartz grains
	<2-5%	altered grains/sericite and chlorite (feldspar and/or rock fragments?)

Cement/Diagenesis: <2% dolomite cement
Interpretation: green quartzite facies

Sample #: **91-20a, 91-20b** Rock Name: mudstone
Other description: reddish stained, slightly/faintly laminated
Grain size: mud to silt
Mineralogy: quartz, muscovite, and altered grains
Interpretation: purple shale facies

Sample #: **91-20c** Rock Name: quartz wacke
Other description: greenish, laminated
Grain size: silt to very fine-grained sand
Mineralogy: quartz rich, some muscovite, and altered grains
Interpretation: purple shale facies

Sample #: **91-20d** Rock Name: quartz-hematite-chlorite shale vein fill
Grain size: quartz grains- few mms+ in size
Textures: chlorite mainly lining fracture sides, then quartz and hematite infill
Mineralogy:

Grains	~85%	quartz, cryptocrystalline at edges of fracture to more equigranular towards vein center, lots of fluid inclusion trains
	<5%	hematite laths (bright red) up to 1.2 mm long, and a few equigrannular plates
	<10%	chlorite (greenish), radiating spherules, laths up to 0.5 mm long
Matrix	shale (fractured host rock)	

Cement/Diagenesis: vein infilling
Interpretation: vein from purple shale facies {Contemporaneous intergrowth of quartz and hematite, as well as some chlorite, infilling a vein}

Sample #: **91-21a** Rock Name: quartzite (quartz arenite)
Grain size: medium- to coarse-grained sand (0.25-0.8 mm)
Textures: interlocking sutured grains (more a metamorphic quartzite than most other samples)
Mineralogy:

Grains	> 90%	quartz and overgrowths (minor)
	<5-10%	altered grains/sericite and chlorite (feldspar and/or rock fragments ?)

Interpretation: green quartzite facies

Sample #: **91-21b** Rock Name: quartzite (quartz arenite)
Grain size: medium-grained sand (0.2-0.4 mm)
Textures: subrounded to rounded grains
Mineralogy:

Grains	> 95%	quartz and overgrowths (minor)
	<2-4%	altered grains/sericite (feldspar and/or rock fragments?)
Matrix	<2%	clay/sericite (some pseudomatrix from altered and chloritized grains)

Interpretation: white quartzite facies

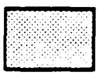
APPENDIX D MEASURED SECTIONS

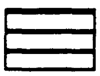
Partial Measured Sections of the Big Cottonwood Formation in Sec. 20, T2S, R2E

1) Locality 91-13, North side of Storm Mountain Dam site (~ 80 m section)
2) Locality 91-16, Section east of Storm Mountain Quartzite sign (~ 60 m section)
3) Locality 91-17, Top of "S-curve", Rd. 152 (~ 30 m section)

Legend


Sandstone, quartzite


Siltstone, shale


Rhythmites (sandstone and shale)


Cross-bedding


Wave ripples

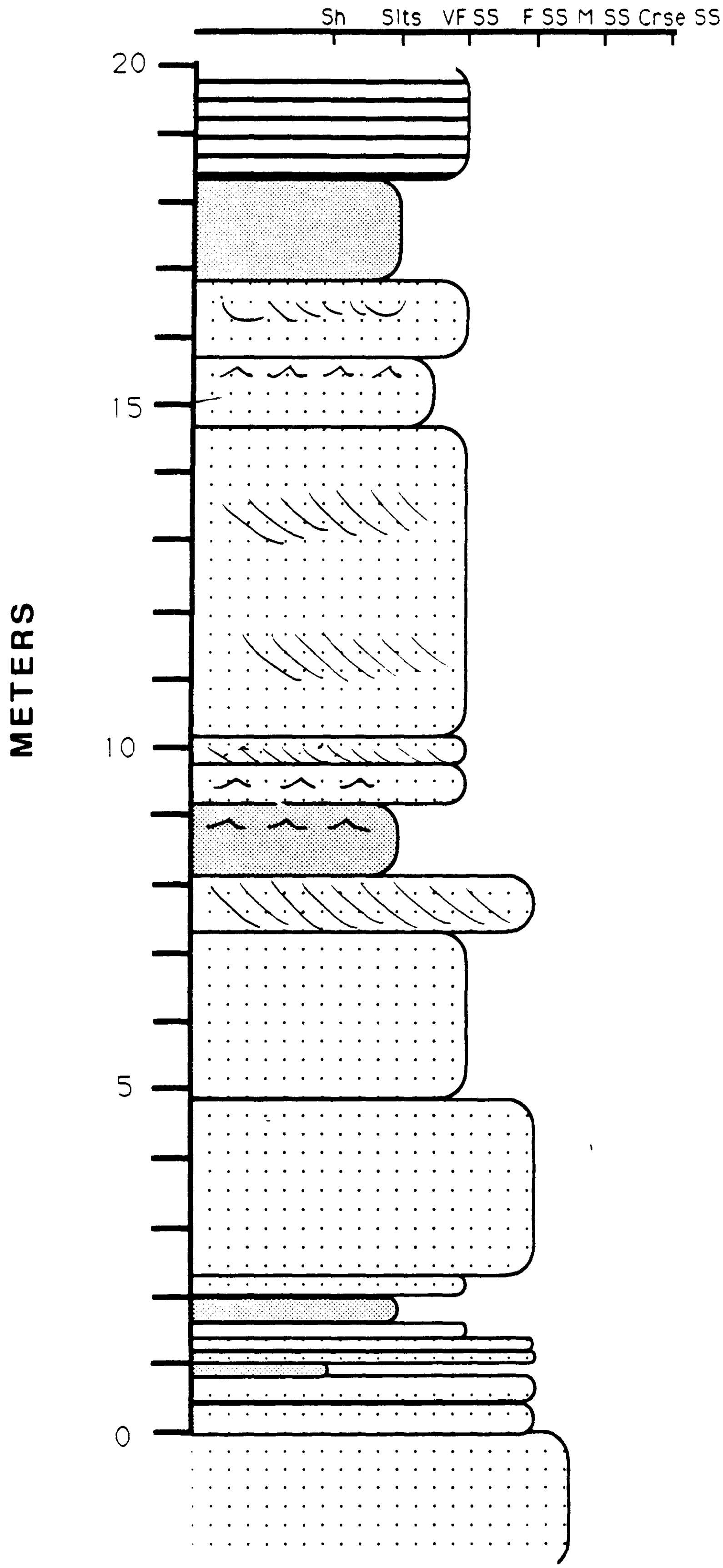

Shrinkage / Desiccation cracks


Mud rip-up clasts

Abbreviations

Crse ss	=	coarse-grained sandstone
M. ss	=	medium-grained sandstone
F. ss	=	fine-grained sandstone
V. f. ss	=	very fine-grained sandstone
slts	=	siltstone
sh	=	shale

Partial Measured Section, Proterozoic Big Cottonwood Fm.,
Storm Mountain Dam Site (north side), Sec. 20, T2S, R2E
Locality 91-13



DESCRIPTION

Thin interbedded V.f. ss and slts, rhythmic laminations at base, rhythmites

Thinly laminated sandy slts, tectonically altered

V. f. ss, tcs, troughs ~ 25 cm deep x 70 cm wide

V.f. ss to slts, ripples at top

V.f. ss, faint cross-bedding? tectonically altered

V.f. ss, 5 sets of sm tabular cross-bed sets, tangential toes

V.f. ss, ripples?

Thinly laminated slts to v.f. ss, some ripples

F. ss, tabular cross-bed tangential toes

V.f. ss, beds ~ 2 - 5 cm thick

F. ss

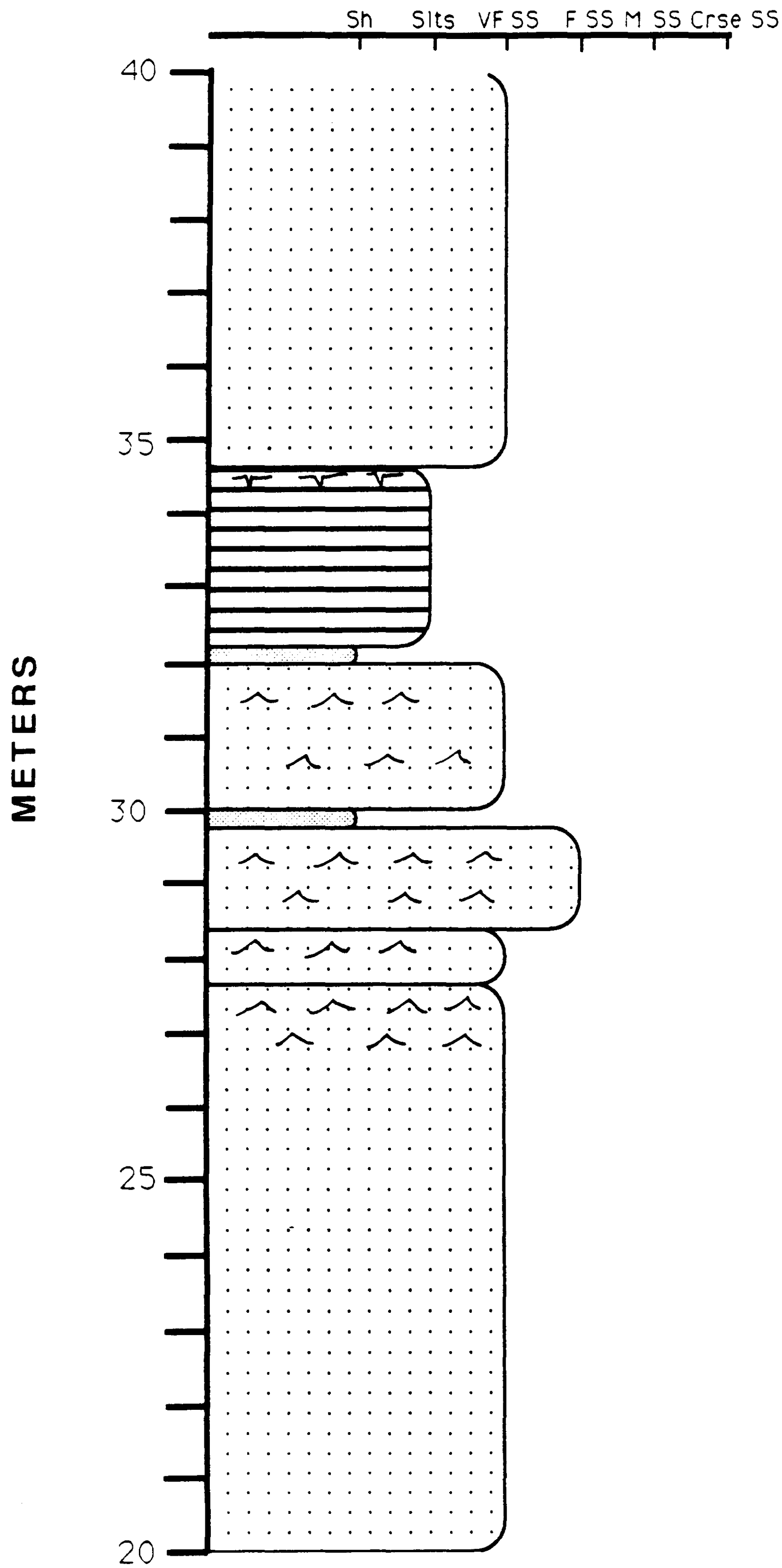
V.f. ss, thin beds

Slts-sh

Thin V.f. ss and sh

F. ss, resistant knob at west end of Storm Mt reservoir dam

Partial Measured Section, Proterozoic Big Cottonwood Fm.,
Storm Mountain Dam Site (north side), Sec. 20, T2S, R2E
Locality 91-13



DESCRIPTION

V.f. ss, few cm thick beds

Rhythmic laminated sh to slts, rhythmites, scattered desiccation cracks upper 30 cm

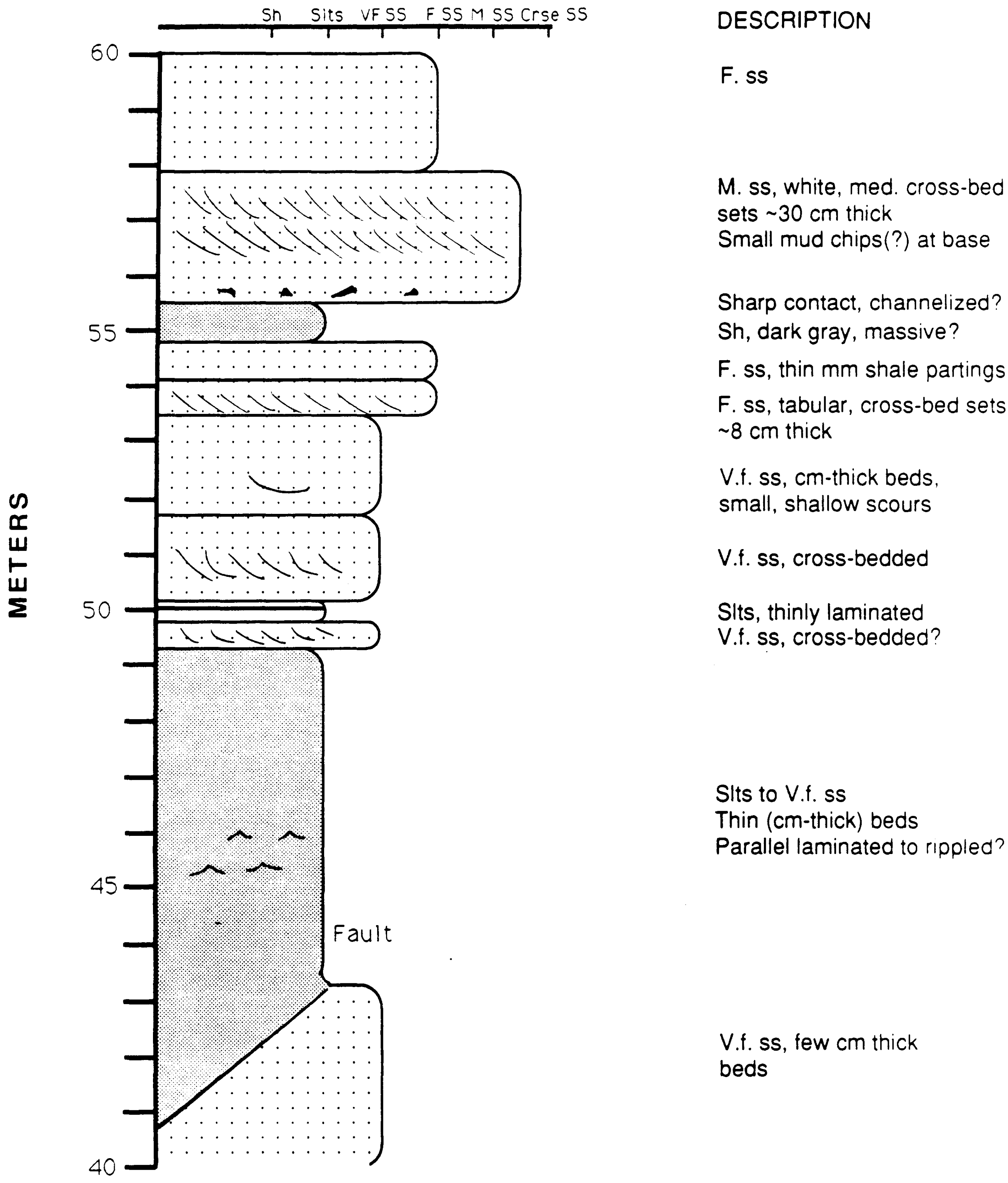
V.f. ss, ripples

F. ss, ripples throughout, ripple top

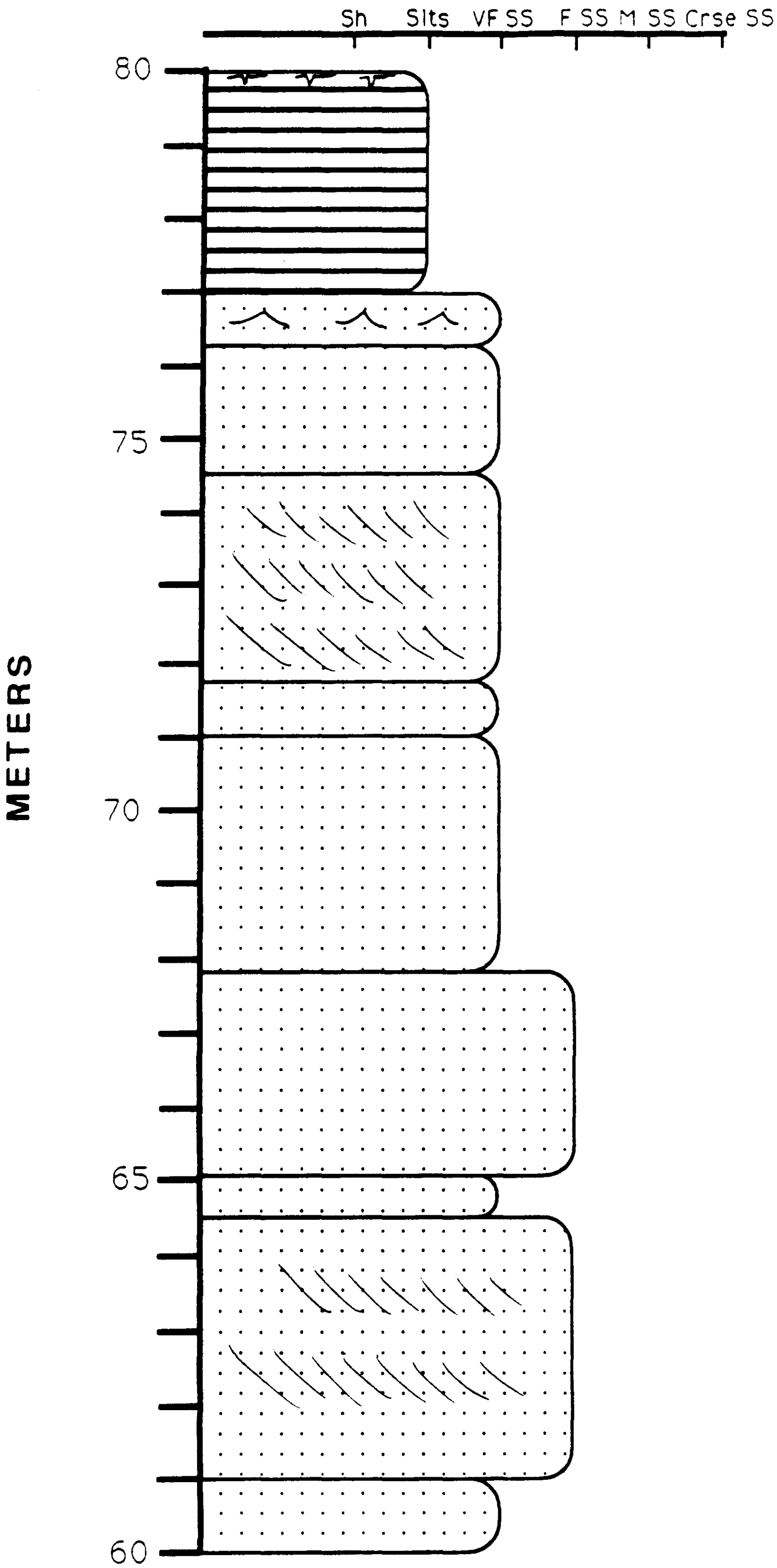
V.f. ss, beds ~ 15 cm thick, ripples

Thin interbedded v.f. ss and slts, linguoid ripples at top

Partial Measured Section, Proterozoic Big Cottonwood Fm.,
Storm Mountain Dam Site (north side), Sec. 20, T2S, R2E
Locality 91-13



Partial Measured Section, Proterozoic Big Cottonwood Fm.,
Storm Mountain Dam Site (north side), Sec. 20, T2S, R2E
Locality 91-13



DESCRIPTION

Slts, rhythmites, cm thick beds (2-4 cm), internal "pinstripe" laminations, large-scale truncations?, desiccation cracks towards top

V.f. ss, rippled

V.f. ss, cm thick beds up to ~10 cm thick, variable bed thicknesses due to tectonism?

V.f. ss, crossbedded?

V.f. ss

V.f. ss, ~12 beds, beds thin upwards, separated by thin shale partings (~40 cm thick beds at base, ~15 cm beds at top)

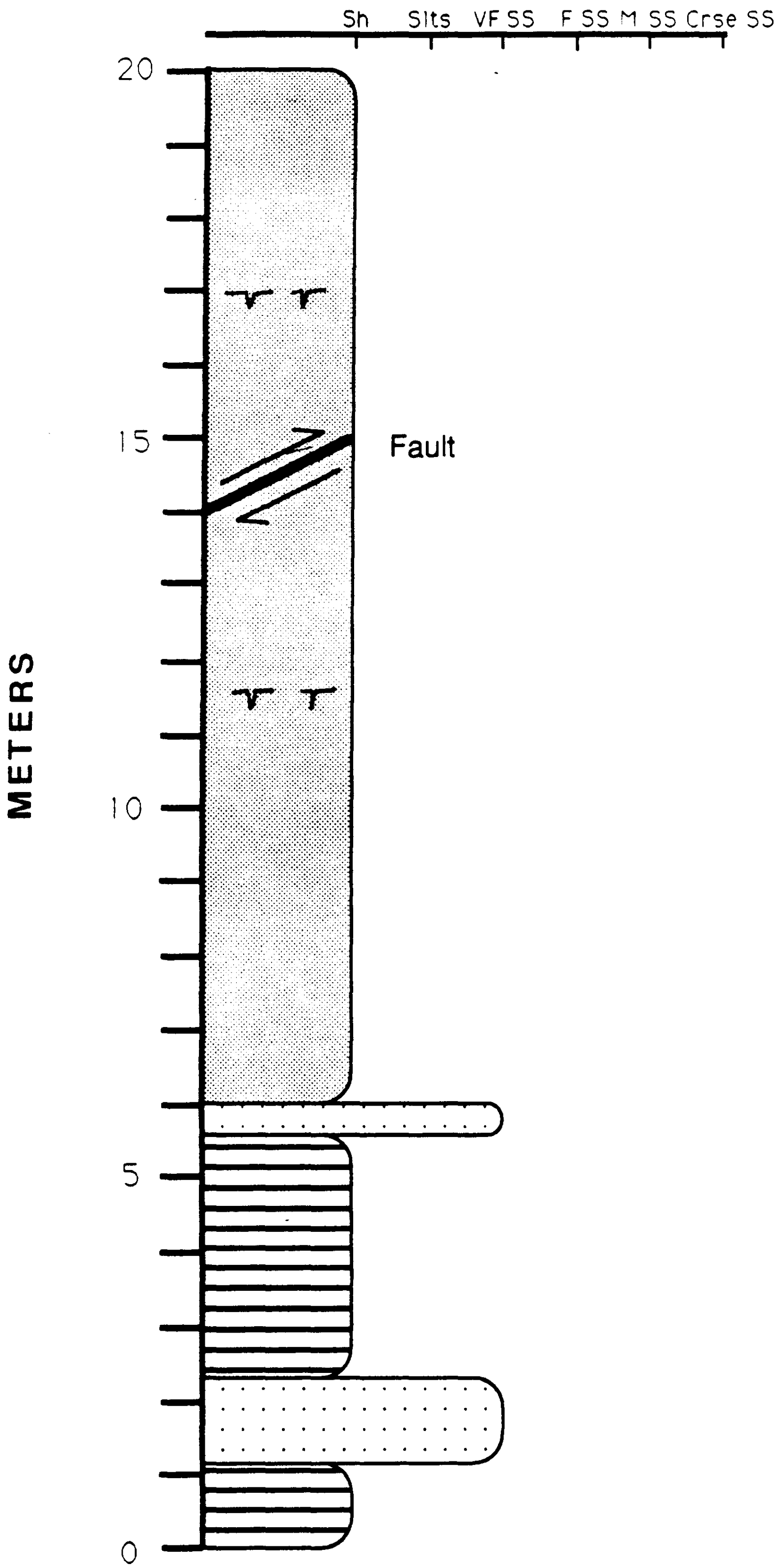
F. ss

V.f. ss

F. ss, faintly cross-bedded

V.f. ss, beds ~ 20 cm thick

Partial Measured Section, Proterozoic Big Cottonwood Fm.,
Storm Mountain Quartzite Sign, Sec. 20, T2S, R2E
Locality 91-16



DESCRIPTION

Sh, dark grey, ripples, "pinstripe" laminations

Sh, dark grey, ripples, "pinstripe" laminations and rhythmites

V.f. ss, faintly laminated? weathered

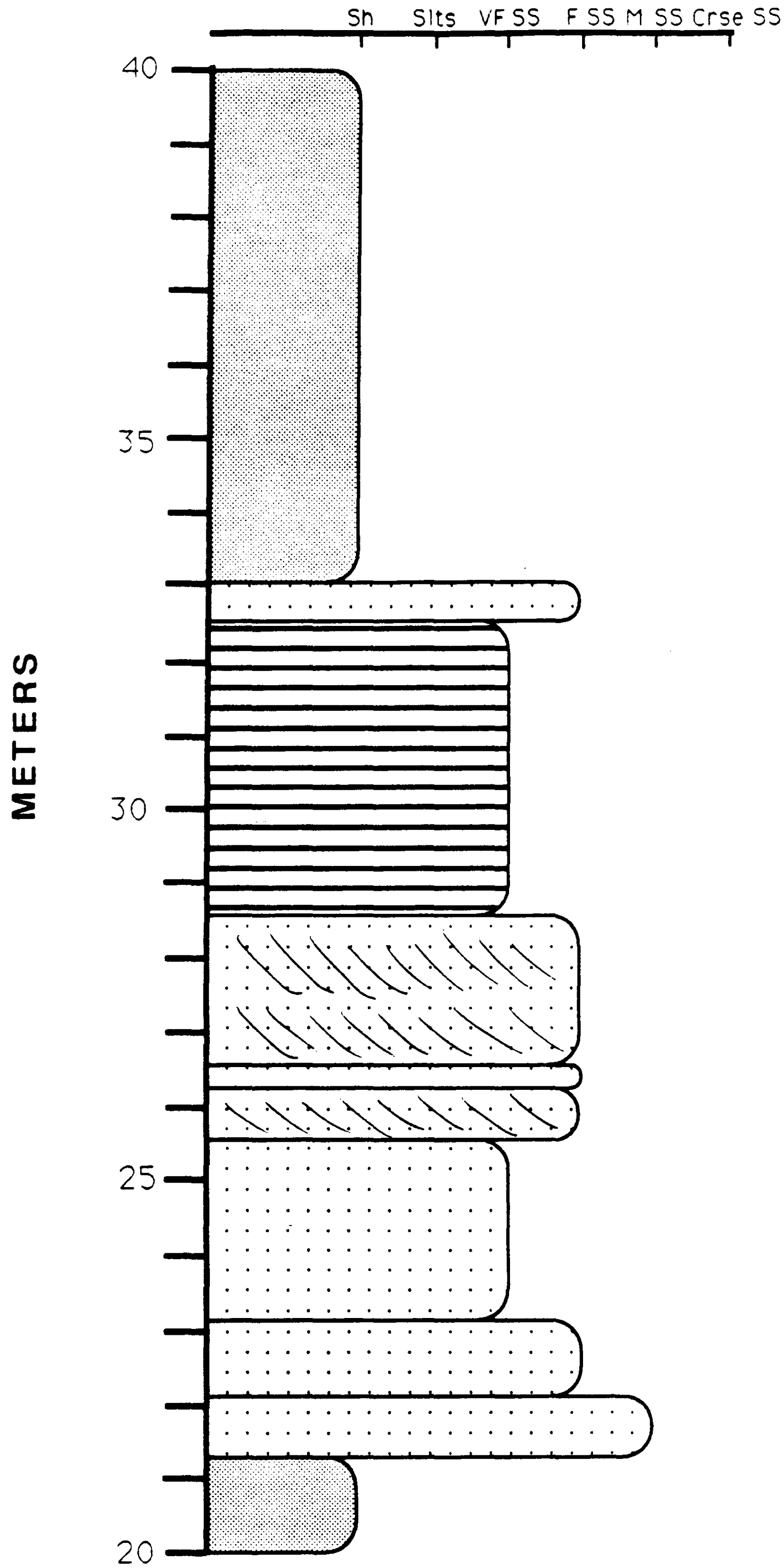
Sh, dark grey, well-laminated. "pinstripe" laminations and rhythmites

Slts to V.f. ss, greenish-grey faintly laminated

Sh, faintly laminated

Small faults with 30+ cm offset
Rhythmites, vertical bundles

Partial Measured Section, Proterozoic Big Cottonwood Fm.,
Storm Mountain Quartzite Sign, Sec. 20, T2S, R2E
Locality 91-16



DESCRIPTION

Sh, thinly bedded, "pinstripe" laminations

F. ss, quartzite laterally pinches and swells

Mix of sh and ss beds, (cm thick) some rhythmic bands, rhythmites, variable bedding due to tectonism

F. ss to M. ss, cross-bedded

F. ss to M. ss, white quartzite, cross-bedded (~30° angles)

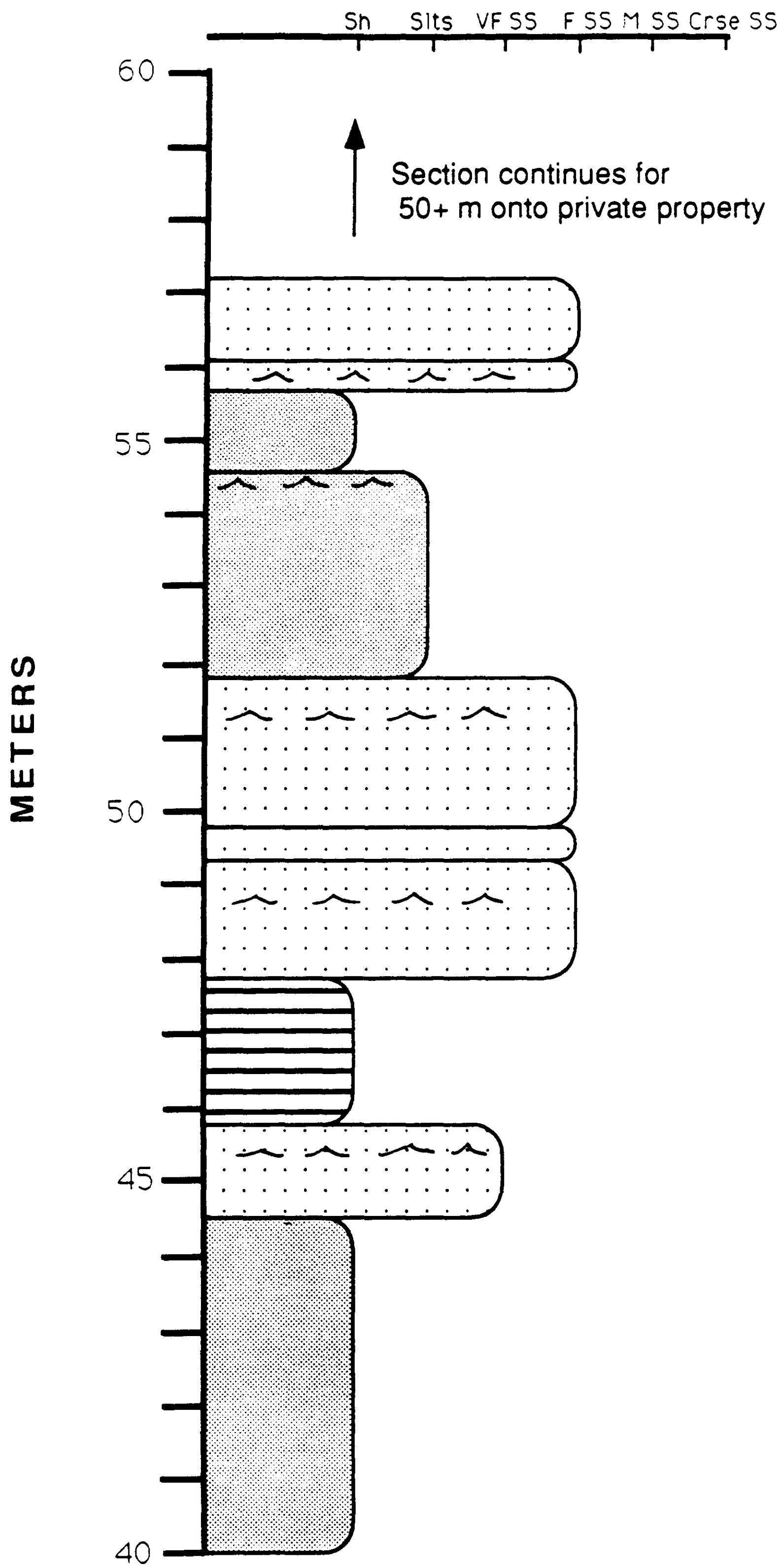
V.f. ss, chaotic mix of banded slts and quartzite, upper 30 cm inversely graded?

F. ss, quartzite, greenish

M. ss, quartzite, graded?

Sh, dark grey

Partial Measured Section, Proterozoic Big Cottonwood Fm.,
Storm Mountain Quartzite Sign, Sec. 20, T2S, R2E
Locality 91-16



DESCRIPTION

Sh, dark grey, "pinstripe" laminations, rhythmic bedding

F. ss, quartzite

F. ss, inversely graded?, ripples

Sh, dark grey, laminated

Sh, "pinstripe" laminations, more sand-rich and rippled at top

F. ss, quartzite, ripples, "pinstripe" laminations

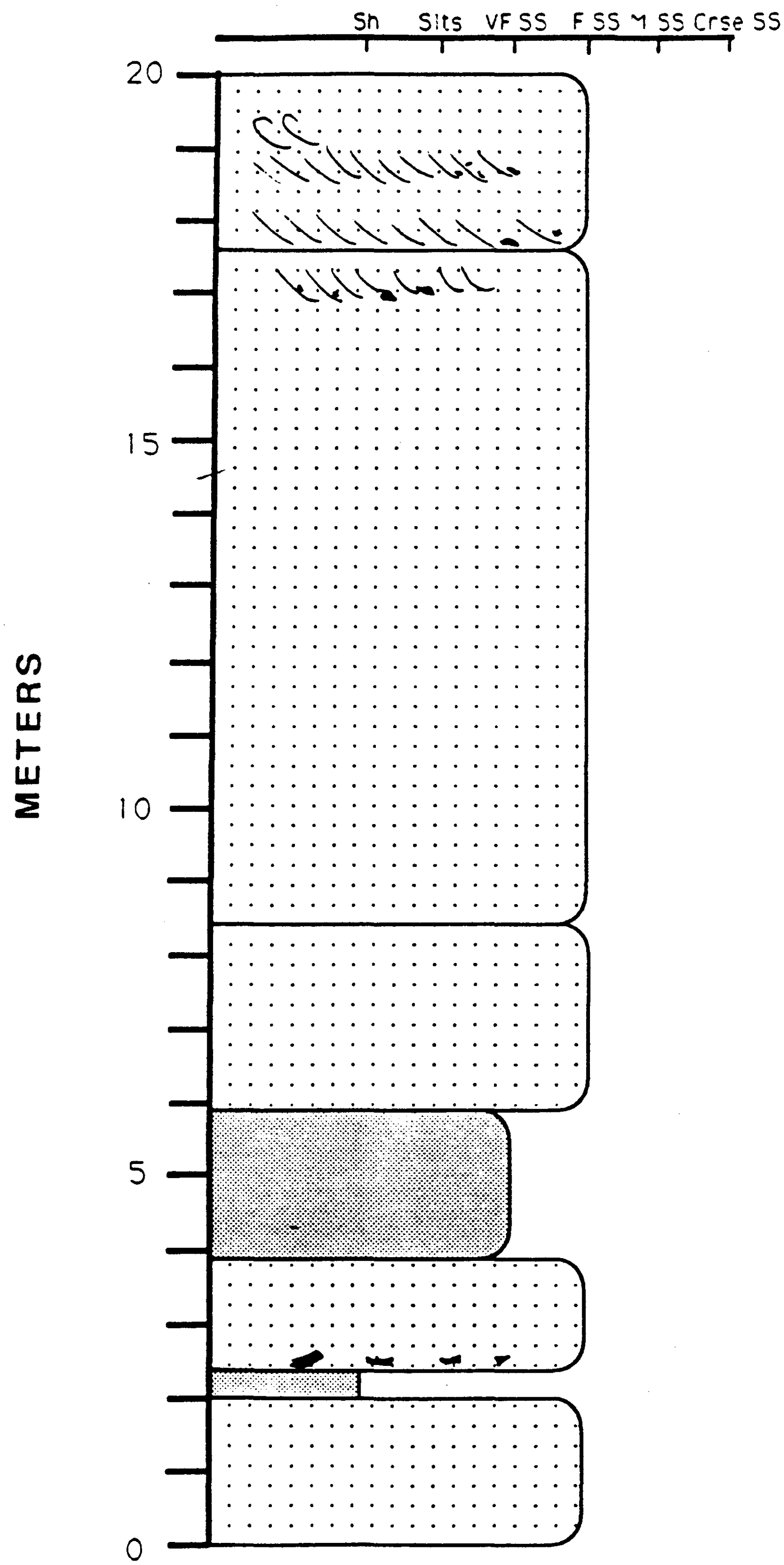
F. ss, quartzite, ripples, "pinstripe" laminations

Sh, rhythmic bedding, rhythmites

Vf. ss, climbing ripple bands ~1-2 cm thick, starved ripples, "pinstripe" laminations

Sh, thinly bedded "pinstripe" laminations

Partial Measured Section, Proterozoic Big Cottonwood Fm.,
Top of "S-curve", Road 152, Sec. 20, T2S, R2E
Locality 91-17



DESCRIPTION

F. ss, cross-bedded, ~10-20 cm thick sets, tangential toes, one overturned set

F. ss, quartzite, cross-bedded in upper 20 cm, scattered mud clasts at base of cross-bedded tangential toes

F. ss, quartzite

Sharp contact

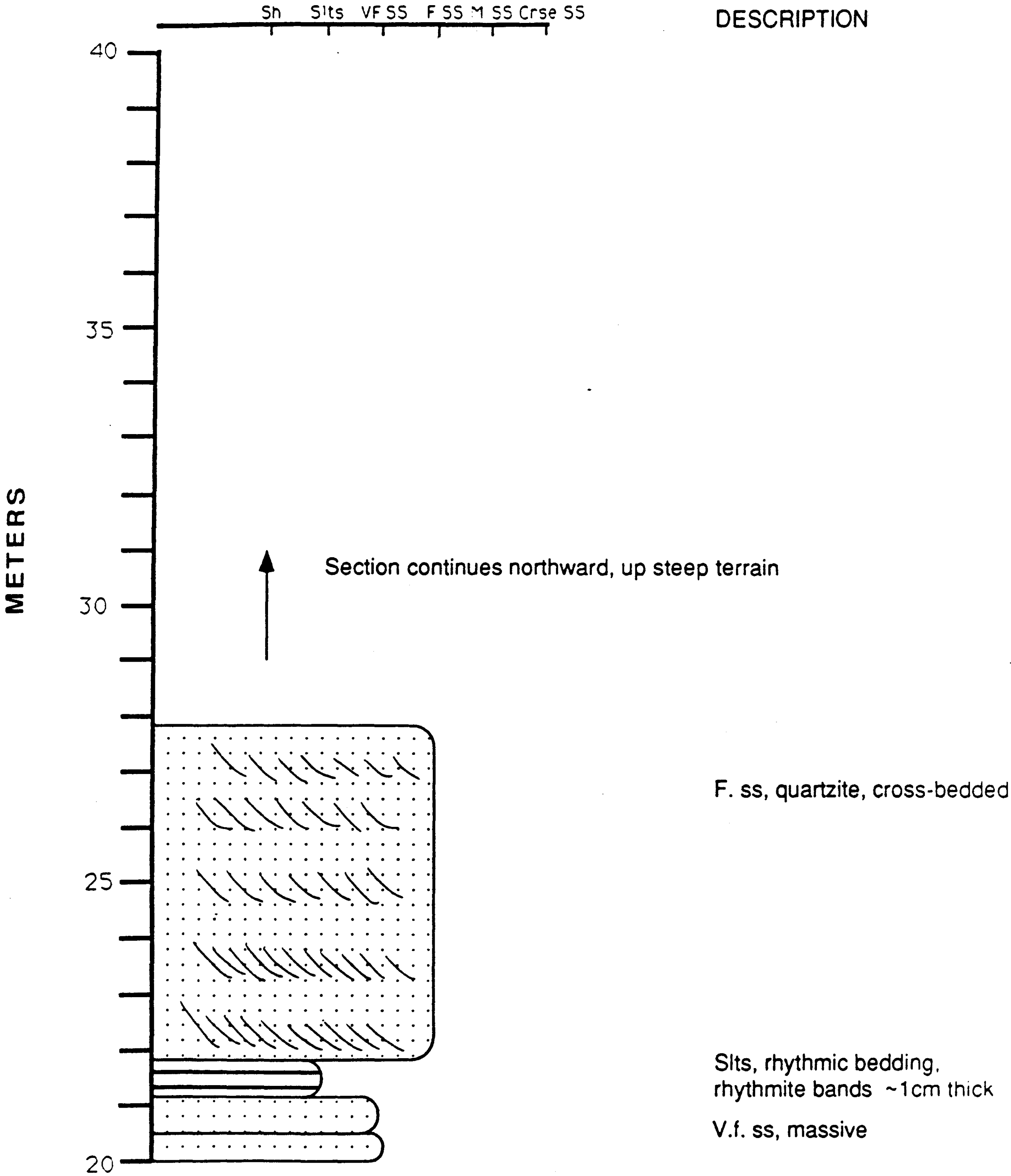
Slts, thin 4-10 cm thick beds. ripples, "pinstripe" laminations

F. ss, quartzite, rip-up clasts at base

Sh, is laterally cut out

F. ss, quartzite

Partial Measured Section, Proterozoic Big Cottonwood Fm.,
Top of "S-curve", Road 152, Sec. 20, T2S, R2E
Locality 91-17



APPENDIX E PALEOCURRENT DATA

Table E-1. Best paleocurrent data from Big Cottonwood, Big Cottonwood Canyon

Note: Although other measurements were taken, including some within the Mutual Formation, these data, though few, represent the best points.

Locality	Original			Description	1st Rotation			2nd Rotation		
(See figure 1)	Bedding	T &	P		Bedding	T &	P	Bedding	T &	P
91-20	345, 72 E	160	13	bidir. ⊥ to rip. crest	26, 38.2 E	131.1	36.6	270, 0 N	308.1	0.6
(Ancient		350	16	bidir. ⊥ to rip. crest		165.4	26.8		338.7	0.3
Sea sign)		130	59	bidir. ⊥ to rip. crest		70.5	27.9		256.9	0.9
91-16	346, 60 E	350	8	bidir. ⊥ to rip. crest	45.6, 35.3 S	158.9	32.5	296.6, 0 N	335.1	0.5
(Stm										
Mt sign)	0, 69 E	125	64	bidir. ⊥ to rip. crest	38.2, 50 E	64.4	26.7	315, 0 N	254.9	0.8
91-13	320, 70 NE	65	69	unidir. x-bed sets	2.1, 16.8 E	45.5	11.4	270, 0 N	226.7	0.3
(dam site		105	57	unidir. x-bed sets		67.0	15.0		247.9	0.3
Stm Mt)										
	330, 60 NE	330	0	bidir. ⊥ to rip. crest	41.3, 21.6 E	138.1	21.5	303.7, 0 N	137.6	0
		48	59	bidir. ⊥ to rip. crest		221.7	0.3		221.6	0.4
	317, 64 NE	335	34	unidir. rip. foresets	17.2, 11.3 E	168.9	4.6	33.7, 0 E	348.6	0.8
	320, 64 NE	330	23	bidir.⊥ to rip.crest	88.8, 18.4 S	157.6	8.1	317.4, 0 E	337.5	9.1
	340, 64 NE	15	49	bidir. ⊥ to rip. crest	36.3, 31 E	201.9	9.0	126.1, 0.2 S	199.3	0.6
91-17	300, 40 N	320	17	unidir. x-bed sets	134.3, 20.4 S	147.2	3.9	191.3, 0 W	327.7	0.8
("S-curve")		330	25	unidir. x-bed sets		159.2	6.9		340	1.9
91-19	340, 76 E	0	53	unidir. x-bed sets	16.3, 36 E	194.8	1.6	287.1, 0 N	194.1	0.4
(Stm Mt										
creek bed)										
91-21	80, 65 N	350	66	bidir. ⊥ to rip. crest	210.9, 40 W	17.9	12.0	135, 0 W	13.3	1
(Moss Ledge)										

Abbreviations:

T & P = Trend and Plunge   Stm Mt=Storm Mountain

bidir. = bidirectional flow indicator which can be in either direction (180 degrees)

unidir. = unidirectional flow indicator which indicates one dominant flow direction

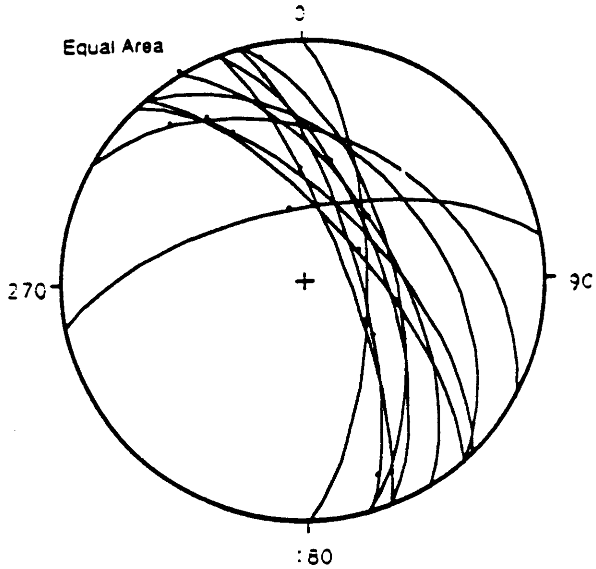
⊥ = perpendicular   x-bed = cross-bed   rip.= ripple

On rotations: From this data of measured beddings, assume a anticlinal fold axis is ~ 35 (trend), 60 (plunge)

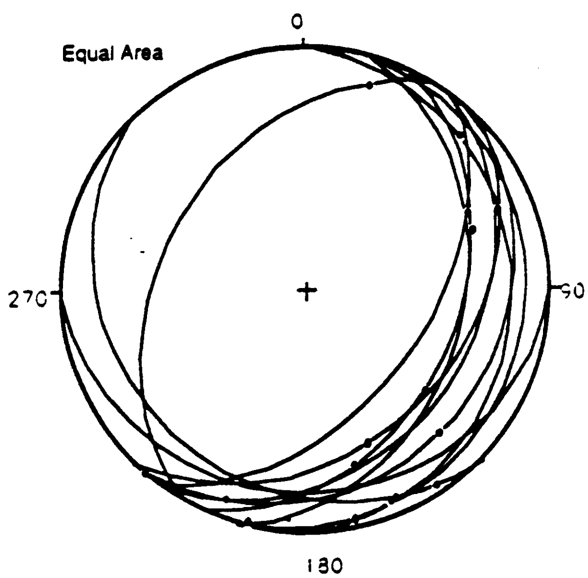
First rotation: 125 (azimuth), 0 (plunge), 60 (degrees)

Second rotation brings limbs of anticline fold up to horizontal

Stereonet Plots of Big Cottonwood Data from Table E-1.

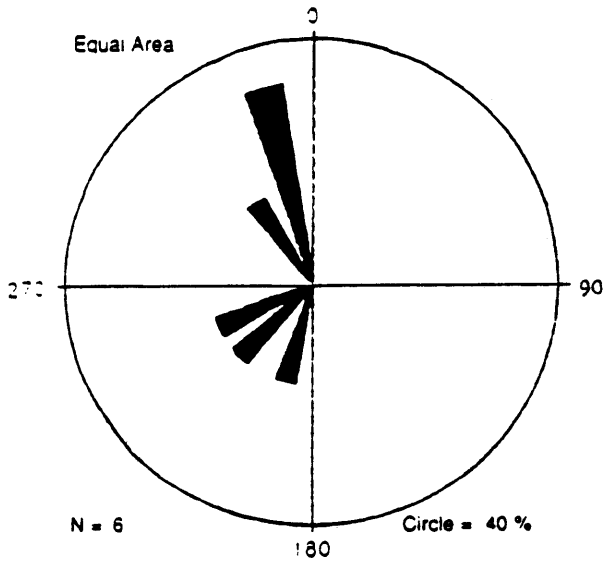


A. Original bedding plane attitudes (uncorrected) with small points representing paleocurrent measurements within beds (big circles). Fold axis is at about a trend and plunge of 35° and 60° respectively.

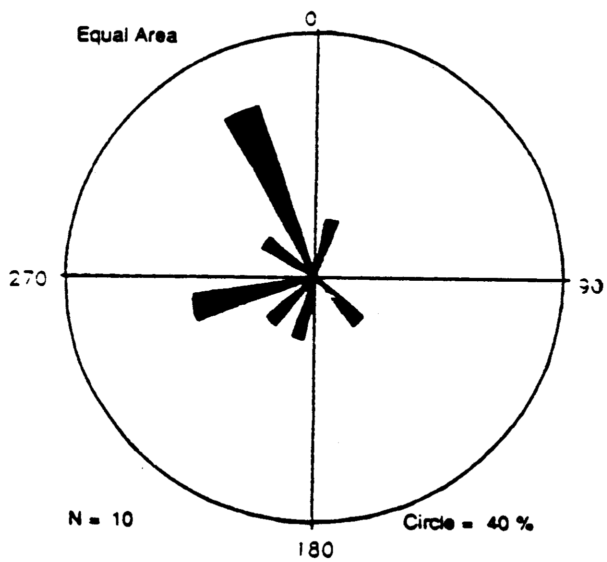


B. First rotation of beds and paleocurrent measurements from A.. about a fold axis 125° azimuth (35° +90°) and 60° rotation.

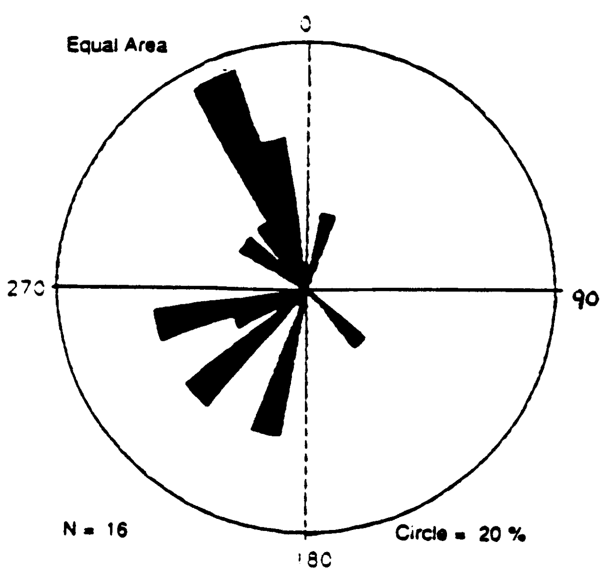
Rose Diagrams of Big Cottonwood Data from Table E-1



C. **Unidirectional paleocurrent measurements** (e.g., cross-bed sets) after a second rotation (unfolding limbs of anticline). The largest petal (33%) is between 340°-350°, with a mean vector at 283°.



D. **Bidirectional paleocurrent measurements** (flow direction perpendicular to ripple crests) after a second rotation (unfolding limbs of anticline). The largest petal (33%) is between 330°-340°, with a mean vector at 290°.



E. **All paleocurrent measurements** (combined unidirectional and bidirectional data of C. and E.). The largest petal (33%) is between 330°-340°, with a mean vector at 287°.