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The Stratigraphy and Sedimentology of the Middle Proterozoic Grinnell Formation, Glacier National Park and the Whitefish Range, NW Montana

By

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Approved by

Don Winston

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The Stratigraphy and Sedimentology of the Middle Proterozoic Grinnell Formation, Glacier National Park and the Whitefish Range, NW Montana

Director: Don Winston

The Grinnell Formation, in Glacier National Park and the Whitefish Range is a bright red argillite with interbeds of white quartzarenite. Stratigraphic sections were measured at three localities in Glacier National Park, and one in the Whitefish Range. Six principal sediment types described from these sections, are arranged in a stratigraphic framework composed of five lithostratigraphic units, which are correlated across Glacier National Park into the Whitefish Range. From the lateral continuity of these units and from process interpretations of the sediment types, the following depositional model is proposed.

Unconfined, episodic sheetfloods carried coarse sand (medium- to coarse-grained sand sediment type) from the southeast across broad, distal sand and mudflats. The coarse sand thins and fines from Glacier National Park westward into the Whitefish Range. Similar sheetfloods from the southwest carried fine sand, silt and clay northeastward across the sand and mudflats and interstratified their fine sediments with the coarse sand. Flood deposits from the southwestern source fine and thin distally across the sandflats, passing from the very fine- to fine-grained sand sediment type to the flat-laminated silt sediment type. Floods crossing the exposed mudflats deposited thin silt layers, which graded up to clay (silt to clay couplet sediment type) as the lake waters expanded across the flats in response to flooding. Clay of the resulting silt to clay couplets was desiccated and cracked as the lake level subsided. Floods reaching the lake formed sediment plumes, which deposited graded silt to clay couplets that were not desiccation cracked. Deposits of suspension plumes thinned in distal, restricted areas to millimeter-scale silt to clay laminae of the microlamina sediment type. Some suspended sediments that reached Glacier National Park were mostly clay, and, upon repeated desiccation, formed the disrupted desiccated mud sediment type.

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Acknowledgments

I would like to dedicate this work to Patricia J. Kuhn, an educator in the Maryland Public School system for over 25 years who died in 1982. Her enthusiasm for education and her love for her students will always be a model for me.

My thanks to Don Winston for his unending enthusiasm for the Belt Basin, many enlightening talks, his to ability to frail and sing "Nine Pound Hammer" around a campfire, and especially his careful review of this manuscript.

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Special thanks to fellow Belt workers Chris Cronin and Marvin Woods, whose interaction and constant input were greatly appreciated. Also, my thanks to shirpa Seth Brandenberger, Clyde Lockwood of the the National Park Service for providing maps, and the encouragement of many friends in Glacier Park.

Finally, my thanks to Linda Young, whose moral support and love of Glacier Park, have carried me through many difficult moments.

Chapter 1

Introduction

The Grinnell Formation in Glacier National Park and the Whitefish Range (Fig. 1-1) consists of bright red to purple argillite with green argillite interbeds and white to brown, hematitic, cross-bedded quartz arenite beds, particularly near the top of the formation. It is commonly recognized as continuous red outcrops along the eastern edge of the Lewis Overthrust with spectacular outcrops in the Two Medicine area and in the Many Glacier area in Glacier National Park. The Grinnell was named by Baily Willis (1902) with its type locality at Mt. Grinnell which draws its name from famed naturalist, writer, and Glacier Park promoter, George Bird Grinnell.

Although stratigraphic and sedimentologic investigations of the Grinnell Formation by Fenton and Fenton (1937), Horodyski (1983), Conner (1984), Whipple et al. (1984), Earhart et al. (1984), Smith (1963), and Barnes (1963) have provided significant information, no detailed sedimentologic study of the Grinnell has been undertaken. Furthermore, a lack of detailed stratigraphic sections from the east side of the Belt Basin, has hindered correlations within the Ravalli Group across the basin to the west.

The purposes of this study are three fold: 1) To correlate stratigraphic sections in Glacier Park and the Whitefish Range; 2) Examine facies relationships in these sections and interpret the sedimentology; 3) To search for the provenance of

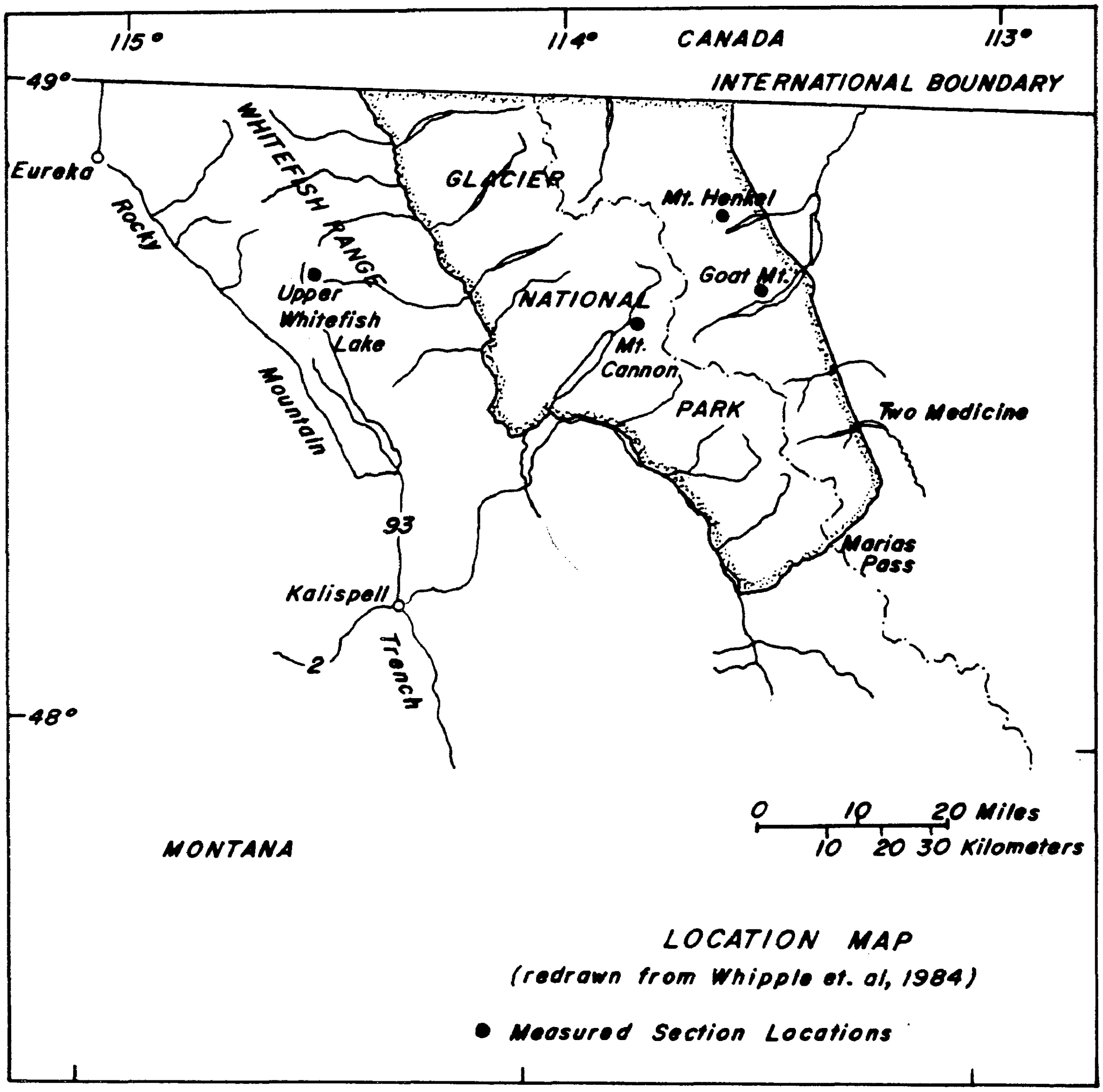

Figure 1-1: Location Map.
Glacier National Park and the Whitefish Range in northwest Montana. Measured sections are denoted by dots. Redrawn from Whipple et al., 1984.

the Grinnell, using paleocurrent analysis and relate paleocurrent directions to the depositional environment of the Grinnell.

Three stratigraphic sections were measured in Glacier National Park and one section in the Whitefish Range. These sections were chosen to provide correlation from the east side of Glacier Park to the west side and into the Whitefish Range. From there, sections measured by Christopher Cronin (University of Montana) in the Mission, Swan, and Flathead Ranges are used for further comparison of facies changes south from Glacier Park and the Whitefish Range.

Based on data gathered from stratigraphic sections, I constructed a sedimentologic framework based on "sediment types". The dominance of a particular sediment type through large stratigraphic intervals, led to the recognition of lithostratigraphic units. Although these units are most clearly defined on the east side of Glacier Park, they can be correlated to other stratigraphic sections in this study to the west.

Based on stratigraphic continuity of the above units across Glacier Park to the Whitefish Range, sedimentologic data, and paleocurrent analysis, I believe that deposition of sediment in the Grinnell Formation reflects episodic sheetfloods which carried medium- to coarse-grained sand across a distal alluvial sand and mud flat bordering a shallow, enclosed or restricted sea. Whether this sea is marine or lacustrine in origin could not be determined from the results of this study alone. However, preliminary results of work to the south and west of Glacier Park and the Whitefish Range (Christopher Cronin, Don Winston, University of Montana, 1986), indicate a lacustrine setting for Ravalli Level rocks to the west.

1.1. Regional Stratigraphic Setting

The thick sedimentary sequence of the Belt Supergroup was deposited in a northwesterly trending basin between approximately 1450–850 million years ago (Winston, 1986a; Harrison, 1972; Smith and Barnes, 1966). The Belt Basin presently occupies eastern Washington, northern Idaho, western Montana, and southern Canada where it is known as the Purcell Basin. Smith and Barnes (1966) deliniated four major stratigraphic subdivisions: the lower Belt, the Ravalli Group, the Middle Belt Carbonate, and the Missoula Group. In the western part of the Belt Basin, the Ravalli Group consist of the Burke, Revett, and the St. Regis formations (Fig. 1–2).

In Glacier Park, the Appekunny, Grinnell, and Empire formations (Whipple et al. 1984) have been assigned to the Ravalli Group (Fig. 1–2). However, Harrison (1972) synonomized the Grinnell Formation with the Spokane Formation, recognizing Walcott's type locality from the Spokane Hills (Walcott, 1899) and used the name Grinnell for rocks near Fernie, B.C. and in the Whitefish Range. Mudge (1977) agreed with Harrison's correlation but synonomized the Greyson with the Appekunny. Harrison (1972) had previously used the name Greyson for these rocks south of Glacier Park to Helena and Butte, Montana. More recent correlations by Cronin, Kuhn and Winston (1986) correlate the uppermost Appekunny and the whole of the Grinnell of Glacier Park, with the Burke, Revett, and St. Regis of the Coeur d'Alene district (Fig. 1–3).

Of these formations the Grinnell is characterized by medium to coarse, quartz arenite, sharply interbedded with red and green argillite. It varies considerably in thickness in Glacier National Park, the Flathead Region, and the

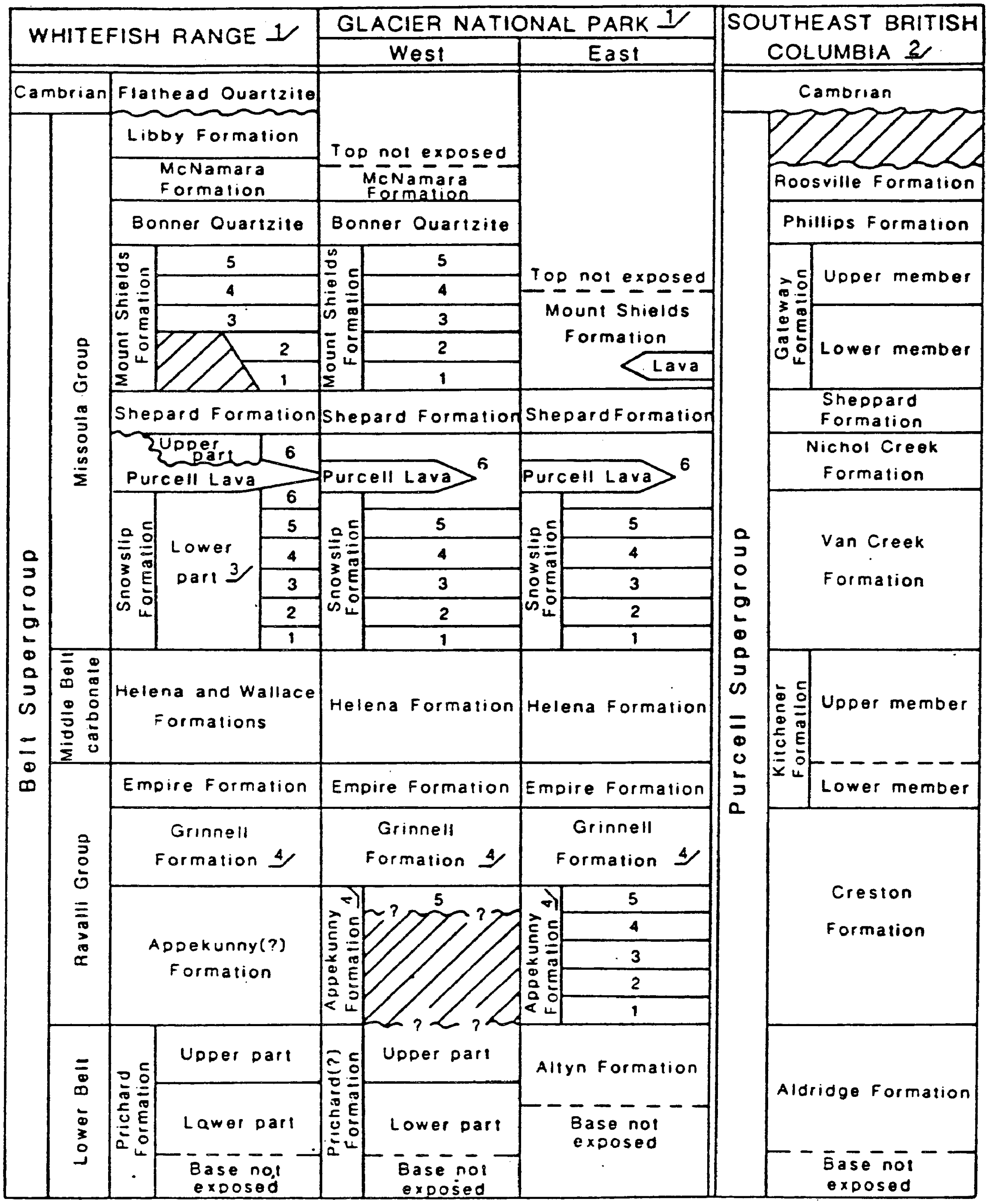

Figure 1-2: General Belt Stratigraphy; Whipple et al., 1984.

Whitefish Range. Willis (1902) estimated the Grinnell to be between 1000 to 1800 feet thick in the northeastern part of Glacier Park. Corbett and Williams (in Ross, 1959, p. 32) found the Grinnell north of Cosley Lake to be 1,361 feet thick. Fenton and Fenton (1937, p. 1887), working throughout the whole of Glacier Park, measured thicknesses of 1500-3500 feet. They failed to recognize imbricate faults which caused unusual thickening of some sections. Dyson (1949, p. 7) found more than 3000 feet in several places. Erdmann (1947, p. 130) measured the Grinnell in Bad Rock Canyon, west of Glacier Park near the present Hungry Horse Dam, and found the Grinnell to be 2400 feet thick. Ross (1959) noted exceptionally thick sections of 4000-5000 feet in the Swan Range, thinning northward into the Flathead Range. He estimated the whole formation in the southern part of Glacier National Park to be about 2000 feet thick. Childers (1963) calculated a thickness of 2400 feet for the Grinnell at Marias Pass in southern Glacier Park. Whipple et al., (1984) found that the Grinnell in the central Whitefish Range thickens to about 3,500 feet. Measured sections in this study showed the Grinnell in Glacier Park to be 1850-2150 feet thick. An incomplete section (3,300 feet, this report) measured in the Whitefish Range probably exceeds 4000 feet (Whipple, 1986, personal comm.).

South of Glacier Park, in the Helena salient, the Spokane Formation probably occupies the position of the Ravalli Group. The name Spokane was named for red argillite from the type locality in the Spokane Hills described by Walcott (1899). Although Harrison (1972) and Godlewski and Zieg (1984) correlate the Spokane with only the St. Regis to the west, Winston (1986a) argues that the Spokane, comprises

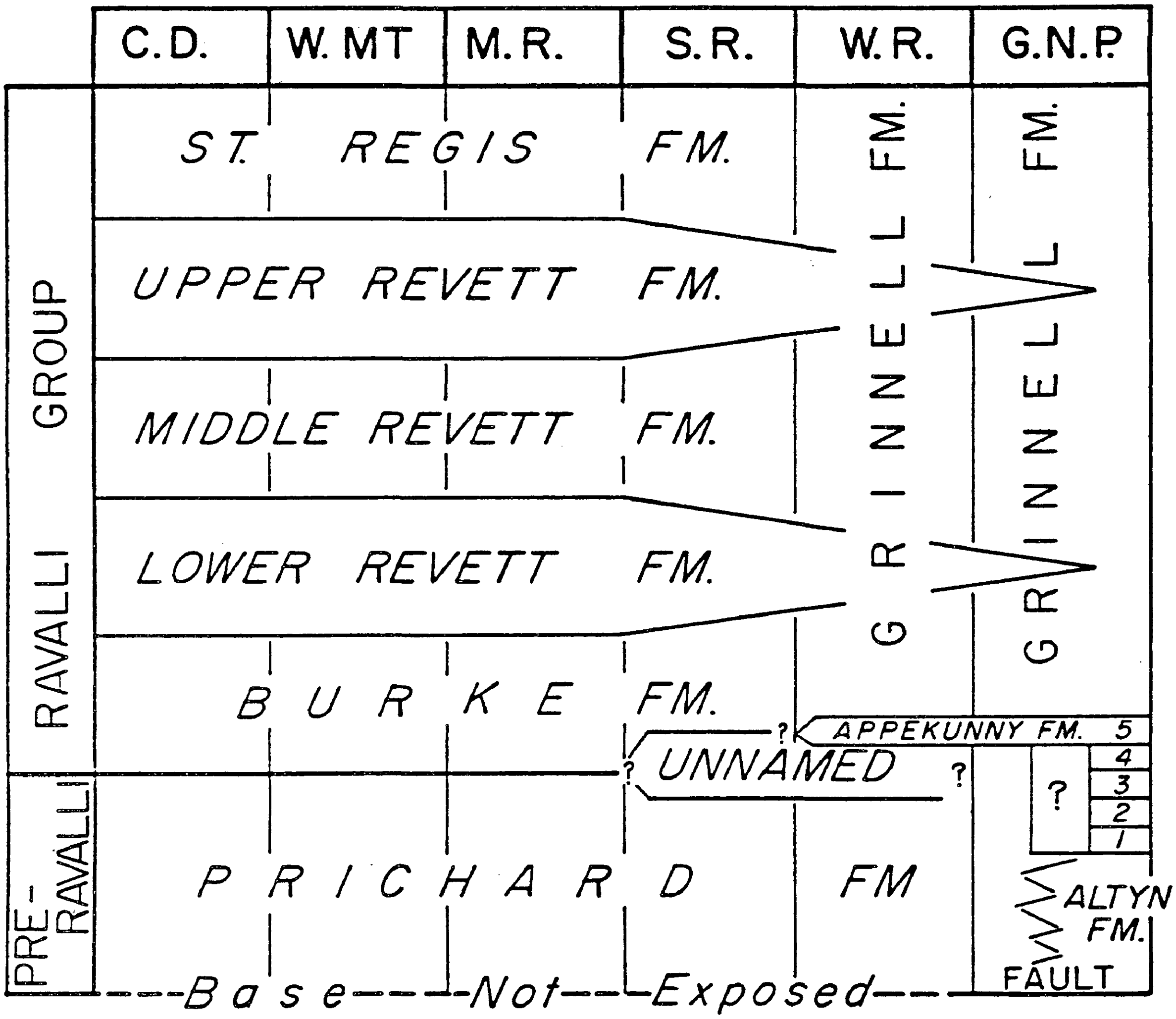

Figure 1-3: Ravalli Group Stratigraphy; Cronin, Kuhn and Winston, 1986.
C.D.: Coeur d'Alene District, W.MT.: western Montana, M.R.: Mission Range, S.R.: Swan Range, W.R.: Whitefish Range, G.N.P.: Glacier National Park.

the Ravalli Level rocks of the Helena Embayment and southern Belt Basin and passes laterally westward into the Burke, Revett, and St. Regis formations. In addition, Winston (1986a) suggests that coarse siltite beds low in the Spokane (Conner, 1982) may represent eastern tongues of the Revett Formation which are lost in other correlations as they pass eastward. Although Harrison (1972) suppressed the name Grinnell in favor of its southern correlative, the Spokane Formation, the U.S. Geological Survey now retains the name Grinnell for Glacier Park only (Harrison, 1986, personal comm.).

Clearly, correlation within the Ravalli Group across the Belt Basin has warranted further study. Stratigraphic clarification and detailed sedimentologic interpretation of the Grinnell are important Belt problems and form the basis of this study of the Grinnell Formation in Glacier National Park and the Whitefish Range.

1.2. Structural Overview

Glacier National Park and the Whitefish Range lie within the eastern Late Cretaceous to Paleocene thrust belt of northwestern Montana (Winston, 1986d). Although most of the disturbed belt is characterized by a long history of deformation, Belt rocks in Glacier National Park lie on the relatively undeformed Lewis Plate and have undergone only very low grade, greenschist facies metamorphism. As a whole, the Lewis Plate is structurally intact and forms a northwesterly trending, doubly plunging syncline. The Whitefish Range is structurally separated from Glacier Park by the northwest trending Flathead Fault (Fig. 1-4) and possibly by a thrust fault (Constaneous, 1981).

Late Cretaceous to Paleocene thrust faulting was followed throughout the disturbed belt by longitudinal normal faulting, represented by listric normal faults (Mudge, 1970). One such fault, the northwest trending Flathead Fault, splays southward into the Blacktail, Roosevelt, and Nyack faults. Faults with similar trends, west of Glacier Park, make up the Rocky Mountain Trench and Purcell Anticlinorium (Price and Kluuver, 1974). Extentional block faulting has continued through the Cenozoic (Harrison et al., 1980; Harrison, 1974; Mudge, 1970, 1977; Mudge et al., 1977).

Recent mapping along the Lewis Thrust (Gregory Davis, personal comm., 1985) has revealed numerous stacked imbricate thrust sheets, particularly in the zone of the Lewis thrust, which greatly complicate the simplified map of Ross (1959). However, structurally uncomplicated sections were chosen west of the Lewis thrust to avoid stratigraphic repetition. Recognition of the five members of the Appekunny Formation (Whipple et al., 1984) help identify imbricate thrust sheets along the Lewis Thrust in Glacier Park (personal comm., Jim Whipple, July, 1985) and were important in distinguishing the base of the Grinnell at the Goat Mountain section where imbricate thrusting causes an appreciable amount of thickening. Translation along the Lewis Thrust is estimated at between 24 km (15 mi) and 64.4 km (40 mi) (Mudge, 1970, 1977; Price and Kluuver, 1974).

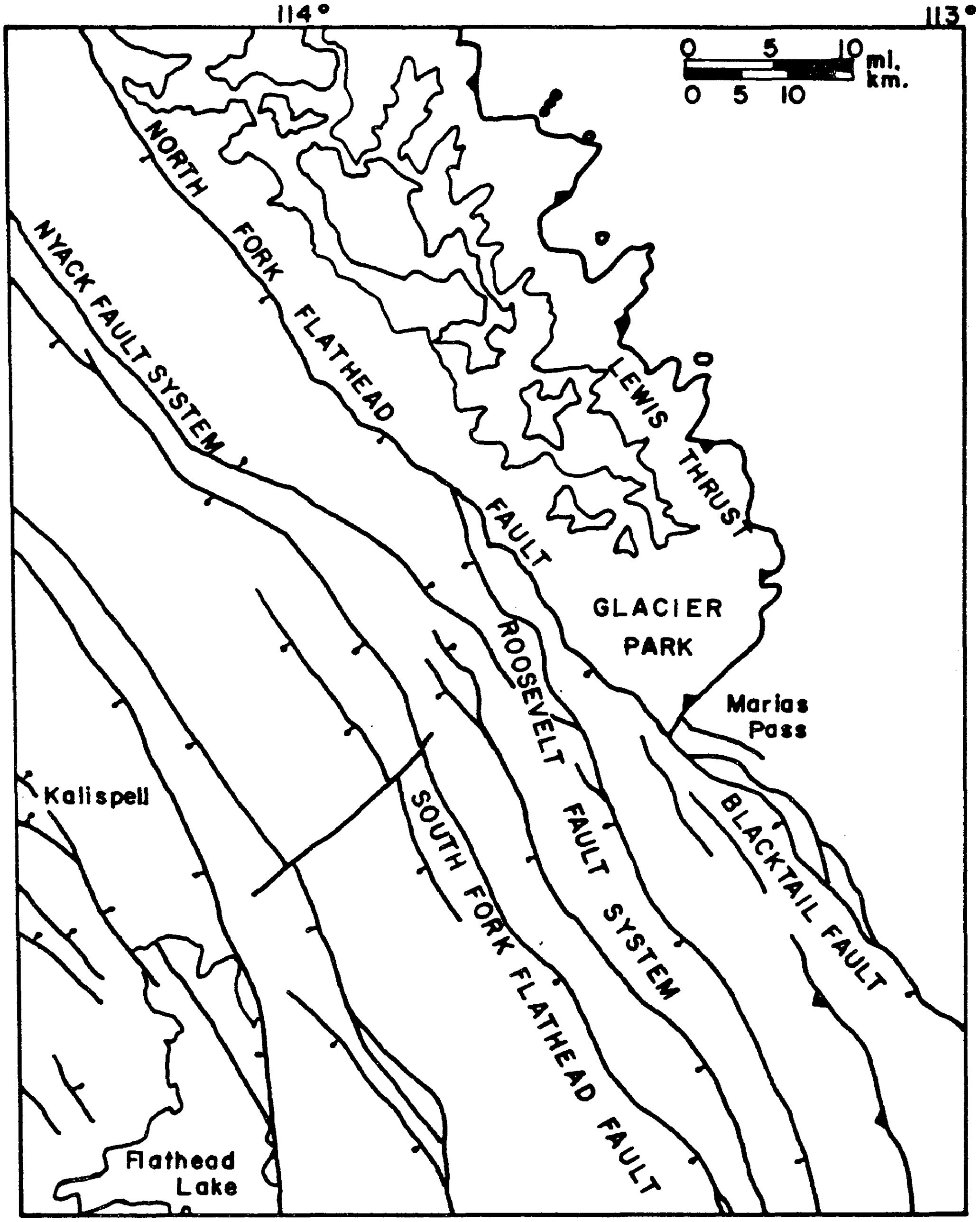

Figure 1-4: General Structure after Mudge, 1970 and Constaneous, 1981.

1.3. Stratigraphic Boundaries of the Grinnell

The boundaries of the Grinnell Formation are generally transitional with the Appekunny Formation below and the Empire Formation above, throughout the Flathead and Swan Ranges (Ross, 1959). In Glacier National Park and the Whitefish Range (this study), the Appekunny-Grinnell boundary is transitional but the Grinnell-Empire boundary is very sharp at most localities. The Appekunny-Grinnell contact was placed where bright green mudcracked argillite and finely coupleted argillite of Appekunny member 5 (Whipple et al., 1984, p. 39), passes upward to dominantly mudcracked red argillite (Willis, 1902; Ross, 1959). Sharp contacts between the Grinnell and the Empire formations were recorded at Mt. Henkel and in the Whitefish Range sections and in a section measured near Grinnell Glacier with Jim Whipple and Omar Raup in August, 1985. At Mt. Henkel and at Grinnell Glacier, as well as a section reconnoitered at Sperry Glacier, a clean quartz arenite bed, stained bright orange by limonite altering from oolitic pyrite, marks the base of the Empire Formation.

1.4. Previous Work

Willis (1902) first defined the Grinnell Formation in Glacier National Park as follows:

> "A mass of red rocks of predominantly shaley argillaceous character is termed the Grinnell argillite from its characteristic occurrence with a thickness of about 1800 ft. in Mt. Grinnell."

Willis observed ripple marks and mudcracks and "the irregular surfaces of shallow water deposits" in the Grinnell, and compared these characteristics to rocks of the Devonian Chemung and Catskill formations in New York. Barrell (1906, p. 566) proposed that some of the formations of Glacier Park might indicate "subaerial origin by river aggradation." This was reiterated by Daly (1912, p.83) who believed it also explained the origin of the Kintla Formation of the Missoula Group and "possibly a limited thickness of Grinnell and Appekunny beds." Calkins (Emmons and Calkins, 1913, p. 34) regarded the correlative Spokane Formation as flood plain in origin, but assigned other Belt formations to marine or estuarine sedimentation.

Fenton and Fenton (1937) showed great insight in interpreting ripple bedforms as the result of wave oscillation, and distinquished between subaerial desiccation cracks commonly seen in the Grinnell, and subaqueous or syneresis cracks characteristic of the Appekunny Formation. In addition, they recognized that most of the mudchips, so common in the Grinnell and other Belt Formations, were reworked mudcracked polygons. On the basis of color, sedimentary structures, stromatolitic biostromes, and other supposed "fossils", Fenton and Fenton (1937) supported a marine interpretation for the Belt Basin. Winston (1986b, p. 114-119) points out that pseudofossils (Cloud, 1968) and most criteria cited as marine indicators are now equally well known from lakes and lake deposits.

Ross (1959) mapped the Grinnell Formation in Glacier National Park, and described its character and thickness in the Park as well as in the Flathead and Swan Ranges. He also provided some of the first photomicrographs of Grinnell rocks and described original compositions as ranging from a siliceous mudstone or siltstone to a somewhat arkosic sandstone.

Smith (1963) and Barnes (1963) working in the Whitefish Range, extensively mapped and observed Belt formations and described detailed stratigraphic and sedimentologic changes in the Grinnell. They suggest two source areas for the Grinnell: an eastern source providing material for the white quartzarenites, and a western source providing the bulk of the material in the Grinnell Formation and its correlatives. Smith (1963, p. 38) was particularly impressed by the coarse-grained quartzarenites of the Grinnell:

> "Although in any single exposure, the coarse grained Grinnell quartzites,...incorporate mudchips from the underlying siltstone layer, and commonly show excellent cross bedding, only minor channeling is present, as if rather than being distributed in seperate, well defined channels, each bed had been spread as a more or less continuous sheet across a preexisting mudcracked surface".

Barnes (1963, p. 54) also noted the lack of channeling throughout the Belt:

> "There is little or no evidence of channeling in Belt rocks, and the extensive mud cracking would seem to indicate that diurnal tides did not exist".

Both authors interpreted the Belt Basin to have been lacustrine and Smith (1963) uses the Green River Formation as an analogous depositional environment to the Belt. Their interpretations were quite significant in that they refuted the Fentons' marine interpretation for the Belt.

McMechan (1981), working in the Purcell Supergroup in British Columbia and Alberta, also provided detailed stratigraphic and sedimentologic data for the Creston Formation, correlative with the Grinnell and Appekunny formations of Glacier National Park. Members C-3, C-4, and C-5 of the Creston, contain siltite, argillite couplets and tabular lenses of white, fine-to coarse-grained quartz arenite which she (1981, p. 597) interpreted as "the fill of a migrating network of broad tidal channels". It appears that these three members correlate with the Grinnell Formation to the south in Glacier Park. McMechan also found that the coarse-grained siltite of the C-4 member thinned eastward from the Moyie Lake area, and suggested a western or southwestern source area. On this basis, she argued that these and similar coarse grained siltites of member C-4 from other areas, represented distal fine grained tongues of the Revett Formation (Harrison, 1972).

Although Harrison (1972) proposed a marine interpretation for the Belt, Winston (1986b) and Winston et al., (1984) interpret the Belt as an intracratonic, enclosed basin having an environment analogous to that which formed the Green River Formation. Horodyski (1983, p.402) interpreted the upper sandy unit of the Grinnell Formation as alluvial plain deposits transected by ephemeral braided or anastomosing streams, subject to periodic sheet floods. In this model "the middle red argillite (Fenton's Red Gap Member) would represent a more distal or peripheral facies than the upper sandy unit, and other units might represent marginal facies developed where the alluvial plain merged with a presumably marine body of water" (Horodyski, 1983, p. 402). Whipple et al. (1984, p. 33) also state that the Grinnell is in part a fluvial facies.

Working in the western part of the Belt Basin, White et al. (1977) and White and Winston (1982) interpreted the quartzite wedge of the Revett in the Coeur d'Alene District as a vast alluvial fan sequence dominated by braided stream and sheetflood deposition on a northeasterly paleoslope. Although Bowden (1977) and Mauk (1983) both interpreted the Revett as a deltaic marine sequence, Alleman

(1983) interpreted the Revett to have formed in an alluvial sheetflood environment. The overlying St. Regis records the return to mudflat deposition (Winston, 1986b, p. 88).

This study interprets in detail the sedimentary environments of the Grinnell by constructing a sedimentologic classification based on sediment types. These in turn comprise lithostratigraphic units which are correlated between stratigraphic sections through Glacier National Park and into the Whitefish Range. The interpretations of individual sediment types are combined with the stratigraphic framework provided by the lithostratigraphic units to provide a depositional model for the Grinnell Formation.

Chapter 2

SEDIMENT TYPES

2.1. Introduction

According to Winston (1986b, p.89), previous rock type terminology used to describe Belt rocks has the following inherent problems:

> 1. "Rock types, as they have been applied, are mostly thick, often mappable units of rock which record a variety of sedimentary processes and environments; they are not appropriate for sedimentary description and interpretation at a detailed scale;
> 2. Some rock types are defined largely by aspects resulting from diagenetic processes which do not necessarily coincide with sedimentologic processes; rock color is one of these aspects.
> 3. Metamorphism has also been incorporated in the rock terminology with confusing results."

To reconcile these problems Winston (1986b) described thirteen sediment types applicable to Belt rocks, which describe prediagenetic and premetamorphic sedimentary textures, structures and composition at a detailed scale. Six sediment types are recognized in the Grinnell:

1. Medium- to coarse-grained sand
2. Very fine- to fine-grained sand
3. Flat- laminated silt
4. Desiccated mud

5. Silt to clay couplet
6. Microlamina

Of these, the microlamina sediment type has been described by Winston (1986b,d) and by Woods (1986). The couplet sediment type combines the even and lenticular sediment types of Winston, and the desiccated mud, flat-laminated silt, very fine-to fine-grained sand, and medium-to coarse-grained sand sediment types, are new.

2.2. Discussion

The term "quartzite", as discussed by Winston (1986b), conveys the idea of a tightly cemented quartz sandstone. However, most Belt quartzite, including quartzite in the Grinnell, contains up to 10% feldspar or its altered products, and varies from very tightly quartz cemented feldspathic quartz sandstone, to partly carbonate cemented quartz sandstone. I will use the term "quartzarenite" to avoid genetic interpretations attached to "quartzite" and to encompass varying degrees and kinds of diagenetic cementation.

Because of the confusion resulting from rock type terminology; argillite, siltite, quartzite (Harrison and Campbell, 1963), this study will use the sediment type terminology for sedimentary description, leaving rock description to describe gross lithology.

2.2.1. Medium- to Coarse-Grained Sand Sediment Type

Description

This sediment type lends to the Grinnell Formation its character in the field. It forms continuous beds of white quartzarenite that stand out in relief from the red argillite groundmass of the Grinnell. Medium- to coarse sand ranges from moderate- to well-sorted, to bimodally sorted sand and mud. It is generally subrounded- to well-rounded, white to brownish, siderite and quartz cemented, feldspathic quartz sand, that forms even, tabular beds, which extend for more than 1km across outcrops with little change in thickness. Individual beds with sharp, scoured bases and sharp tops range from 2cm to 1m thick (Fig. 2-1). They occur in sequences up to tens of meters thick interstratified with desiccated mud, rare silt to clay couplets, flat-laminated silt, and rare, thin beds of very fine- to fine-grained sand (Fig. 2-2). Fining or coarsening upward sequences are absent. Mudchips, accreted mudballs (up to 10cm in diameter) built of accreted mudchips, and pelloidal mud and clay are common in the basal portions of most beds and occur throughout the entire thickness of some beds. Mudchips occasionally form small lag concentrations in shallow depressions. Reactivation surfaces which truncate foreset laminae are generally rare but occur locally in some beds, and are defined by discrete, thin mud drapes. More common erosional scours truncate stoss sides of small and large scale ripples. Bipolar cross-beds occur locally in some beds as tabular sets separated by thin mud drapes and less commonly as sets directly deposited on one another. Wavy and lenticular bedding are also common, however flaser bedding was not observed.

Flat-laminated beds containing numerous mudchips and mudballs comprise the basal portions of many medium-to coarse-grained sand beds. These commonly pass upward to unidirectional planar, tangential and trough cross-beds. Large mudchips and mudballs decrease upward. Foresets are generally well expressed by imbricated mud chips, very thin clay drapes which are only rarely mudcracked, hematite staining or heavy mineral lags. Planed-off ripples were rarely observed but noteably occurred at the tops of medium-to coarse-grained sand beds capped by the desiccated mud sediment type. Straight-crested, bifurcating, symmetric ripples with internal unidirectional cross-beds commonly occur at tops of sand beds and are capped by the desiccated mud sediment type and less commonly by the silt to clay sediment type (Fig. 2-3 and 2-4).

Interpretation

The plane beds, common in the basal portions of medium- to coarse-grained sand sediment type are attributed to upper regime flow conditions. This interpretation is well supported by experimental studies of high flow velocities in water depths up to 1m (Southard, 1971; Simons, et al., 1965; Harms et al., 1982). In addition, plane bed phase boundaries were obtained for flows deeper than 1m in medium grained sand, 0.35-0.60mm in diameter, by Rubin and McCulloch (1980) (Fig. 2-5). Although depth and velocity of flow in the Grinnell can only be approximated, flows deeper than 1m would plot well within the upper flat bed field of Rubin and McCulloch's diagram (Fig. 2-5). Wavy bedding (up to 1m in wavelength) on an outcrop scale may record antidunes formed at higher flow velocities and may be similar to those observed in ephemeral floods by Rahn (1967).

The transition from upper regime plane beds to lower regime large scale bedforms, indicates an upward decrease in current velocity within continuous flow. This interpretation is supported by the studies of Costello and Southard (1981), who defined bed phases for coarse sands (0.4–1.0cm in diameter) in the lower flow regime and found that stability fields for the various phases could be plotted in a graph of mean velocity versus sediment size (Fig. 2–6) for constant flow depth (15cm). Over a wide range of low velocities, ripples constituted the most stable bed configuration. Costello and Southard (1981) also found that a fairly consistent transition zone between regular straight-crested and sinuous-crested large ripples could be drawn over a wide range of flow depths from less than .1m to more than 10m. The continuum of bedforms predicted under waning flow conditions in Fig. 2–5 (Rubin and McCulloch, 1980), is reflected in the decrease in scale of cross-beds in the Grinnell.

Wind wave reworking of bedforms in ponded water formed rounded, symmetric ripple crests and small symmetric, oscillation ripples with unidirectional foresets and was followed by suspension sedimentation of silt and clay. Their distinct presence at the top of beds separating large scale cross-bedded sand from overlying silt or mud beds, and their presence as isolated ripple trains in mud, provide further support for cessation of flow followed by wave oscillation of ponded waters before suspension sedimentation. Planed off ripples near the tops of some sand beds, also indicate rapidly falling water level.

By combining the sedimentologic interpretation gleaned from the vertical sequence of sedimentary structures with the flat tabular bedding of the sediment type, one may propose the following depositional interpretation. The medium- to coarse-sand sediment type was deposited by floods in upper regime flow which carried medium- to coarse-grained sand across sand and mud flats which incorporated mudchips from previous mudcracked polygons, formed accreted mudballs, and deposited sand in cross-bedded and flat-laminated beds (upper plane bed). Horodyski (personal communication, 1986) suggests that lateral tracking of very broad depositional lobes of medium- to coarse-grained sand across desiccated mud flats in the Grinnell occurred in response to variations in topography, and might explain sharply interbedded sand/mud sequences. Sand-sized material was transported as bedload and finer material as suspension load. As current velocity decreased, flow shifted to the lower flow regime, forming straight- to sinuous-crested large ripples that migrated over the sediment surface to produce tabular sets of planar, tangential, and trough cross-beds. After the floods passed, extensive flat surfaces were dotted by ponds and suspended sediments were deposited as silt to clay couplets and microlaminae.

Cut reactivation surfaces (McCabe and Jones, 1977) formed locally as flow changed directions, scouring into lee faces of large and small-scale straight-crested and lunate ripples. Stoss-side erosion occurred as straight- to sinuous-crested large ripples scoured into previously deposited bedforms. Mud drapes which commonly define reactivation surfaces and separate tabular sets of large scale cross-beds, indicate suspension settle out following deposition of medium to coarse sand. Erosional scours from unidirectional currents are unlike reactivation sufaces and appear to represent reworking of bedforms by waning flow. Similar scouring occurs in rapidly shallowing flows where flow regime increases to form trough cross-beds which scour into preceeding bedforms (Harms et al., 1982). Locally bipolar cross-beds formed in response to a change in flow direction. Bipolar cross-bedding is not exclusive of tidal sequences but also forms in fluvial sequences as well (Williams, 1971).

Examples of meter scale tabular sheets of cross-bedded sand sharply interbedded with mud, are not known from marine or lacustrine systems. Coarse cross-bedded sand at the head of the Gulf of California occurs in the tidal channels rather than on the flats (see Thompson, 1968, 1975). However, similar deposits containing tabular sheets of cross-bedded sand sharply interbedded with mud, are documented from alluvial and ephemeral stream deposits (Tunbridge, 1981; McKee et al., 1967; Williams, 1971).

Friend (1978) described fluvial sandstones from the Devonian which are similar to these sand beds and show 1) unimodal paleocurrent trends, 2) downstream decrease in grain size and thickness, 3) downstream decrease in cross strata thickness, 4) downstream increase in silt, small scale stratification and flat bedding and 5) planar, laterally extensive bedding without channels. Laterally extensive sandstone sheets, 10 to 150cm thick with sharp bases and unimodal cross-beds occur in Carboniferous beds of the Ebro Basin in Spain and are interpreted as sheet flood deposits which formed at the distal margin of an alluvial fan (Heward, 1978).

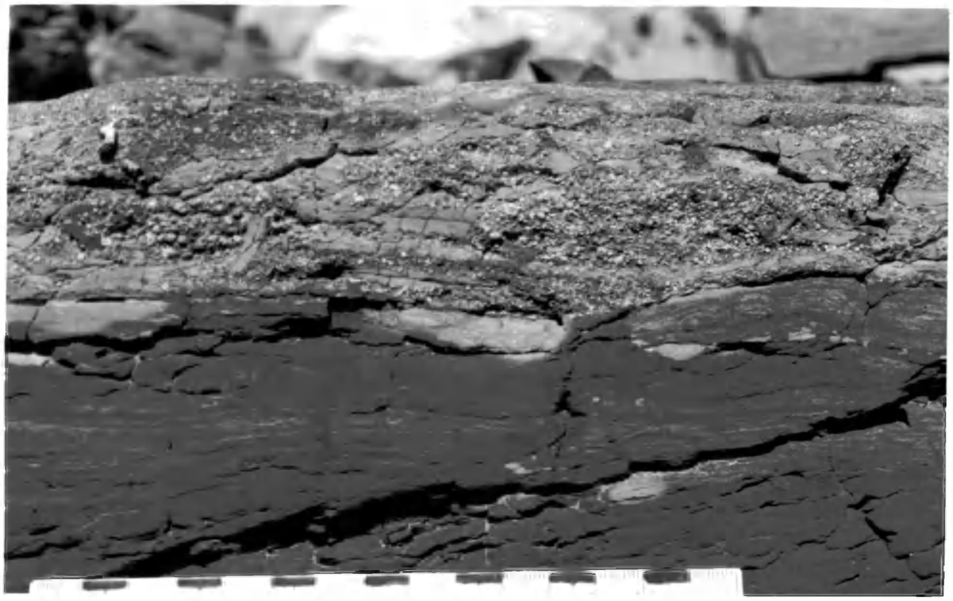

Figure 2-1: Medium- to coarse-grained sand sediment type.
Flat-laminated and cross-bedded, feldspathic quartzarenite. Bed contains numerous mudchips and is in sharp contact with desiccated mud interbed. Unit 3 at Mt. Henkel.

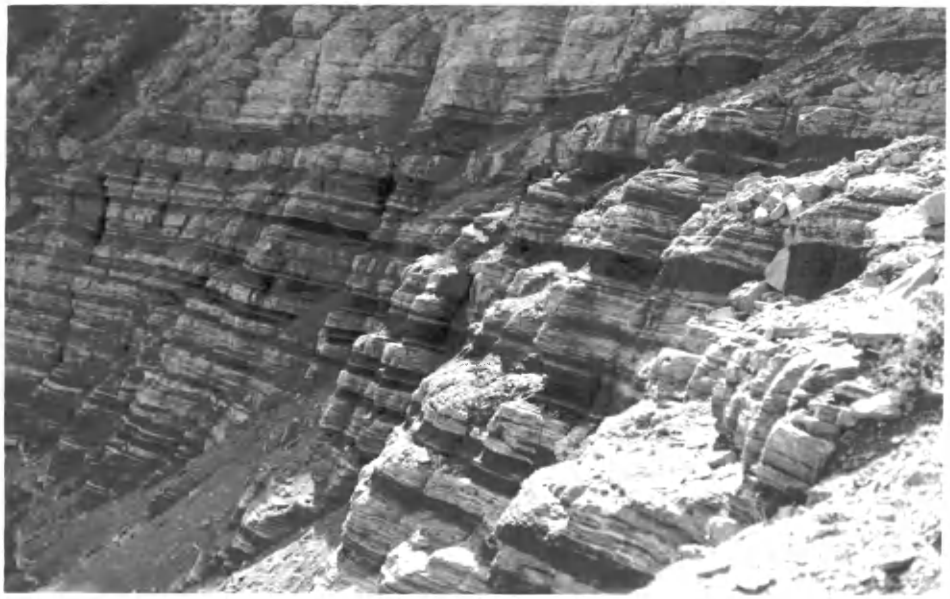

Figure 2-2: Stacked medium- to coarse-grained sand and mud sequence.
Individual sand and mud beds are up to 1.5m thick, are sharply bounded, and laterally continuous for up to 1km. Unit 5 at Mt. Henkel.

Figure 2-3: Large ripples in medium- to coarse-grained sand.
Large symmetric-crested ripples show characteristic bifurcations. Ripples are 30cm from crest to crest and 6cm in height and are the result of wave oscillation. Mt. Henkel section (approx. 1500 ft.)

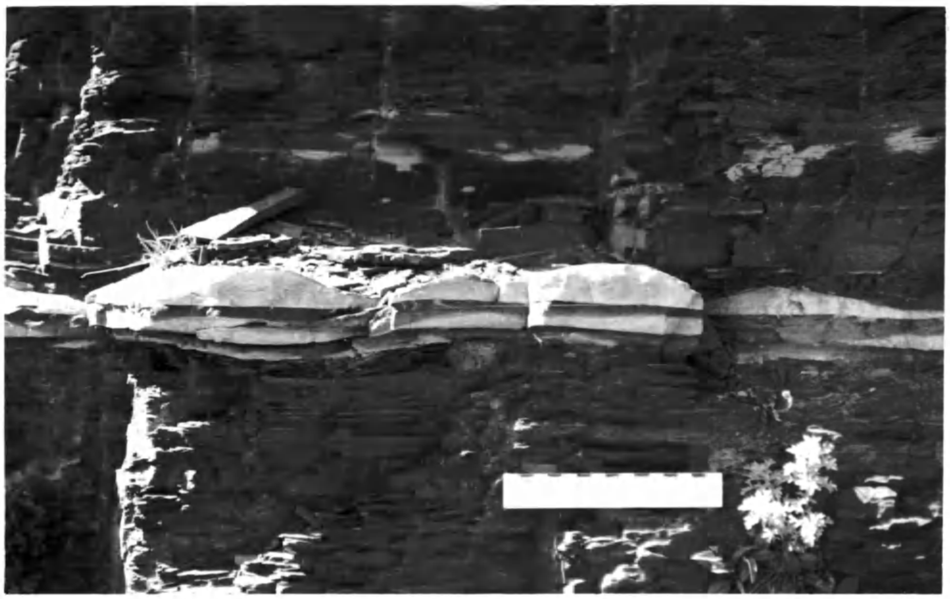

Figure 2-4: Ripples in medium-grained sand.
These symmetric-crested ripples are 25cm from crest to crest and 3cm in height, and also represent wave oscillation over the sand surface. Note the microlaminated mud above and below the ripple sets.

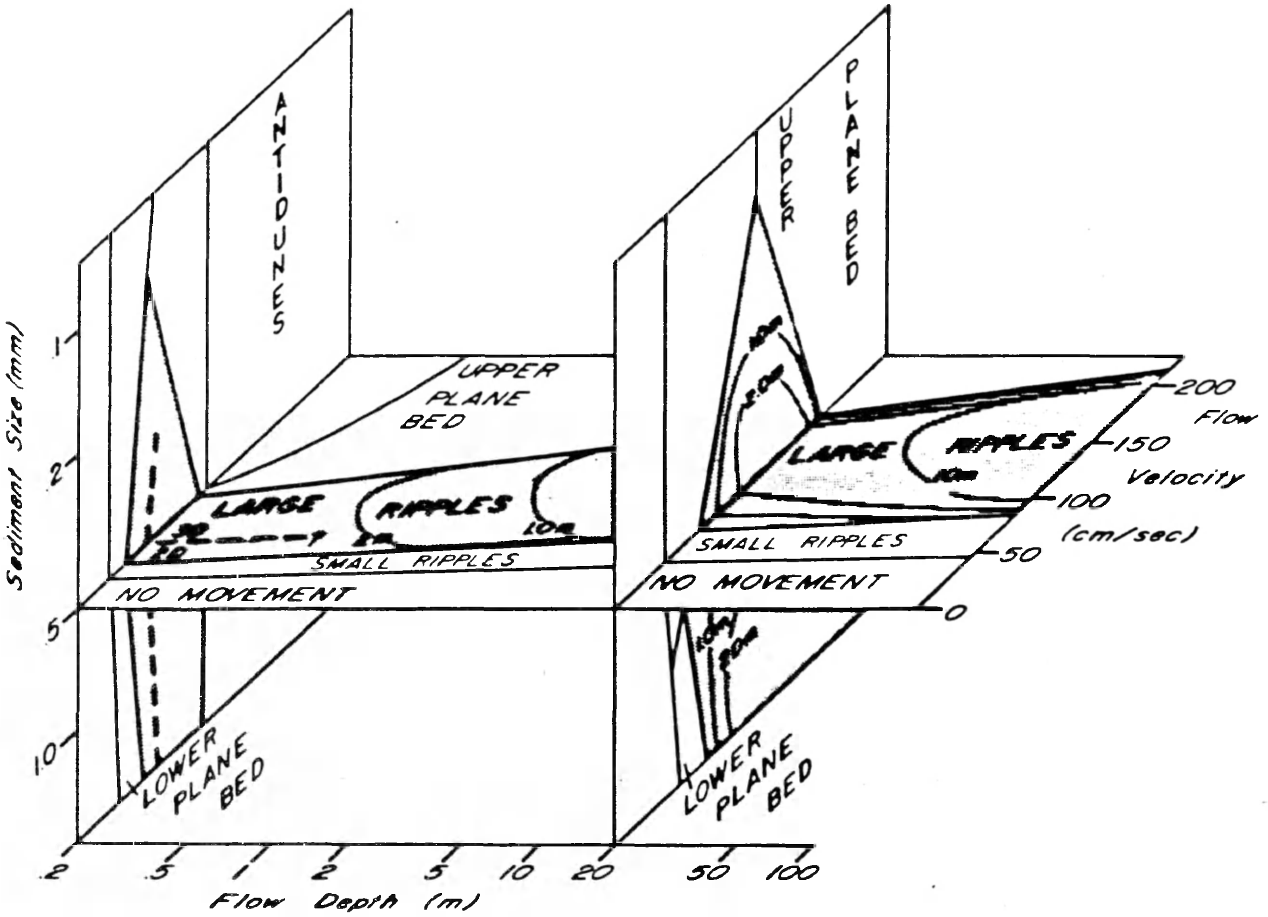

Figure 2-5: Rubin and McCulloch, 1980.
Generalized depth-velocity-size diagram showing relationships among bed phases in flumes and natural flows for a wide change of flow depths.)

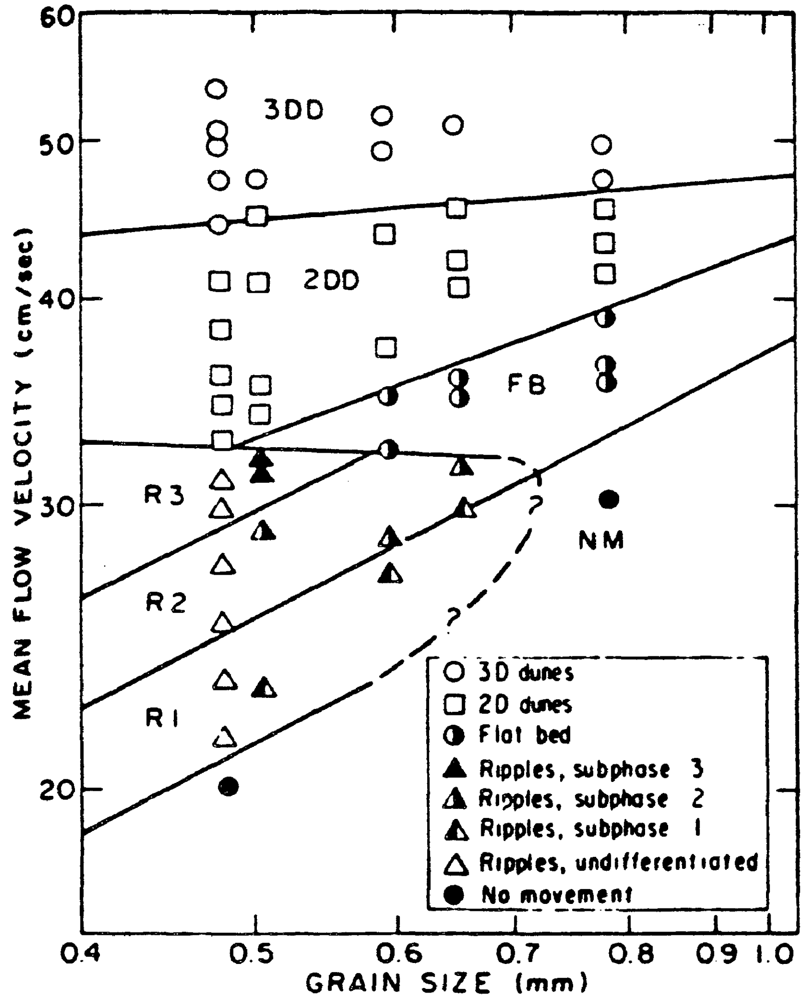

Figure 2-6: Costello and Southard, 1981.
Bed phases observed in flume runs, plotted on a size-velocity diagram for a flow depth of approximately 15cm.

2.2.2. Very Fine- to Fine-Grained Sand Sediment Type

Description

The very fine- to fine-grained sand sediment type is mostly moderate to well-sorted, very fine- to fine-grained, subangular to well rounded, white to brownish, sideritic, feldspathic quartz sand. Flat-laminated, laterally continuous beds, 2-14 cm thick, commonly grade upward to tabular sets of planar cross-bed sets, generally 6-10cm thick, or to clayey mudcracked or rippled tops. These ripples are generally straight to bifucating and symmetric- crested. Scour pits below ripples are less than 1-2cm deep. Small scale (up to 1cm thick) climbing ripples are common in cross section and are clearly observed where both stoss and lee faces of the ripple form are preserved (Fig. 2-7). Load casts occur commonly at the bases of beds where sand is loaded into finer-grained silt or clay. Liesegang bands are less common but appear as grey-purple to pink bands in some sand beds.

Beds of very fine-to fine-grained sand are common throughout lower stratigraphic intervals of the Grinnell. They occasionally occur in stacked sets, 60-90cm thick, alternating with coarser sands, but are generally developed as isolated flat-laminated beds, lenses, and symmetric crested ripple trains 2-3cm thick.

Interpretation

As in the medium- to coarse-grained sand sediment type, flat laminations which pass upward to large scale cross-beds in this sediment type are recognized in the continuum of bedforms produced under waning flow as upper flow regime

Figure 2-7: Very fine-to fine-grained sand sediment type.
Climbing ripple cross-stratification here is similar to Type B of Jopling and Walker, 1968. Thin, dark interbeds are mud drapes. Small load casts are visible at the top of the photo. Unit 4 at Mt. Henkel.

passes to lower flow regime (Rubin and McCulloch, 1980). As current velocity waned to lower flow regime, migrating straight-to sinuous- crested sand waves formed planar, tangential and rare trough cross-beds (Simons et al., 1965; Jopling, 1966). Climbing-ripple cross-stratification (Types B and C, Jopling and Walker, 1968) and load structures, indicate rapid deposition of sand from traction and suspension and decreasing current velocity. Symmetric-crested small ripples sets up to 4cm thick indicate waning of current velocity and record wave reworking of ripples which migrate under minor asymmetric oscillatory flow to form directed cross-beds (Reineck and Singh, 1967, 1980; Allen, 1968; Innman, 1957; Tietze, 1978; Newton, 1968).

If migration of symmetrical oscillation ripples equals aggradation, climb angle is steep, and oscillation ripples will form climbing ripple cross-beds (Harms et al., 1982) similar to Type B of Jopling and Walker, (1968). Under these conditions it would be difficult to distinguish oscillatory wave formed climbing ripples from current formed climbing ripples in cross section. As migration increases relative to aggradation, ripple troughs erode into previously deposited laminae and only the foresets are preserved (Harms, 1982, Fig. 2-8). However, seen in plan view there is little doubt that these symmetrical crested ripples in the very fine to fine grained sediment type are the product of wave oscillation. Cross sections of these ripple trains indicate little or no climb and record a high rate of migration.

The above processes reflect the following sequence. As in the medium- to coarse-grained sediment type, floods flowing in the upper flow regime deposited plane beds. As current velocity decreased to the lower flow regime, straight- to sinuous-crested large-scale current ripples migrated to form tabular sets of planar, tangential and trough cross-beds 6-10cm thick. Ponding of waters appears to have occurred as a result of water level rise within the basin following each flood event. Wind wave reworking modified current ripples to form symmetric, straight crested ripples with bifurcations. Some planar climbing ripples were formed by dominantly unidirectional flow generally by either waning flood flow or by breaking waves. Finally mud and silt settled from suspension as drapes which became desiccated.

2.2.3. Flat-Laminated Silt Sediment Type

Description

The flat-laminated silt sediment type occurs in the Grinnell as tabular sets of even, continuous, flat-laminated to massive siltite beds up to 25cm thick with sharp bases and sharp tops (Fig. 2-10). The siltite beds are capped by mud or clay drapes, 1-10cm thick (Fig. 2-9). Individual beds have a sheet-like geometry changing little in thickness and are laterally continuous for up to 10's of meters. Stacked, flat-laminated silt beds interstratified with coupleted and desiccated mud, form intervals up to 200 ft. thick, particularly in the Whitefish Range. Silt also commonly occurs as thinner beds up to 6cm thick interbedded with silt to clay couplet and desiccated mud sediment types. Climbing-ripple lamination and ball and pillow structures are both common in the flat-laminated silt sediment type. Some silt beds appear massive and others contain load structures at their bases. Channels are absent and local scour surfaces have no more than a few centimeters of relief at the bases of beds.

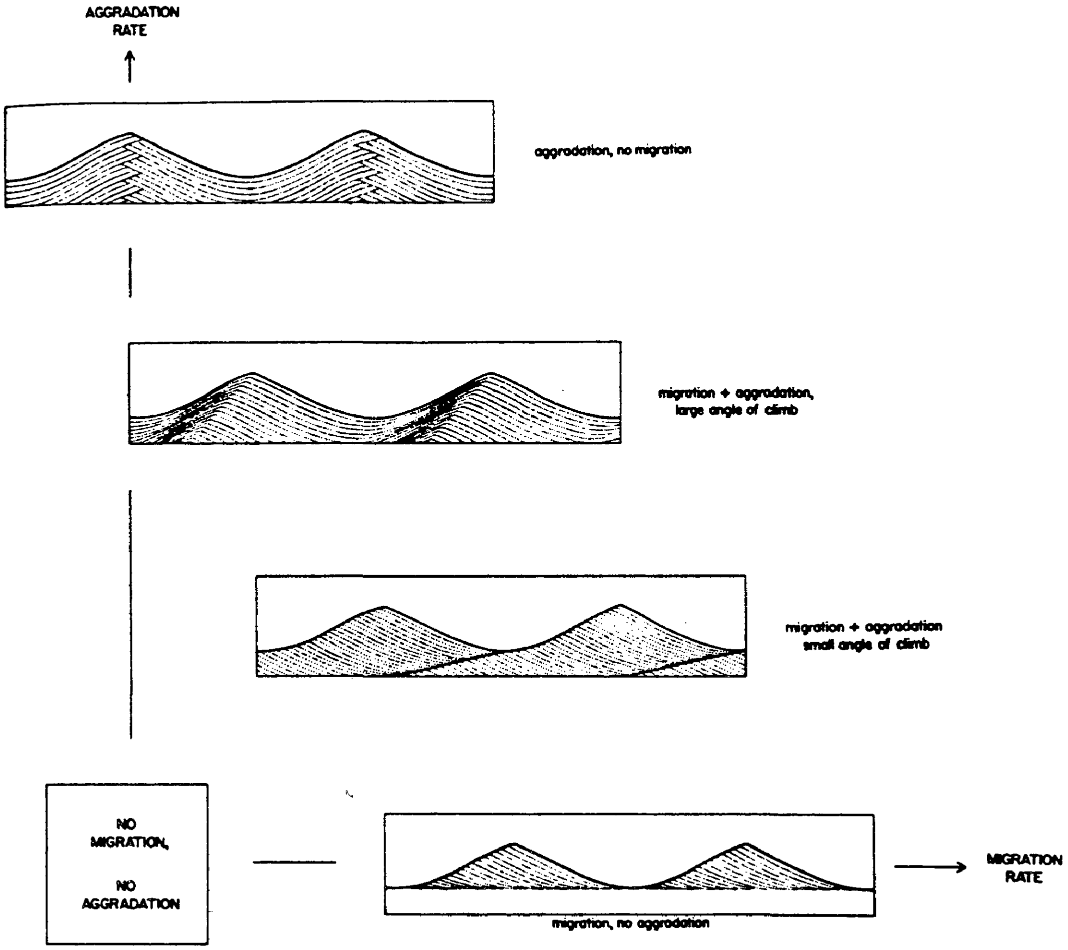

Figure 2-8: Harms, 1982.
Cross-stratification formed by symmetrical oscillation ripples as a function of aggradation rate and migration rate.

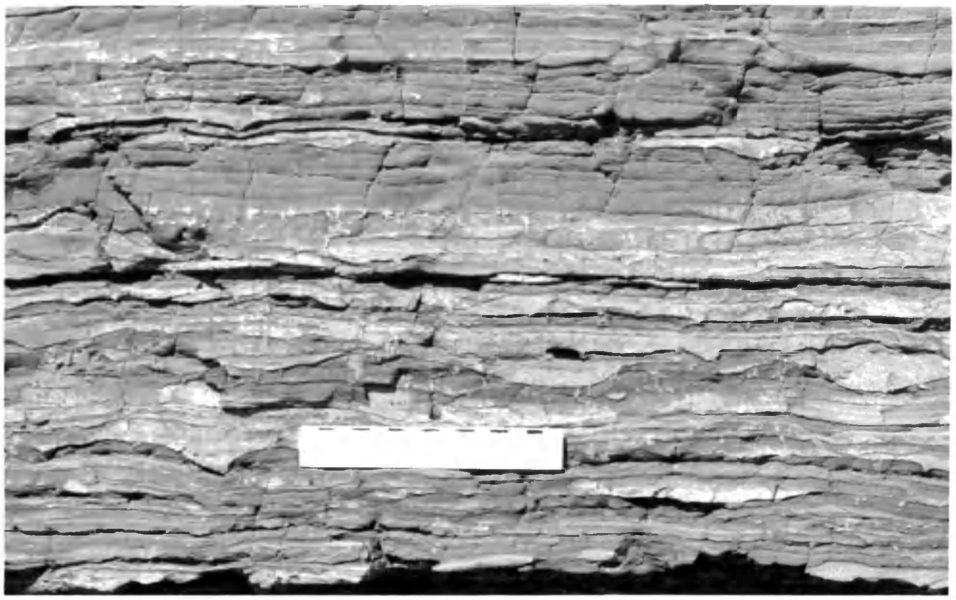

Figure 2-9: Flat-laminated silt sediment type.
Loaded silt layers are 3 to 5cm thick and separated by interbeds of the desiccated mud sediment type. Unit 4 at Mt. Henkel.

Figure 2-10: Laterally continuous, tabular beds of silt.
Silt beds up to 1m thick are separated by desiccated mud interbeds. Unit 4 at Mt. Henkel.

Interpretation

The flat-laminated silt sediment type was deposited from traction and suspension load as laterally continuous, tabular sheets. Flat lamination in coarse silt reflects deposition from upper flow regime (Harms et al., 1982; Reineck and Singh, 1980). Flat-laminated layers which grade upward into climbing-ripple laminae probably reflect waning current velocity from upper-regime plane beds to lower regime current ripples. High angles of climb in climbing-ripple laminae, with preservation of lee and stoss side laminae, are Type B of Jopling and Walker (1968) and indicate that bedload and suspension load deposition were equally important. In these, deposition was rapid (Walker, 1963). Sinusoidal ripples (Jopling and Walker, 1968) directly above Type B climbing ripples, indicate an increasing suspended to traction load ratio.

Massive bedding in silt can form in several ways. Very rapid deposition, or deposition from highly concentrated sediment dispersions can form massive, homogeneous bedding (Blatt et al., 1980, p.136). Destruction of primary sedimentary structures by post depositional liquifaction (Blatt et al., 1980, p.136) or dewatering during compaction (Reineck and Singh, 1980, p.113) may also form massive beds. Rapid deposition from highly concentrated sediment dispersions is suggested by the absence of any remnant sedimentary structures and by abundant load casts in some beds.

Flow alternated with exposure as evidenced by desiccated clay drapes, and this alternation distinguishes this sediment type from fine-grained, continuously submerged deposits such as marine turbidites (Bouma, 1962; Walker, 1978) and deposits in glacial or fluvial deltas (Jopling and Walker, 1968; Jopling, 1965) which contain more abundant soft sediment deformation and lack desiccation cracks (Coleman and Prior, 1982).

2.2.4. Silt to Clay Couplet Sediment Type

Description

The silt to clay couplet sediment type consists of even to lenticular, upward-fining silt and very fine sand layers that grade into silty clay and clay layers. Paired silt and clay layers are together 0.5 to 4.0cm thick. Silt to clay couplets are distinguished from desiccated mud by their proportionately thicker silt and very fine sand laminae and more even and uniform bedding style which reflects less desiccation (Fig. 2-11). Thus they are continuous, even and lenticular layers of fairly uniform thickness. Flat lamination and climbing-ripple cross-beds are occasionally visible in coarse silt layers. Mudcracks, mudchips and fluid escape structures occur in red, hematitic couplets but are not abundant. Green calcareous to dolomitic, silt to clay couplets in the lowermost and uppermost Grinnell generally lack desiccation structures and contain occasional molar-tooth, fluid escape structures and rare incomplete shrinkage cracks. Isolated symmetrical oscillation ripples, 2-4cm thick, contain mostly coarse sand with minor amounts of clay peloids and silicified ooliths (Appendix B, Fig. B-3).

Interpretation

Graded pairs of couplets represent single depositional events in which traction and suspension load deposition of silt was followed by suspension load deposition of clay. Although in some rocks couplets are attributed to vertical accretion of silt and clay settling out of suspension (Harms et al., 1982), the presence of flat lamination and climbing ripple cross stratification in some silt layers of the Grinnell couplets indicates that coarse silt was occasionally transported by traction (Harms et al., 1982). Green, calcareous to dolomitic, silt to clay couplets that contain incomplete shrinkage cracks (referred to as "subaqueous shrinkage cracks", Whipple et al., 1984) but lack desiccation cracks, represent subaqueous settleout from clouds of suspended silt and clay. Their stratigraphic position indicates that they formed seaward of couplets containing desiccation structures (Smoot, 1978). The presence of silicified ooliths and clay pelloids in isolated small-scale oscillation ripples and lenses of coarse sand record oscillatory wave reworking of sand and mud (Fig. B-3). These may represent very thin sand shoals within more stable bodies of water.

Silt to clay couplets are quite common in lacustrine environments where they often occur as glacial varves, as rhythmites deposited by density currents (Sturm and Matter, 1978; Kuenen, 1951; Matthews, 1956; Reineck and Singh, 1980; Harrison, 1975), or as turbid suspension plumes or evaporites in playa lakes (Hardie et al., 1978; Demicco and Kordesch, 1986; Smoot, 1978; Smoot, 1983; Reineck and Singh, 1980; Fouch and Dean, 1982). They are also well documented from restricted marine environments (Olaussen and Olsson, 1969; Byrne and Emery, 1960) at

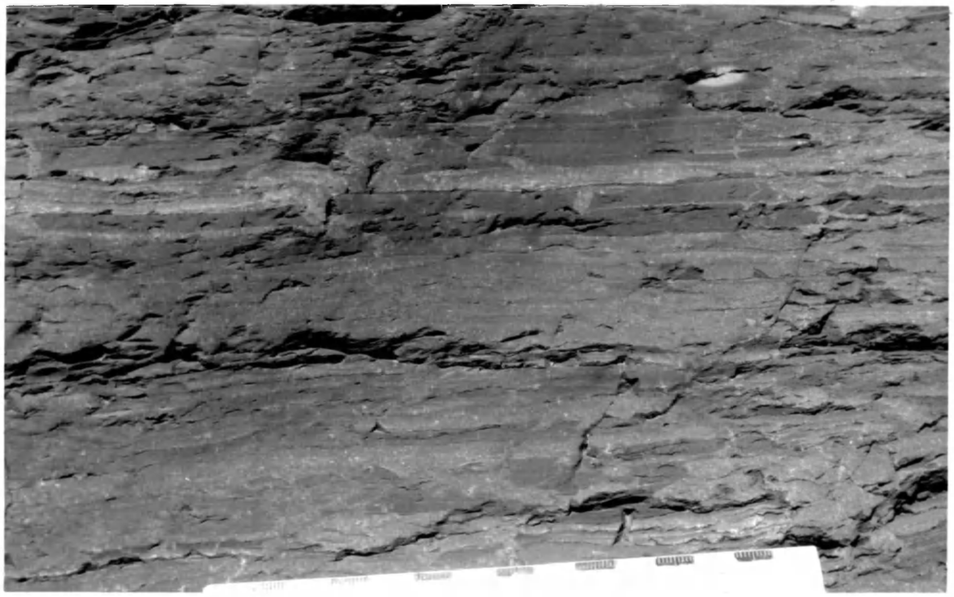

Figure 2-11: Silt to clay couplet sediment type.
Centimeter-scale paired couplets are even and continuous across the outcrop. Darker layers are clay. Pairs represent individual fining-upward sedimentation events. Unit 3 at Mt. Henkel.

depths subject to low oxygen levels, and from deltaic environments (Reineck and Singh, 1980; Coleman and Prior, 1982).

The presence of pyrite or pyrrhotite in green couplets at the base, and at the top of the Grinnell, are evidence of reduction, after deposition in a subaqueous environment. Authigenic pyrite is known to form in clayey silt deposits in bays, lagoons and mudflats of marine environments, and in swamp or freshwater lacustrine environments under reducing conditions (Reineck and Singh, 1980).

2.2.5. Desiccated Mud Sediment Type

Description

Thick mud laminae in the absence of silt laminae, or separated by thin very fine sand, or silt laminae, characterize this sediment type and set it apart from others. The desiccated mud sediment type is composed of clay, mud and faint silt laminations ranging from 0.5 to 4.0cm thick and range to vaguely defined mudcracked silt to clay couplets. Layering is generally difficult to recognize because of the thinness of silt laminae and disturbance resulting from desiccation in most clay layers (Fig. 2-12). Mudcracks, ripped up and transported mudchips which formed mudchip breccias, haloturbation(?), raindrop and hail imprints, and runzel marks, are common in this sediment type. Thin, discontinuous silt laminations, are mostly recognized by greyer color within redder, more clay-rich layers. Silt layers commonly contain ball and pillow structures and climbing ripple laminations. Desiccated mud is distinguished from Winston's (1986b) even couplet sediment type by disturbed bedding, abundant desiccation features, and a lesser amount of very fine- grained sand and silt. Fluid-escape structures are quite common and penetrate up to 50cm of mud sediments. Buried mudcracks appear to have acted as vertical passages for the upward migration of fluids as evidenced by the alignment of mudchips on the sides of interpreted fluid-escape structures. Coarse- to very coarse-grained quartz sand occurs in some beds as "floating", clay-matrix-supported grains, which form indistinct lenses and stringers 1-3cm thick. They are often discernable by reduction spots and bands which follow them the length of outcrops.

Interpretation

Flat silt laminae at the bases of faintly defined muddy silt to clay couplets, probably record upper regime flow. In most laminations and couplets, upper regime flow scoured into the preceeding desiccated mud layer, cutting a sharp base and incorporating numerous mudchips into the bedload. Mudflats became submerged in response to water level rise as the basin flooded and filled. As flow slowed to the lower flow regime, rapid fallout of suspended very fine sand, silt and clay formed occasional climbing- ripple laminae. Load casts in silts loaded into clay and mud layers after deposition. Clay settled from standing water after flow ceased and capped couplets. Fluid-escape structures formed during sediment compaction and extensively disrupted the layers. Subsequent desiccation and cracking of the mudflat surface provided mud polygons for incorporation into the next flow. Taken together, these processes indicate that waters flooded across exposed mud flats, carrying silt and clay in suspension. After water ponded, clay settled from

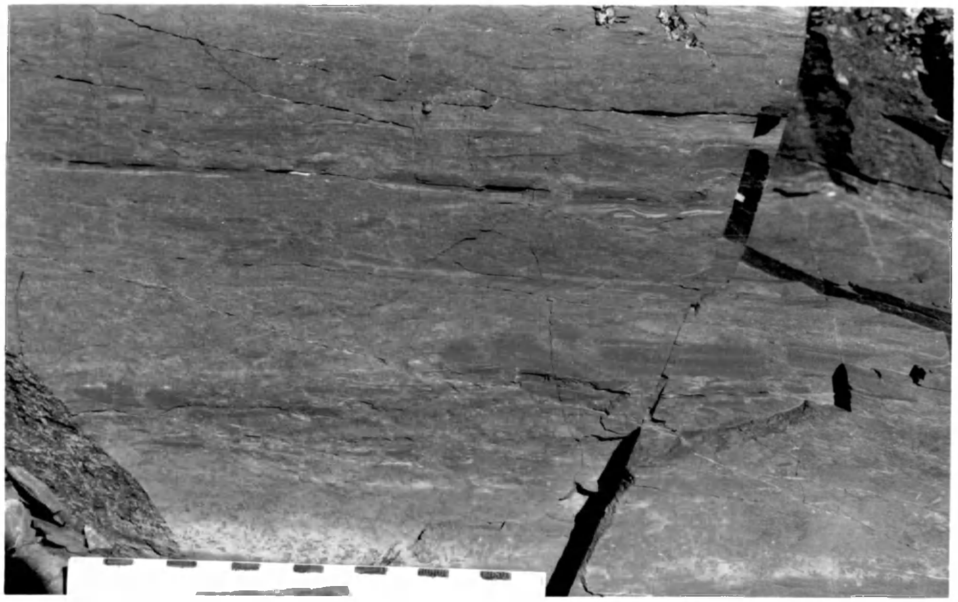

Figure 2-12: Desiccated mud sediment type.
Clay layers and thinner, faint silt laminations are disrupted by numerous mudcracks and fluid escape structures. Unit 4 at Mt. Henkel.

suspension and was later desiccated. Similar mudcracked surfaces occur in a great variety of environments (Reineck, 1967, 1972; Van Straaten, 1954, 1959; Miller, 1975; Fisk, 1959; Clemmy, 1978; Hardie et al., 1978; Picard and High, 1973; Cant, 1982). Runzel marks formed as wind blew over a very thin film of water on muddy surfaces (Reineck and Singh, 1980). Coarse- to very coarse-grained sand that appears to "float" in muddy lenses with unscoured bases, may be deposits that resulted from mudflows, which carried coarse sand and mud across broad flats in a sheetlike fashion (Smoot, 1982).

Although Fenton and Fenton (1937, Plate 5) interpreted "bumpy" casts on clay surfaces as raindrop imprints, bubbles and hail pits, some of these may represent some form of haloturbation. I observed unquestionable raindrop imprints on only one surface of mudcracked polygons at Goat Mountain. Hail imprints were commonly found in broken talus but were rarely observed in place. Small bubble-shaped cavities were rare and often contained a recrystallized lining of quartz or calcite.

2.2.6. Microlamina Sediment Type

Description

The microlamina sediment type consists of very thin (generally < 3mm), discontinuous to laterally persistent, clay-rich mud laminae that are generally graded from silt up to clay and lack sedimentary structures common to other sediment types (Fig. 2-13). Winston (1986b) defines three microlamina varieties, two of which commonly occur in the Grinnell: 1.) a terrigenous variety where silt laminae are overlain by carbon poor, hematitic, or chloritic clay laminae, frequently mapped as red or green argillite, and 2.) a calcareous variety containing tan weathering, dolomitic silt interlaminated with dolomitic clay. The third variety, carbonaceous microlaminae, was not observed in the Grinnell. The calcareous variety decreases from the top of the Appekunny into the base of the Grinnell through an interval containing interlaminated molar-tooth structures, cryptalgal laminae, and rare stromatolites. The red, hematitic and green chloritic varieties occur in other parts of the formation, but most commonly as thin intervals interbedded with the silt to clay couplet sediment type. Red, hematitic microlaminae are occasionally cut by mudcracks. Dolomitic green to tan-weathering microlaminae occur again near the top of the Grinnell and appear to increase upward into the base of the Empire Formation.

Interpretation

Microlaminae in the Grinnell are interpreted to record settling of suspended fine mud out of relatively quiet water on flat surfaces in protected environments with a very slow rate of sediment accumulation. Silt laminae of individual microlaminae represent influx of suspended sediments in quiet water settings. These sediment influxes may represent the most distal deposits of land-generated floods (Woods, 1986) or may record settling of fine material from suspension clouds produced by shoaling waves (Reineck and Singh, 1980, p. 121). The terrigenous variety probably occurred seaward from the reach of flood generated turbid suspension clouds that deposited the even couplet sediment type (Winston, 1986b). In a sourceward direction it becomes interbedded with the silt to clay couplet sediment type in the Grinnell. However, the calcareous variety appears to have accumulated in shallow, protected environments where sparse stromatolites low in the Grinnell may have served as barriers to terrigenous sediment as reported by (Woods, 1986). Organic mats which incorporated aragonite or high magnesium calcite mud organically precipitated as cryptalgal laminae or chemically precipitated in water supersaturated with respect to calcium magnesium carbonate, may represent an additional process which contributed to the formation of this variety, particularly at the base of the Grinnell.

The pencil thin lamination of this sediment type, its interbedding with the silt to clay couplet sediment type, and the rarity of desiccation features, indicate deposition in a subaqueous environment, below fair weather wave base, or in shallow protected environments, where waves did not rework suspension

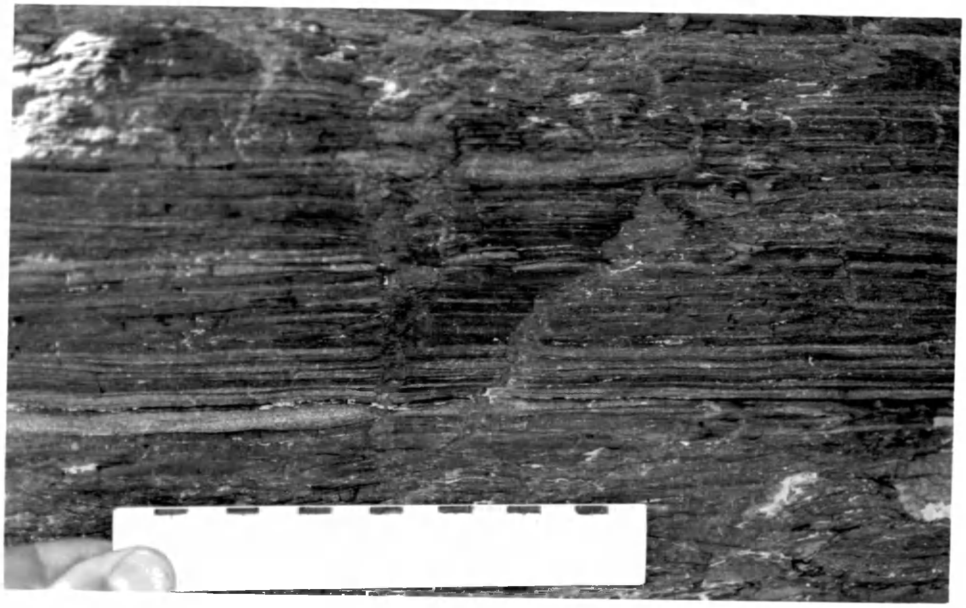

Figure 2-13: Microlamina sediment type.
Pencil thin laminations record settling of fine mud from suspension in quiet water.
Unit 3 at Mt. Henkel.

sediments. The presence of mudcracks in some hematitic microlaminae indicate settle out of suspended clay followed by drying.

Chapter 3

LITHOSTRATIGRAPHIC UNITS

Five informal lithostratigraphic units can be recognized in the Grinnell Formation of Glacier National Park and in the Whitefish Range (PLATE 1). Each is characterized by a dominant sediment type, and they are best developed in the Mt. Henkel section, which serves as a standard reference section for the informal units. The units can be correlated to the other sections, where their sediment types are compared to those in the Mt. Henkel section. A general description, lateral facies relations to other measured sections, and an overall interpretation is provided for each of the following units (see Appendix C for exact locations of measured sections).

3.1. UNIT 1 (0–265 ft.)

Unit 1 is principally green and red argillite consisting of desiccated mud, microlamina, silt to clay couplet, and very fine- to fine-grained sand sediment types. Scattered beds of the medium- to coarse-grained sand sediment type occur near the middle, and increase upsection. Unit 1 is conformable with the informal fifth member of the Appekunny Formation (Whipple et al., 1984).

Desiccation cracks and mudchips are common on exposed surfaces of the desiccated mud sediment type, and rarely in the couplet or in the microlamina sediment types. Molar–tooth structures occur in green dolomitic beds of microlamina and silt to clay couplet sediment types at the base of the unit. Other sedimentary structures in this unit include fluid escape structures in green dolomitic silt to clay couplets, and flat laminations and low-angle tangential cross-beds in the very fine- to fine-grained sand sediment type. The very fine- to fine-grained sand sediment type is common in Unit 1 as isolated continuous beds, 1-10cm thick. This sediment type also occurs as rare, stacked intervals separated by beds of the desiccated mud and silt to clay couplet sediment types, up to 60cm thick. The lowest bed of the medium- to coarse-grained sand sediment type in Unit 1 at Mt. Henkel occurs at 195 feet and is a clean, white, structureless arenite with a scoured base. Beds of this sediment type increase upsection to Unit 2 and contain trough and tabular-planar cross-beds, mudchips, and imbricated mudchips. Accreted mudballs are rare.

Rare stromatolites occur near the top of Unit 1 where the medium- to coarse-grained sand sediment type becomes more common and contains tabular planar and tangential cross-beds. Horodyski (1983, p. 402) noted the same stromatolite zone in his measured section of Mt. Henkel and described the stromatolites as "mound shaped dolomitic stromatolites, 5-20cm high and 10-50cm wide." He attributes the scarcity of stromatolites to a high rate of terrigenous sedimentation. This bed correlates with a single stromatolite bed observed by Rezak (1957) and Horodyski (1983) along the Going-to-the-Sun Road west of Rising Sun Campground.

Unit 1 at Goat Mountain contains thicker intervals of desiccated mud, microlaminae, and silt to clay couplet sediment types, as well as interbeds of the flat-laminated silt sediment type. These correlate well with Unit 1 at Mt. Henkel. A 25-foot sequence of interbedded flat-laminated silt and desiccated mud sediment types occurs at the base of the Goat Mountain section, overlain by stacked sequences of the medium- to coarse-grained sand sediment type sharply interbedded with beds containing desiccated mud and silt to clay couplets. The medium- to coarse-grained sand sediment type occurs at a slightly lower position than at Mt. Henkel.

At Mt. Cannon, the base of the Grinnell Formation occurs in a 200 to 300-foot thick covered interval along McDonald Creek, near its confluence with Avalanche Creek. Because Unit 1 was not recognized in the lowest outcrops of the Grinnell along McDonald Creek it probably lies within this covered interval above the highest beds of Appekunny member 5 (Whipple et al., 1984). Unit 1 is approximately 1600 feet thick in the Whitefish section and consists of alternating intervals of bright green argillite containing the microlaminae and silt to clay coupleted sediment types, purple argillite containing the silt to clay coupleted sediment type, and variagated purple and green argillite containing microlaminae, silt to clay couplet sediment types, and thin intervals of the desiccated mud sediment type. The lowest intervals of bright green silt to clay couplets and microlaminae in Unit 1 also contain wispy lenses of brownish, sideritic, fine-grained sand.

3.2. UNIT 2: (265–405 ft.)

Unit 2 at Mt. Henkel contains all of the sediment types: medium- to coarse-grained sand, very fine- to fine-grained sand, flat-laminated silt, desiccated mud, silt to clay couplet, and microlamina. However, stacked beds of medium- to coarse-grained, mudchip-rich sand (intraformational conglomerate) with interbeds of the desiccated mud sediment type, dominate this unit and occur in sequences up to 10 feet thick. The top of Unit 2 is marked by the highest thick bed of medium- to coarse-grained sand sediment type. Although very fine- to fine-grained sand is generally more thinly bedded (2-10cm) than medium- to coarse-grained sand, both types occur in sets capped by straight- crested to sinuous-crested symmetric ripples containing unidirectional cross-beds. These are mostly capped by desiccated mud drapes. Abundant mudchips are more common in medium- to coarse-grained sand then in finer sand in Unit 2. Accreted mudballs were absent from sands in this unit.

The top of Unit 2 is well defined at Goat Mountain by the highest medium- to coarse-grained sand beds, which here also characterize Unit 2. At Mt. Cannon, Unit 2 appears to pinch and cannot be recognized as a distinct unit. However, rare, thin lenses and layers of the medium- to coarse-grained sand sediment type which are included in Unit 3, may represent the westernmost distal tongues of Unit 2. Unit 2 does not extend into the Whitefish Range and the lowest thin beds of the medium- to coarse-grained sand sediment type here are also included in Unit 3.

3.3. UNIT 3: (405–880 ft.)

Unit 3 is easily distinguished at Mt. Henkel as a bright red argillite characterized by the desiccated mud sediment type. Silt to clay couplet and microlaminae sediment types are relatively rare in this unit. Thin lenses and indistinct stringers of coarse- to very coarse sand occur in the desiccated mud sediment type as mud-supported grains and, many are discernable by reduction spots along the outcrop. Beds of angular to rounded mudchips, mudcracks, and fluid-escape structures are common throughout Unit 3. The flat-laminated silt sediment type contains load casts and climbing ripples and occurs in beds up to 15cm thick in the lower portion of this unit (405–572 ft.), but is rare in the upper portion (572–880 ft.), where the desiccated mud sediment type predominates.

This unit is very well exposed at Goat Mountain and is about as thick (450ft.) as at Mt. Henkel. At Mt. Cannon, Unit 3 thickens to more than 750 feet and contains thin lenses and layers of the medium- to coarse-grained sand and flat-laminated silt sediment types. An undetermined amount of this unit occurs within the covered interval beneath this section, above Unit 1. In the Whitefish Range Unit 3 thins to approximately 200 feet thick. Beds of the desiccated mud sediment type again dominate this unit and contain thin interbeds of the medium- to coarse-grained sand and flat-laminated silt sediment types.

3.4. UNIT 4: (800–1280 ft.)

Unit 4 is characterized by abundant beds of the flat–laminated silt sediment type. The lateral continuity, and general thickness (30–90cm) of abundant silt beds, separate this interval as a distinct unit. Interbeds consist mostly of desiccated mud, microlaminae, and silt to clay couplet sediment types.

Load structures and climbing ripples are common in beds of the flat–laminated silt sediment type, and beds are sharply separated by mudcracked clay drapes or thin beds of the desiccated mud sediment type. Occasional thin beds of the medium– to coarse–grained sand sediment type increase upward. Thin (1–10cm) beds of very fine– to fine–grained sand are also common in this unit and are capped by straight–crested, symmetric unidirectional ripples with clay drapes.

This unit passes to thicker beds of the flat–laminated silt and very fine– to fine–grained sand sediment type at Goat Mountain, and to abundant flat–laminated silt, very fine– to fine–grained sand, and red and green to tan–weathering dolomitic silt to clay couplet sediment types at Mt. Cannon. In the Whitefish Range it is expressed as a 950–foot thick interval dominated by beds of the flat–laminated silt and desiccated mud sediment types with thin, minor lenses of the medium– to coarse–grained sand sediment type. Silt to clay couplet and microlamina sediment types are rare, and occur mostly within green argillite intervals in the lower portion of Unit 4.

3.5. UNIT 5: (1280–1822 ft.)

Unit 5 contains all of the sediment types, but the medium– to coarse-grained sand sediment type characterizes it as a distinctly separate unit. Stacked, mudchip-rich, medium- to coarse-grained sand beds are similar in character to those of Unit 2. However, mudchips and accreted mudballs (up to 10cm in diameter) increase noticeably in abundance in this unit. Individual sand beds are thicker (up to 60cm) and occur in more thickly stacked intervals than those in Unit 2. The uniform coarseness of some mudchip-rich sand beds obscures internal stratification, causing some beds to appear massive. However, flat-laminated, mudchip-rich sets commonly pass upward into abundant tabular-planar, tangential and trough cross-bedded sets. Foresets average 25–35 degrees, and are easily distinguished by heavy mineral laminae and by oxidation or reduction of mudchips and thin clay drapes. Reactivation surfaces and bimodal cross-beds occur in some cosets.

Approximately 90% of all ripple forms are symmetrical in profile and range from straight to nearly straight and bifurcating forms. The remaining 10% consists of asymmetric catenary (lunate) and linguoid forms. All of the above ripples occurred on the upper surfaces of resistant beds and were observed both in plan view and in cross-section.

Contacts between sand and mud interbeds in Unit 5 are sharp. Occasional scour surfaces at the bases of sand beds are mostly less than a few centimeters in relief. Muddy interbeds consist primarily of the desiccated mud sediment type. At Mt. Henkel a green interval of the microlamina and silt to clay couplet sediment types occurs in Unit 5 from 1180-1230 ft.. An oolitic pyrite bed at 1835 ft. marks the top of the Grinnell Formation and the base of the Empire Formation.

At Goat Mountain the apparent thickness of this unit is expanded more than 1500 feet by imbricate thrusts. There, only the base of Unit 5 was measured and occurs at the same stratigraphic level as at Mt. Henkel. At Mt. Cannon, Unit 5 is thicker and passes mostly to stacked tabular beds of medium- to coarse-grained sand, and abundant tabular beds of flat-laminated silt, desiccated mud and silt to clay couplet sediment types. In the Whitefish Range, Unit 5 passes to a thinner interval containing desiccated mud and silt to clay couplet sediment types separated by much thinner stacked lenses and interbeds of the medium- to coarse-grained sand sediment type. Sections measured by Christopher Cronin (University of Montana, 1986) in the Flathead, Mission and Swan Ranges (Cronin et al., 1986) demonstrate the southward continuation of Unit 5 as a recognizable unit high in the Spokane Formation.

3.6. Depositional Processes of the Lithostratigraphic Units

The interbedded dolomitic to hematitic silt to clay couplets and microlaminae low in Unit 1 at Mt. Henkel, record subaqueous accumulation of sediments from suspension, partly reworked by wave oscillation. Upward passage to the desiccated mud sediment type indicates subaerial exposure on extensive bordering flats. Thin, rare beds of medium- to coarse-grained sand sediment type record flooding across these flats. To the west at Mt. Cannon and north in the Whitefish Range, the absence of the medium- to coarse-grained sand sediment type, decrease of the desiccated mud sediment type, and the increase in the relative amount of silt in silt to clay couplets and microlaminae, indicate a basinward trend in which suspension sedimentation dominated. Upward coarsening of Unit 1 at Mt. Henkel by an influx of coarse sand into a region containing sparse stromatolites, indicates the progradation of a sand flat over a desiccated mudflat and offshore suspension dominated system.

Unit 2, characterized by abundant beds of the medium- to coarse-grained sand sediment type, interbeds of the desiccated mud sediment type, and minor beds of the flat-laminated silt sediment type, may represent the distal reach of ephemeral floods carrying coarse sand in traction and silt and mud in suspension onto an expansive subaerially exposed sand and mudflat. Upper flow regime plane beds, in the medium- to coarse-grained sand sediment type, which grade up into tabular-planar, tangential and trough cross-beds, indicate rapid deposition of sediment followed by decreasing current velocity. Suspension settle out of silt and mud occurred below the critical velocity required for entrainment of medium- to coarse-grained sand, probably during slack water phase or ponding of water at the end of each depositional event. Oscillatory flow reworked sand to form wave-oscillation ripples and rounded crests of large current ripples (Stear, 1985).

The thin distal alluvial sand flats of Unit 2 do not extend to Mt. Cannon. The medium- to coarse-grained sand sediment type of Unit 2 passes to the west to the silt to clay couplet and microlaminae sediment types of Unit 1 and the desiccated mud sediment type of Unit 3. Although, Unit 2 may occur within the covered section at Mt. Cannon, sediment types in the lower portion of the

Whitefish Range section characteristically lack interbeds of the medium- to coarse-grained sand sediment type and record a more distal environment controlled by suspension sedimentation. Tabular beds of flat-laminated silt sediment type at the top of Unit 2 may record the distal reach of sheet-like bodies of very fine-grained sand and silt originating from a southwestern source (McMechan, 1981). These beds were included within Unit 2 on the basis of their interbedding with more abundant beds of the medium- to coarse-grained sand sediment type. Similar beds occur in the lower part of Unit 3 of the Goat Mountain section and may occur within the covered lower portions of the Grinnell at Mt. Cannon and the Whitefish Range.

Dominance of the desiccated mud sediment type in Unit 3, indicates extensively exposed, desiccated mud flats. Periodic floods ripped up mudcracked polygons and transported them as mudchips which were deposited in thin conglomerates. In-place disruption by fluid-escape structures is extensive in some beds. Tabular beds of the flat-laminated silt and very fine- to fine-grained sand sediment types continue from Unit 2 up into the lower part of Unit 3. Climbing-ripple cross-stratification in these beds indicates rapid deposition from suspension (Blatt et al., 1984). Occasional mudflows(?) transported coarse sand up to 1mm in diameter across the mudflats (Smoot, 1982). Thin oscillation ripples consisting of coarse sand, ooliths, and mud pelloids which occur in Unit 3 in very thin red silt to clay coupleted intervals, may represent thin shoals directly adjacent to the desiccated mud sediment type.

Interbedding of the flat-laminated silt sediment type with the desiccated mud sediment type characterizes Unit 4 at Mt. Henkel. The lateral continuity of silt beds, for 10's of meters, is particularly striking, and indicates sheetlike deposition of silt over broad, flat surfaces prone to subaerial desiccation. Lesser amounts of interbedded silt to clay couplets and microlamina, reflect occasional submergence of the flat in the Mt. Henkel and Goat Mountain sections. Westward thickening of Unit 4 and decreasing amounts of the desiccated mud sediment type to the west, indicate a western source for the silt in Unit 4.

Thick intervals containing tabular beds of flat-laminated silt, silt to clay couplet and desiccated mud sediment types in Unit 4 in the Whitefish Range, correlate quite well with silt beds at similar stratigraphic levels in sections measured in the Mission and Swan and Flathead Ranges by Christopher Cronin (University of Montana, 1986). He interprets these to represent distal tongues of the upper Revett Formation (Cronin et al., 1986). These also occur at similar stratigraphic levels as McMechan's (1981) C-4 member of the correlative Creston Formation which contains tabular beds of silt which she believes are distal tongues of the upper Revett Formation. Increasing amounts of the medium- to coarse-grained sand sediment type upwards in Unit 4 signal the return of a prograding sandflat. This may have occurred in response to a decrease in the influx of very fine- to fine-grained sand and silt.

Stacked beds of the medium- to coarse-grained sand sediment type, sharply separated by interbeds of the desiccated mud sediment type characterize Unit 5. Rapid westward thinning of the medium- to coarse-grained sand sediment type in the Whitefish Range indicates an eastern source terrain for medium- to coarse-grained sand in the Ravalli Group. Stratigraphic continuity of these beds to the south is demonstrated by their presence at similar stratigraphic levels in the Spokane Formation of the Flathead, Mission and Swan Ranges (Christopher Cronin, University of Montana, 1986).

Similar sequences of interbedded sands and muds in the Phanerozoic are interpreted as sheet-flow deposits of distal alluvial fans and ephemeral streams. Hubert and Hyde (1982) interpreted graded sandstone beds from the Upper Triassic Blomidon redbeds in Nova Scotia, to represent decelerating sheet-flow deposits on an alluvial sandflat playa. They form upward-fining and thinning cycles of sharply bounded sandstones and siltstones beds with planar laminations and tabular-planar cross-beds. Upward fining cycles are attributed to channel avulsion during 100 to 1000 year floods which carried sand, silt and clay far out onto the mudflats. Hubert and Hyde (1982) concluded that very fine-grained sand and silt were washed downstream as medium- to coarse-grained sand accumulated. As velocity decreased under waning flow, fine sand, silt, and mud settled out and accumulated in a sourceward direction, capping coarser sand beds. Although the same depositional processes appear to have occurred in the Grinnell, the lack of upward-fining sequences such as these in the stacked sand/mud beds of Units 2 and 5, further demonstrates the absence of a fine-grained sand and silt population from the east. Sharp interbedding, laterally continuous sand beds, abundant cross-bedding, and planar laminations in sand beds of Units 2 and 5 of the Grinnell are quite similar to the Blomidon red beds.

Tunbridge (1981) described ephemeral flow deposits in the Devonian

Trentishoe Formation in southwest England, which he interprets to represent sheetflooding of a low lying alluvial plain. The similarity of these beds to sand beds in the Grinnell is remarkable. Characteristics common to both include; 1) lateral continuity of beds for more than 100m with little thinning, 2) sheet-like geometries of most sand beds, with flat bases and tops, 3) absence of channels, merged channel fills or evidence of lateral accretion of sand sheets, and 4) abundant planar-laminated beds. Interbedded sand/mud sequences in the Trentishoe Formation which Tunbridge (1981) interprets as flood extremity deposits are similar to sand/mud beds in Unit 5 of the Grinnell (Fig. 4-4).

Parallel-laminated sands in the Trentishoe are on the order of 1m thick, similar to beds in the Grinnell. Tunbridge (1981) investigated bed thicknesses of other sheetflood deposits and also found a relative thickness of 1m and rarely thicknesses of 1.5m for individual flood events (McKee et al., 1967; Williams, 1971; Allen, 1974). Tunbridge's (1981) study is perhaps one of the most significant contributions in describing ephemeral flow deposits characterized by sheetfloods.

Other authors have described multistory sand deposits formed from flooding and filling of ephemeral stream beds, which extended as unconfined flows on adjacent floodplains (McKee et al., 1967; Stear, 1985; Turner, 1986; Williams, 1970,1971; Rahn, 1967; Scott et al., 1969; Glennie, 1970). These characteristically contain flat-laminated, laterally continuous sand beds, and in many cases also contain cross-bedded deposits from the migration of large bedforms under waning flow conditions (Williams, 1970, 1971; McKee et al., 1967; Scott et al., 1969; Picard and High, 1973).

Chapter 4

INTERPRETATION OF DEPOSITIONAL ENVIRONMENT

4.1. Discussion

The sediment types that comprise the lithostratigraphic units were deposited in a wide variety of depositional environments. The environment of any particular sediment type cannot be interpreted unless it adequately conforms to the interpretation of all the sediment types in their relative stratigraphic positions.

Some deep water environments, such as the deeper parts of fluvial and glacial deltas (Theakstone, 1976), in which suspension settle out produces silt to clay couplets and microlaminae, may be initially ruled out because of shallow water features such as planed-off ripples and oscillation ripples, and because of emergent features, such as runzel marks, desiccation cracks, and raindrop imprints (Clemmy, 1978). In turn these sedimentary structures must be interpreted in their close association with flat-laminated and high-angle cross-bedded sand layers which appear to indicate episodic floods with rapidly waning flow. The relationship of sediment types to each other in the Grinnell, and most noteably, the presence of wave oscillation-formed ripples at the tops of sand beds, limit depositional interpretations to intertidal marine, marginal lacustrine, or distal alluvial sedimentation.

The intertidal marine interpretation is here rejected. The report of herringbone cross-beds, lenticular and wavy bedding, reactivation surfaces, desiccation cracks, stromatolites, and oscillation ripples (Horodyski, 1983; Whipple et al., 1984; Fenton and Fenton, 1937), might together be taken as compelling evidence for marine deposition of the Grinnell. Other authors describe these sedimentary structures from known tidal deposits (Ginsburg, 1975; Weimar et al., 1982). However, several points are worthy of note. The regressive Appekunny - Grinnell sequence does not fine upward as would be expected in a tidally dominated marine regression (Klein, 1977). Instead the Grinnell Formation contains two coarsening-upward sequences (Fig. 4-1), in which Units 2 and 5 are the coarsest intervals. Bipolar cross-beds, often referred to as tidally deposited "herringbone cross-beds" (Ginsburg, 1975; Reineck and Singh, 1980), may also form in divergent foreshore and washover beds of small beaches along ephemeral lacustrine shorelines (Winston et al., 1984).

Although the absence of flaser bedding (Reineck and Wunderlich, 1968) does not preclude a tidal environment, one would expect well developed flaser bedding in a sediment so rich in sand and mud. Reactivation surfaces, which are common features of tidal flats, are also well documented in fluvial and other environments (Collinson, 1978) and may even be produced in conditions of constant flow where they show concave up orientation (McCabe and Jones, 1977). Finally, Hardie et al. (1978) emphasized that features such as cut and fill structures, low-angle inclined bedding, and heavy mineral lag laminae, are similar to the backshore of a high tidal beach. Thus they conclude that many ancient deposits interpreted as tidal in origin, may in fact, represent lacustrine sequences and should be reexamined. This is true for portions of the Grinnell which merged with a body of water either marine or lacustrine in origin.

According to Horodyski (1983), any depositional environment proposed for the upper sandy member (Unit 5) of the Grinnell Formation must explain the following: 1) Abundant evidence of subaerial exposure, even within sandy cosets, 2) Very fine interbedding of relatively coarse-grained sandy layers with muddy layers and sharp contacts between these layers, 3) Sandstone bed thickness generally 1-10cm and rarely a maximum of 25cm, 4) Continuity of some sandstone beds for more than 100m with little change in thickness, 5) An absence of either coarsening- or fining-upward sequences, 6) An absence of uneven scour deeper than a few centimeters beneath sandstone beds, 7) An absence of sedimentary structure associations of the type commonly present in tidal deposits (Klein, 1977). For these reasons the sedimentologic character of the coarser Grinnell sediments is more adequatly explained in a distal alluvial environment. Multistory, intraclastic sand beds in Unit 5 are more similar to sheet-flood deposits documented by other authors (Tunbridge, 1981; Stear, 1985; Hubert and Hyde, 1982; Williams, 1971; Frostick and Reid, 1977; Cheadle, 1986).

Laterally continuous stratification indicates the deposition of sediment on extremely flat, broad, surfaces. The interbedding of tabular, medium to coarse intraclastic sand with silt and mud, and the persistence of beds along strike for many tens of meters with no variation in thickness or evidence of channeling, can best be explained by large episodic sheet floods which traversed expansive flats (Tunbridge, 1981; Williams, 1971; Rahn, 1967). The upward increase in large and small scale cross-bedding in individual sand beds, capped by mud drape, indicate rapidly waning flow from single flood events. Oscillation ripples capped by desiccated mud, indicate oscillation and wave formation in a ponded body of water. Of these, small-scale oscillation-rippled coarse arenites, which contain ooliths and mud pelloids, probably represent low shoals which migrated in response to occasional wave oscillation. The stratigraphic position of these thin, isolated ripple trains commonly interbedded with the silt to clay couplet and microlaminae sediment types, and the inclusion of these sediment types as thin intervals within the larger framework of the desiccated mud sediment type of Units 3, 4, and 5, indicate occasional fluctuation of water level within a more persistent, long standing lake (or a number of lakes) bordered by extensive mudflats.

Alleman (1983) pointed out that similar sheet-flood events in the lower Revett are analogous to modern internally drained intermontagne bolsons in which sheet floods transport sediment from the lower segments of alluvial fans across alluvial plains (Peterson, 1981; Bull, 1972) Other recent sheet-flood deposits (McGee, 1897; Williams, 1971; McKee et al., 1967; Wasson, 1977; Davis, 1938) show that high velocity episodic floods in ephemeral streams move beyond channel margins as unconfined sheet-like flows which deposit tabular beds of flat-laminated and cross-bedded sand which in some cases contain abundant mudchips and accreted mudballs (McKee et al., 1967). Schumm (1968) also concluded that individual flood events may have occurred as broad sheets prior to an extensive terrestrial plant cover. The absence of channels may certainly be a result of the lack of stabilizing vegetation, but other factors also played a role.

Schumm (1961) believes that aggradation of sediment in topographic low areas greatly increased width to depth ratios. Steadier regimes of river grade and climate combined with more constant or higher rates of sedimentation may also contribute to the lack of channel formation in other ancient fluvial systems (Friend, 1978).

Williams (1971) shows that catenary large-scale ripples are the most common bedform produced by a single flood in medium to coarse sand deposited by rivers entering Lake Eyre in central Australia. Migration of these bedforms produced tabular beds containing large-scale trough cross-stratification and represented 60% of all flood deposits. The migration of longitudinal, transverse, and linguoid bars in these sand bed streams produced sets of tabular-planar cross-beds which represented 25% of all flood deposits. Both processes produced cross-stratification with high-angle avalanche faces (28-36 degrees in large scale trough cross-beds, and 25-34 degrees in tabular-planar cross-beds). Large scale trough cross-stratification is relatively rare in the Grinnell but tabular-planar cross-stratification is abundant. Viewed in the direction of flow, the internal structure of catenary ripples might reveal sets that appear to lense out. Numerous lensing sets of cross-beds on a decimeter scale in some sand beds in the Grinnell may therefore represent the migration of catenary ripples not apparent in plan view and may further demonstrate the existence of large single flood events similar to ephemeral stream floods in central Australia.

Finally, the stratigraphic position of the desiccated mud, silt to clay couplet and microlaminae sediment types, basinward of the coarser sediment types in the Grinnell, demonstrates a fining of sediments across an extremely flat basin floor.

Mudflats, represented by the desiccated mud sediment type, accumulated peripherally along broad sand flats and were extensively desiccated following each flood event. Silt to clay couplets and microlaminae accumulated by settle out of silt and clay from large suspended clouds of sediment added by flood influxes.

4.2. Paleocurrent Analysis

Paleocurrent data collected from a series of medium to coarse sand beds at the base of Unit 5 near Mt. Henkel, produced a current rose with strong northeast and northwest modes (Fig. 4-2). Most individual beds show either a strong northeast or northwest cross-bed dip direction and no beds were internally bimodal.

Medium- to coarse-grained sand appears to have been derived from the east where it entered the basin south of Mt. Henkel and was transported to the northwest by flows from the southeast. It decreases significantly to the west, and to the south in the Helena Embayment (this study; Cronin et al., 1986; Whipple et al., 1984; Smith, 1963; McMechan, 1981). Finch and Baldwin (1982) interpreted turbidite beds in the Prichard Formation to reflect a northwest trending basin axis. Sand transport to the northwest in the Grinnell may reflect the continued flow down a slight gradient toward the basin low point. An eastern source terrain for medium to coarse sand in the Grinnell is further supported by petrographic data (see Appendix B) indicating a provenance from Hudsonian Basement to the east and southeast.

The northeast trend of Grinnell sands at Mt. Henkel may represent northeast transport of coarse sands on the basin floor by flood currents flowing from large alluvial aprons to the west and southwest. This is also in agreement with tabular silt beds in Units 3 and 4 interpreted as distal tongues of the Revett Formation which is dominated by transport from the southwest (Mauk, 1983; Bowden, 1977; Hrabar, 1971).

4.3. Depositional Synthesis

From the lithostratigraphic relationships shown in Fig. 4-1, and the transport directions demonstrated in Fig. 4-2, a depositional model showing the general distribution of sediment types may now be proposed. Figure 4-3 shows the interplay of medium- to coarse-grained sand carried by currents from the southeast, with silt and very fine- to fine-grained sand carried by currents from the southwest. The desiccated mud sediment type is shown in its position distal to both of these sand populations, and is succeeded basinward by the silt to clay couplet and microlaminae sediment types. A low relief landmass to the southeast supplied medium- to coarse-grained sand.

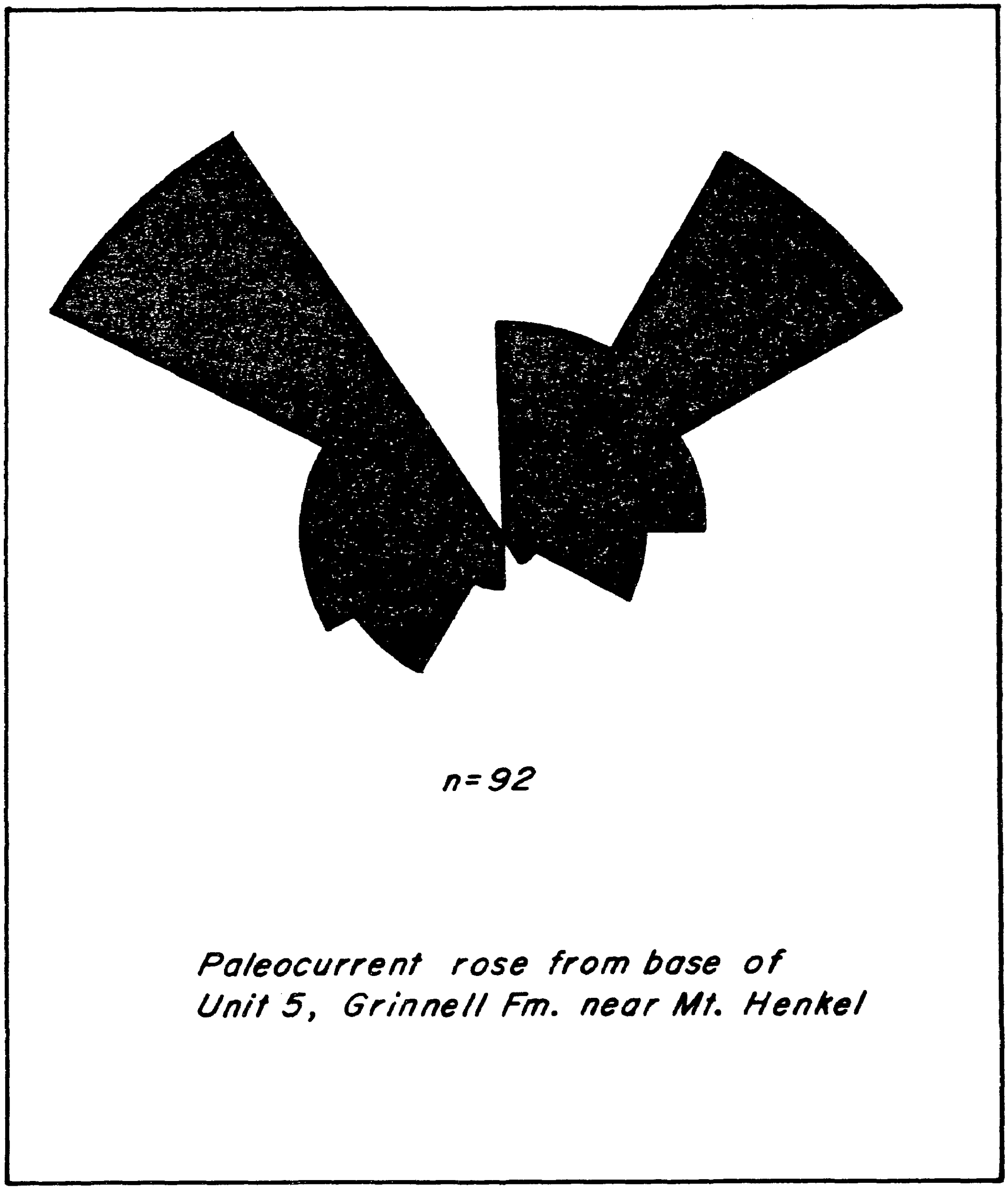

Figure 4-2: Paleocurrent rose diagram.
Dominant current trends are shown to the northeast and northwest. This figure is a compilation of 92 tabular planar cross-beds measured at the base of Unit 5, near Mt. Henkel.

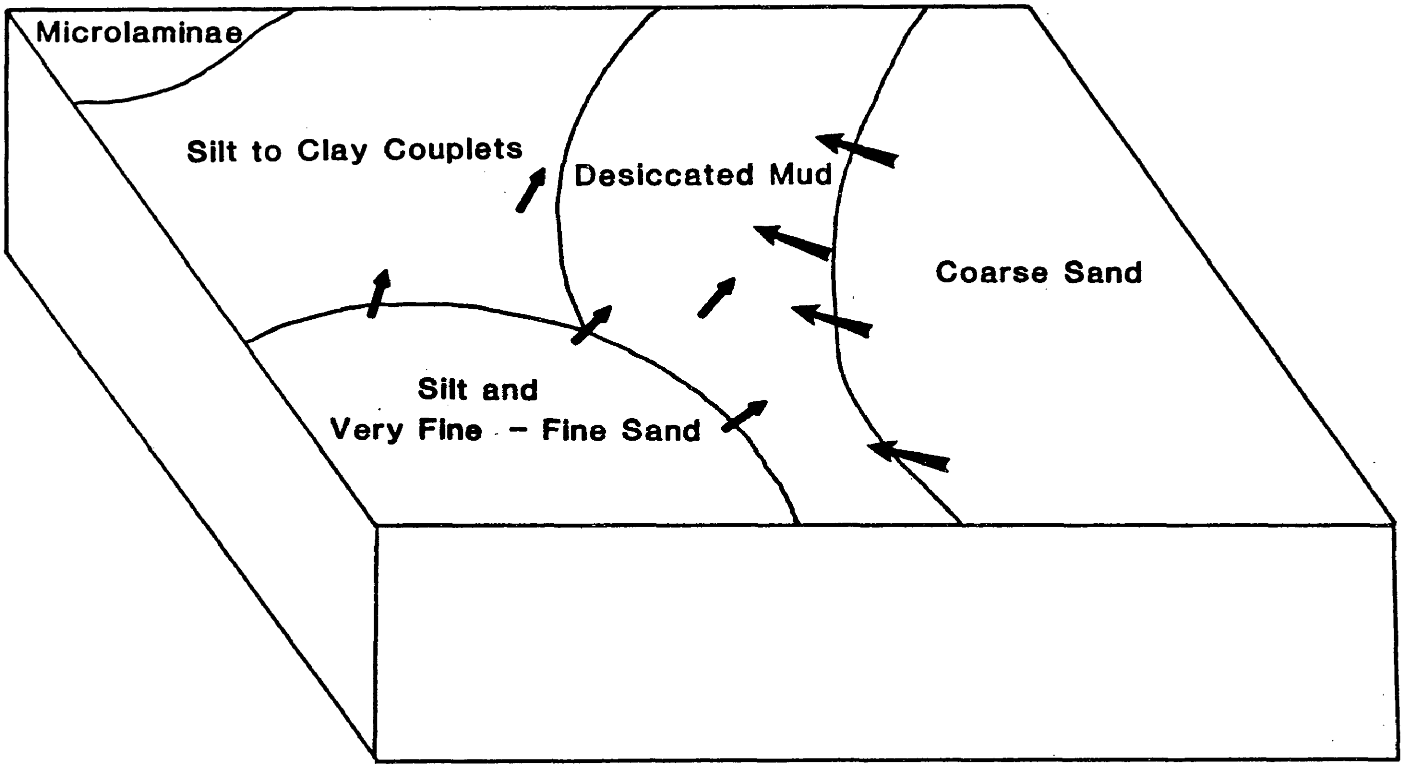

Figure 4-3: Generalized sediment type distribution.
Arrows indicate basinward flow across alluvial sand and mud flats into ponded water. Coarse sand originates from an eastern source and fine sand and silt from a southwestern source.

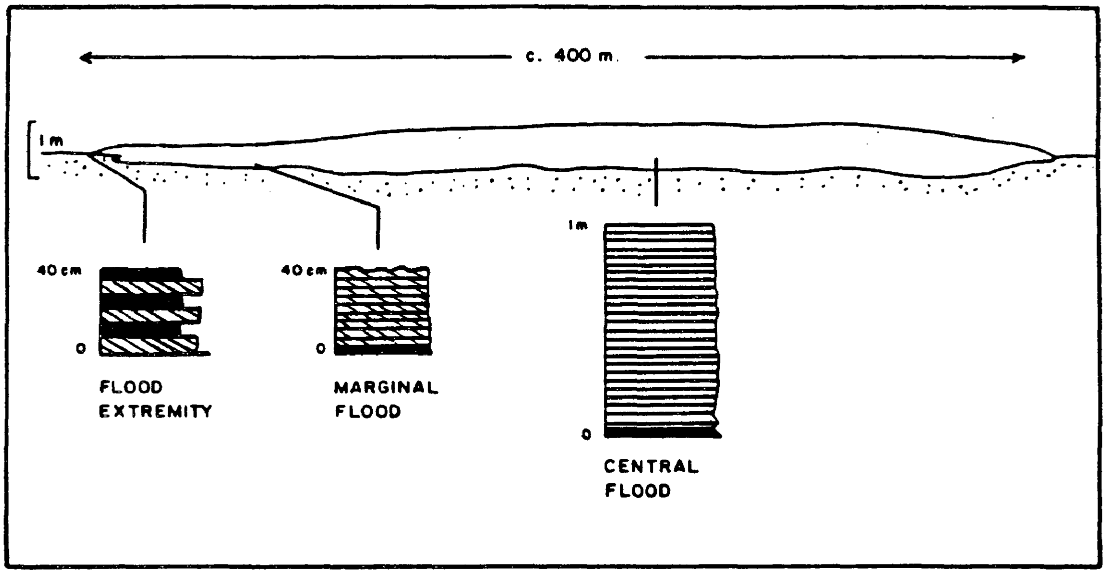

Figure 4-4: Tunbridge,1981; Scott et al., 1967.
Central flood deposits contain mostly flat-laminated sand, marginal flood deposits contain tabular sets of cross-bedded sand, and deposits of the flood extemity contain tabular sets of cross-bedded sand separated by mud.

Chapter 5

Conclusions

Unconfined, episodic sheet floods from the southeast carried coarse sand, across distal alluvial apron surfaces onto broad, sand and mud flats, while similar alluvial sheetfloods from the southwest deposited fine sand, silt and clay onto mudflats to the northeast and distally to the west. The interplay of both alluvial sources produced the unchannelled, multistory sand/mud sequences of the Grinnell Formation (Fig. 4-4). Deposition of these sequences was controlled by subtle variations in topography on the basin floor which caused broad depositional sand lobes to track laterally across desiccated mud flats (Horodyski, 1986, personal comm.). Upper flow regime transported sand at shallow flow depths forming antidunes(?) and abundant plane beds. As the flood waned to the lower flow regime, straight- to sinuous-crested large bedforms produced tabular-planar, tangential, and trough cross-strata. As each flood emptied into the enclosed basin, a severely restricted body of water responded by rapidly expanding over the sandflats. Wind wave reworking of the flooded sandflats, formed straight, bifurcating, unidirectional oscillation ripples. With cessation of flow, suspended mud was deposited as clay drapes on the coarse cross-bedded and rippled sand. As floods flowed farther out across mudflats and into standing water, they deposited progressively finer and thinner layers of the silt to clay couplet and microlamina sediment types. As the sandflats and mudflats drained, waters ponded and were rapidly desiccated to produce extensively mudcracked surfaces (desiccated mud sediment type).

Coarse sand in the Grinnell, derived from a source southeast of Mt. Henkel, decreases to the southwest, where it occurs in sections measured by Christopher Cronin (University of Montana, 1986) in the Mission, Swan, and Flathead Ranges, and also decreases rapidly west of Glacier Park in the Whitefish Range (this study). The eastern provenance of this coarse sand population (Units 2 and 5) is established by westward thinning and a northeastern paleocurrent trend. Tabular beds of silt in intervals on the east side of Glacier Park (Unit 4), thicken considerably to the west at Mt. Cannon, and into the Whitefish Range. Northeastward thinning silt beds in Member C-4 of the Creston Formation, interpreted as distal tongues of the Revett Formation (McMechan, 1981), are similar in grain size and character, and appear at the same stratigraphic level as those in Glacier Park and the Whitefish Range. Therefore, large alluvial floods from the southwest, which I believe to represent Revett floods, deposited very fine sand and silt in Unit 4 of the Grinnell and probably continued to redistribute the prograding apron of medium- to coarse-grained sand in Unit 5 by transporting sand to the northeast. Recent work by Christopher Cronin (University of Montana, 1986) demonstrates that the Revett Formation is stratigraphically more well defined to the south and west in the Mission, Swan, and Flathead Ranges than in Glacier Park or in the Whitefish Range.

Whether the marginal environment which bordered the distal alluvial sediments of the Grinnell was either a marine system (Harrison, 1972) periodically cut off from the sea, or a lacustrine system lacking external drainage as proposed by Winston (1986b) and Winston et al. (1984) for the Belt basin, cannot be proven or disproven on the basis of data contained in this thesis alone. However, the stratigraphic relationship and basinward fining of sediment types, the apparent rapid expansion of a shallow body of water following flood events, and the lack of channels, are strong evidence for a lacustrine interpretation of the finer-grained sediment types of the Grinnell which represent the most basinward deposits. Although many would argue that large-scale tidal channels are not a prerequisite for a marine incursion, it is difficult to imagine such extensive tidal flats, as the Grinnell would represent in a marine system, lacking distinct channelling of any sort. Even more unusual is the lack of fining-upward vertical profiles that record most ancient tidal deposits (Ginsburg, 1975; Klein, 1977). There is no ancient or modern analogue that reasonably explains expansion of an inland marine sea followed by ponding and rapid desiccation. Such a sea would necessarily be cut off from a larger marine system and would essentially be lacustrine.

5.1. Further Research

A more complete paleocurrent analysis of Ravalli Group sediments throughout the Belt Basin would further define the interplay of currents and the effects of fluvial influxes from the east and west sides of the Belt Basin. Further research should also be devoted to the origin of multicycle sands and diagenesis of sediments in the Grinnell. Additional measured sections in the Ravalli Group on the eastern edge of the basin and to the south would supplement this study in determining the exact relationship of the Grinnell Formation to the Burke, Revett, and St. Regis formations to the west, and the Spokane Formation to the south.

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Appendix A

METHODOLOGY

In Glacier Park, sections were measured at Mt. Henkel, Goat Mt., and Mt. Cannon (Fig. 1). In the Whitefish Range, a section was measured on an unnamed ridge due east of West Stryker Ridge, approximately 2.7 miles north of Upper Whitefish Lake. A total of 10,000 feet of section was measured with a clinometer and a Jacobs Staff. Where rocks were exposed, sections were marked in tape every five feet and then described. In describing these sections I compiled a graphic and written log on square ruled graph paper at a scale of 1 inch = 10 feet. Rock samples were gathered from marked stratigraphic sections for petrographic analysis. Cross-bed azimuths were measured using a Brunton Compass and plotted on a stereonet.

Appendix B

PETROGRAPHY OF QUARTZARENITES IN THE GRINNELL

Although the sequence of diagenetic events in the the Grinnell sands are probably quite complex and involve many changes in chemical equilibria of interstitial waters, several trends in the diagenetic history of medium to coarse sands can be recognized:

1.) Mechanical infiltration of clay following deposition

2.) Compaction of sand and mud, evidenced by bent or deformed clay flakes

3.) Hematite pigmentation coats original grain surfaces

4.) Alteration of plagioclase to sericite, and / or authigenic clay (ie., kaolinite / dickite)

5.) Silicification of carbonate ooids to chert

6.) Authigenic quartz overgrowths, partially or completely fill annular pore space and form tightly interlocking mosaic of grains

7.) Dissolution of some authigenic quartz cement and filling of remaining pore space by ferroan dolomite, ankerite, siderite or calcite.

8.) Pressure solution and stress lamellae (shear fabric) form in quartz grains subject to a higher degree of metamorphism

Although most of the Grinnell west of the Continental Divide in Glacier Park is weakly metamorphosed to greenschist facies, samples collected from measured sections on the east side of the Divide are relatively unmetamorphosed. Attention was focused on the medium- to coarse-grained sand sediment type (see discription - pg.22) which represents an eastern to southeastern source terrain. The mineralogy and coarseness of these sands may reflect a nearby cratonic source (Conner, 1984). These sands are generally moderate to very well-sorted, upper fine- to upper coarse-grained, subangular to very well-rounded, and contain detrital mineral assemblages characteristic of granitic and high grade metamorphic sources and multicycle sands (quartz and feldspar) presumably reworked from an uplifted sedimentary source area. Preliminary work by Will Freeman (University of Montana, 1986) suggests the Neihart Quartzite as a potential source for this grain population. The coarsest grain sizes include well-rounded quartz grains up to 1mm in diameter and angular to well rounded mud intraclasts which range up to cobble size.

Because the large amount of clay pellets, clasts, mechanically infiltrated clay and authigenic clay make it difficult to adequatly represent Grinnell quartzarenites by using ternary diagrams (after Krynine, Pettijohn, Folk, etc,...) the following chart (Fig. B-1) summarizes thin sections on the basis of mineral and component percentages.

B.1. Origin of Red Pigmentation

The characteristic red and green coloration of beds in the Grinnell is a product of diagenetic alteration of hematitic and chloritic ions in oxidized or reduced clays (Walker, 1967, 1978; Winston, 1986b). Generally red beds do not become abundant in the stratigraphic record until about 1800-2000my, and indicate that free oxygen began to accumulate about this time (Cloud, 1968). Of numerous hypotheses proposed for the origin of red beds, Ericksson and Vos (1979) found three which they considered to be the most feasible. The red pigment may be 1.) detrital hematite derived from a laterised source terrain (Krynine, 1950); 2.)

MINERAL PERCENTAGES OF THIN SECTIONS

Thin Section #	STRAIGHT QUARTZ	METAMORPHIC QUARTZ	ORTHOCLASE	PLAGIOCLASE	MICROCLINE	CHERT	OOLITHS	CLAY FRAGMENTS	CARBONATE CEMENT	QUARTZ CEMENT	OTHER	GRAIN SIZE
H-993	45-50	1-2	10	7	1	2-3	1	10-15	1	10		med-cs
H-542	50-60	1	10	5		---	1	---	20-25			v.fn-fn
H-1866	50-55	---	5	5	5	1	1	10-15	1-3	10	Chlorite 1	fn-med
H-1916	50-55	1-2	3-5	2-3	3-5	2	--	---	20-30	--	Musc. 1	v.fn-fn
H-1725	80	---	---	---	---	--	--	15	4-5	--	Musc. 1-2	f.fn
H-1963	60-65	1-2	5-8	2-3	4-5	1	--	---	3-5	10-15		med
H-350	60-65	1	10-12	2-3	---	1	--	1-2	--	10-15		fn-med
H-715	50-55	---	5	2-3	---	--	4.5	10-15	15-20	<5		v.fn-cs
H-1835	70-75	---	3	2	3-5	--	---	---	---	10-15	Pyrite 1	med-cs
W-2700	45-50	---	4-5	2	---	1	---	Serrucite 20-25	---	10-15	Chlorite 5	v.fn-med
W-3160	30-35	---	4-5	2	---	--	---	Serrucite 40-45	3-4	10-15	Pyrite 1-2	v.fn-med
W-1630	50-55	---	4-5	1	1	1	---	15-20	2-3	10-15	Pyrite 1-2	fn-med
W-2916	45-50	---	3-5	--	---	--	---	Serrucite 30-35	---	2-4	Chlorite 5	v.fn-med
RG-1(F)	55-60	---	7-8	<1	---	--	---	5-10	15-20	4-5	Pyrite <1	med-cs
LMD 18-2(F)	55-60	1	4-5	<1	---	2	---	15-20	---	10-15	Zircon <1	med-cs
LMD 18-7(F)	60-65	1	8-10	1	1	1	---	8-10	5-8	10	Tourmaline & Musc. <1	med-cs
PT 1-11(F)	55-60	1	4-5	1	---	--	---	10	10-15	10-12	---	med-cs

Numbers represent mineral percentages (1-100%)

H - Mt. Henkel
W - Whitefish Range
PT - Ptarmigan Tunnel

RG - Red Gap Pass
LMD - Lake McDonald

(F) - indicates thin sections cut from float. Exact stratigraphic level unknown.

Figure B-1: Mineral percentages of thin sections. Chart shows relative mineral percentages observed in thin sections of quartzarenites.

diagenetic hematite formed in situ as a result of the conversion of limonite derived from a laterised source terrain (Van Houten, 1968); or 3.) authigenic hematite formed through the diagenetic alteration of iron-bearing detrital silicate or oxide minerals (Walker, 1967; Hubert and Reed, 1978). Of these hypotheses, red pigmentation in the Grinnell appears to represent an authigenic-diagenetic origin. FeO in feldspars and ferromagnesian minerals provide a potential source of iron. Magnetite, which occurs in Grinnell sands is also a possible source of iron in red beds (Hubert and Reed, 1978). However, iron released from silicate minerals by intrastratal solution was probably transported in groundwater at elevated Eh and pH prior to its precipitation on grain surfaces and fractures (Ericksson and Vos, 1979). Ericksson and Vos (1979) suggest this precipitate was in the form of limonite which converted to hematite with alteration (Hubert and Reed, 1978). Furthermore, they found that the age of the red coloration developed at an early stage of diagenesis as evidenced by authigenic quartz overgrowths which post date the pigmentation and terminated the limonite-hematite transition. Such authigenic quartz overgrowths, defined by stainings on sufaces of original, well-rounded, quartz grains, are quite common in the coarse Grinnell sands (Fig. B-2) and also appear as concentric rings on silicified ooids (Fig. B-3).

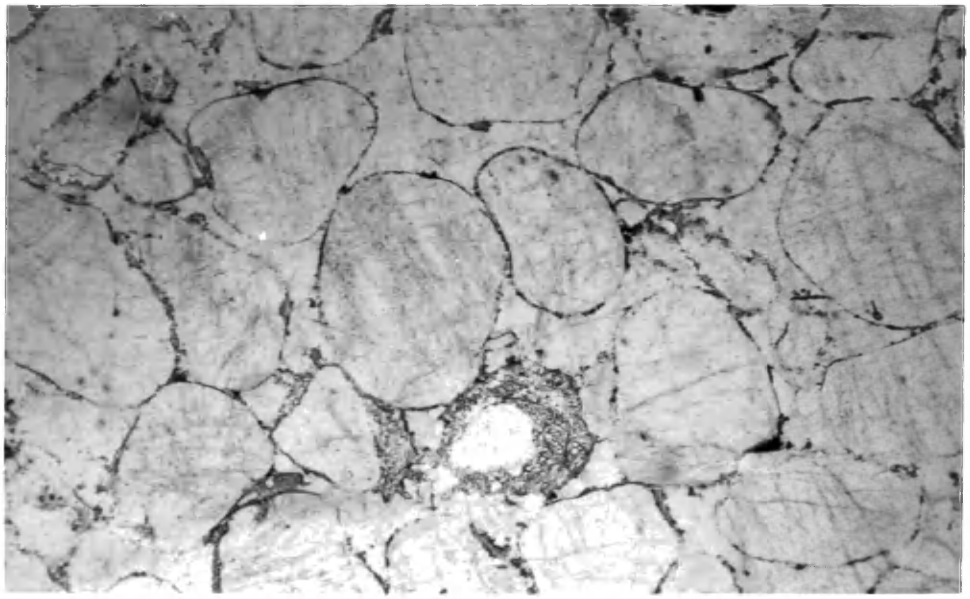


Figure B-2: Authigenic quartz overgrowths.
Well-rounded quartz grains surrounded by syntaxial quartz cement. Grains are well defined by dust coatings on original grain surfaces. Plane light.

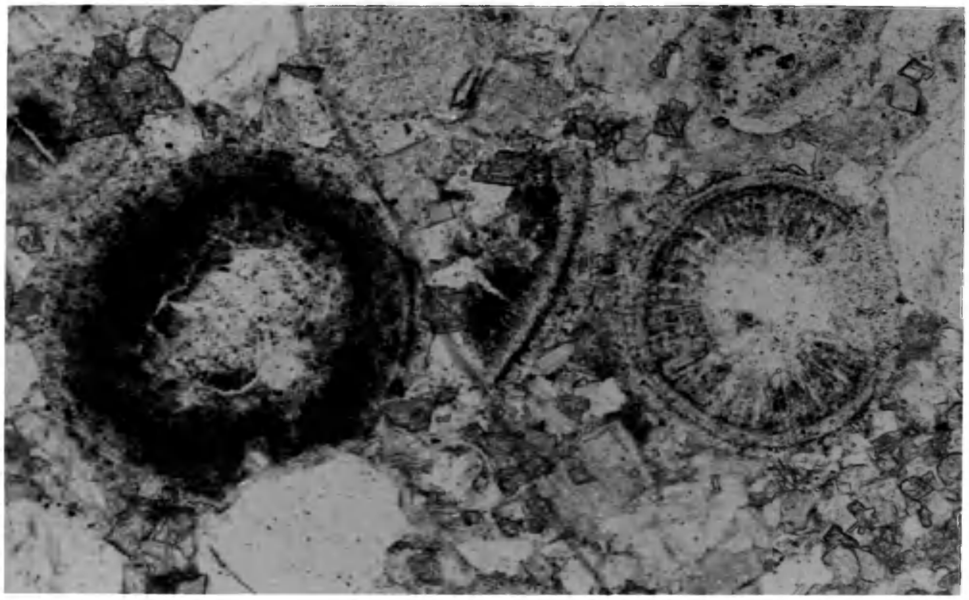


Figure B-3: Hematite coating silicified ooliths.
Concentric accreted rings are well defined on silicified ooliths by hematite rinds. Dissolution of syntaxial quartz cement by dolomite is visible in the center of the photo. Plane light.

Appendix C

MEASURED SECTION LOCATIONS

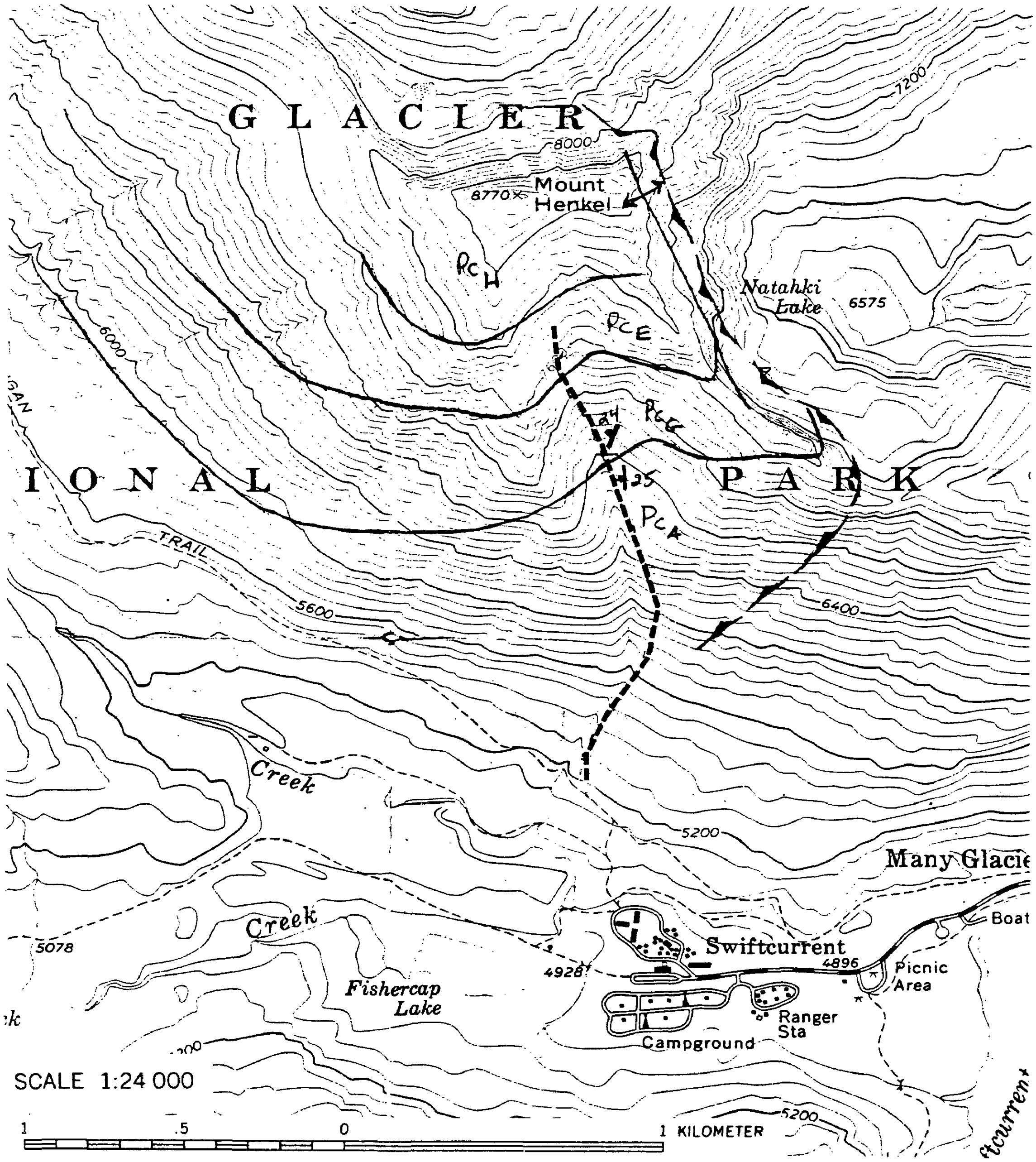


Figure C-1: Mt. Henkel section.
Many Glacier 7.5 minute quadrangle. From Swiftcurrent Motor Lodge ascend the southfacing bowl of Mt. Henkel via the Iceberg-Ptarmigan trail.

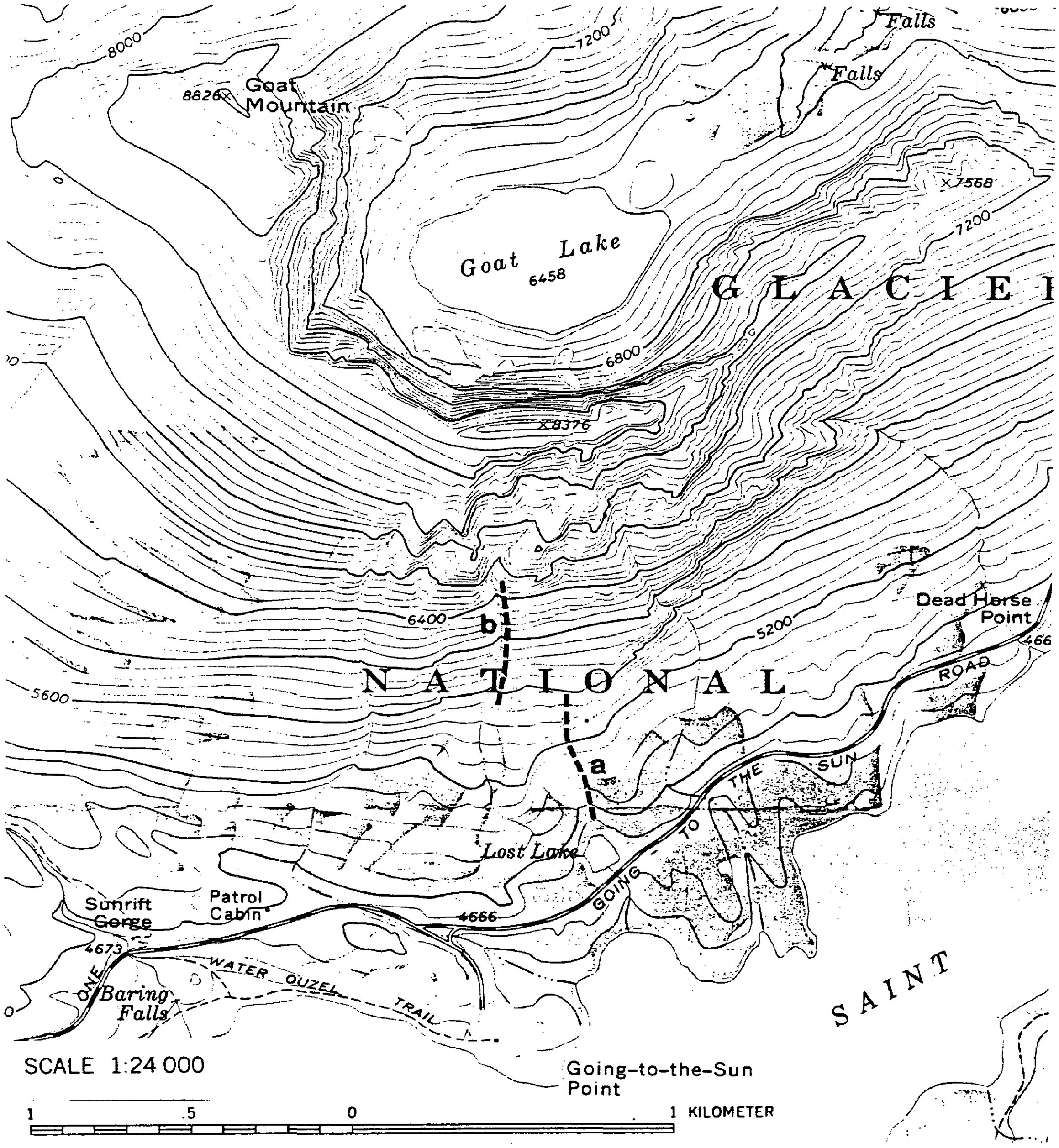


Figure C-2: Goat Mountain sections a and b.
Rising Sun 7.5 minute quadrangle. This section is located above Lost Lake in the large southfacing avalanche chute directly below the summit of Goat Mountain.

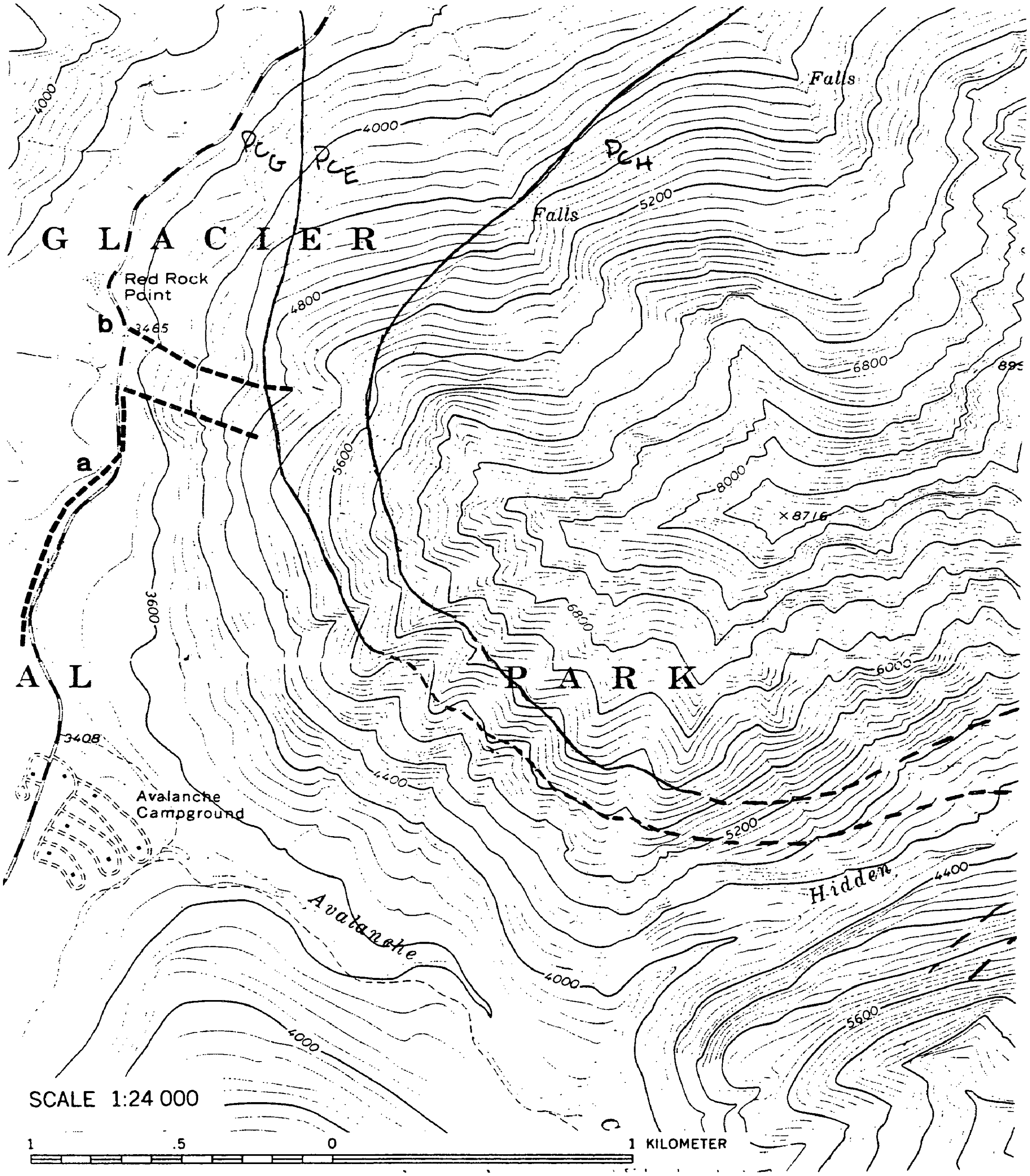


Figure C-3: Mt. Cannon sections a, b, and c.
Mt. Cannon 7.5 minute quadrangle. Section a was measured along McDonald Creek north of Avalanche Campground. Section b begins in the large avalanche chute near Geology Roadstop #18 on the Going-to-the-Sun-Road. Section c was measured on the southwestern slopes of Mt. Cannon at the foot of Avalanche Lake.

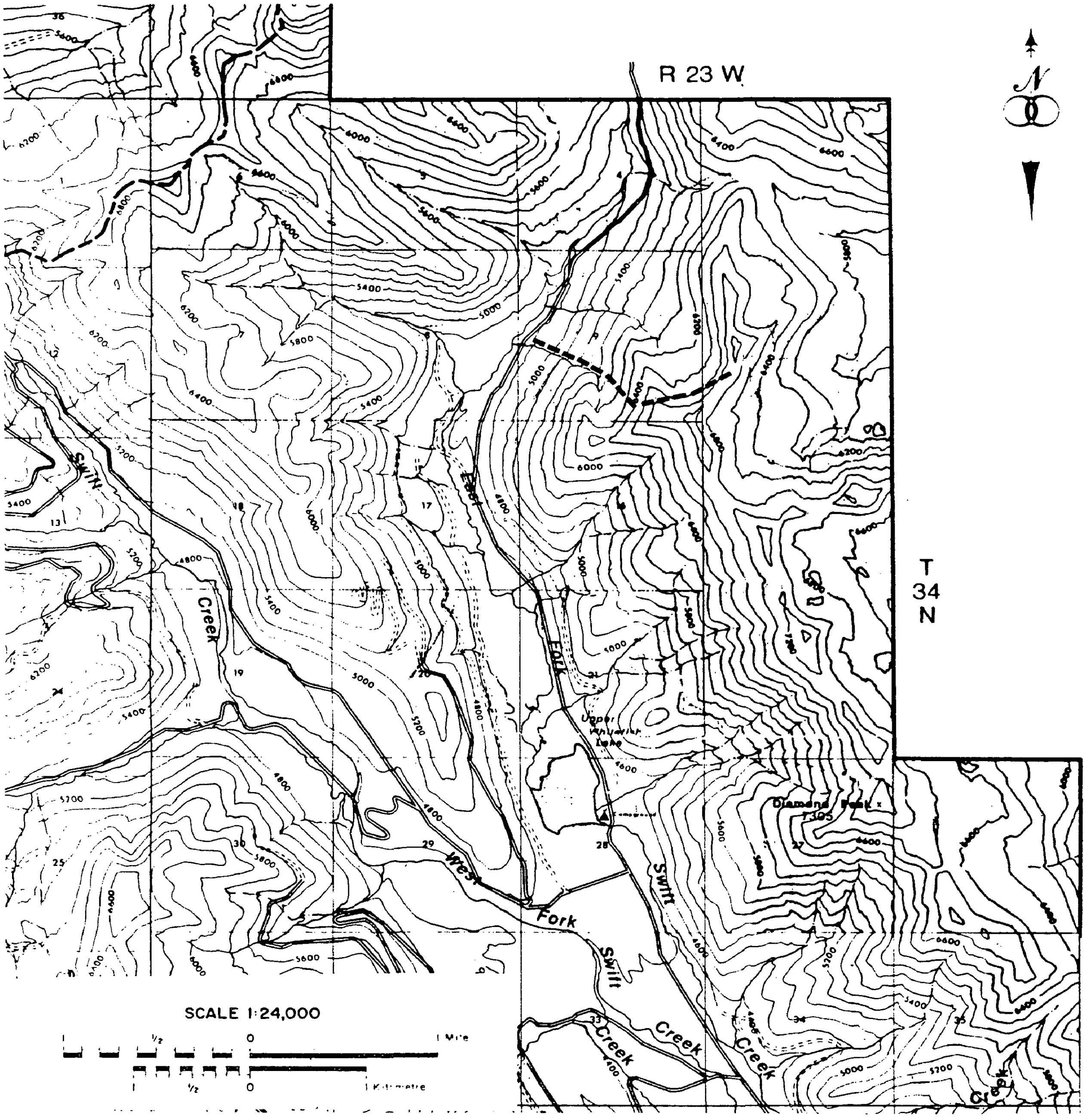
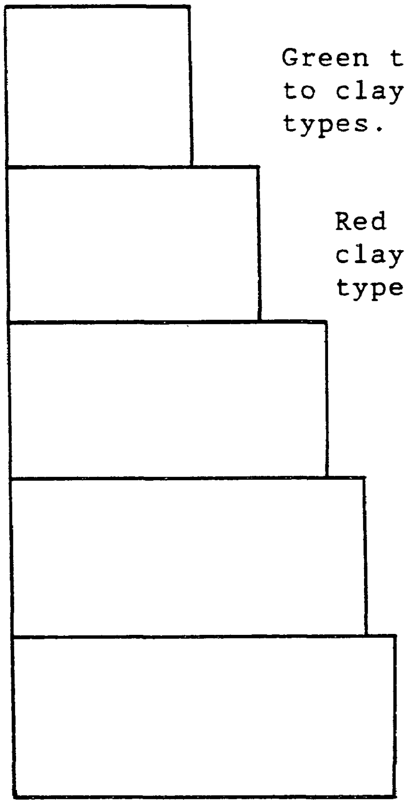


Figure C-4: Whitefish Range section.
Northern half of the Stillwater State Forest map, 1:24000. Section located 2.7 miles north of Upper Whitefish Lake on westfacing slope of unnamed ridge.

Appendix D

MEASURED SECTION PROFILES

KEY TO MEASURED SECTIONS



Green to tan-weathering, dolomitic, silt to clay couplet and microlamina sediment types.

Red to purple, desiccated mud, silt to clay couplet, and microlamina sediment types.

Flat-laminated silt sediment type (varies from pink to green in color).

Very fine to fine-grained sand sediment type.

Stacked beds of the medium to coarse-grained sand sediment type.

- Abbreviations used in section notes -

MCS - Medium to coarse-grained sand sediment type
VFFS - Very fine to fine-grained sand sediment type
FLS - Flat-laminated silt sediment type
DM - Desiccated mud sediment type
CPL - Silt to clay couplet sediment type
ML - Microlamina sediment type

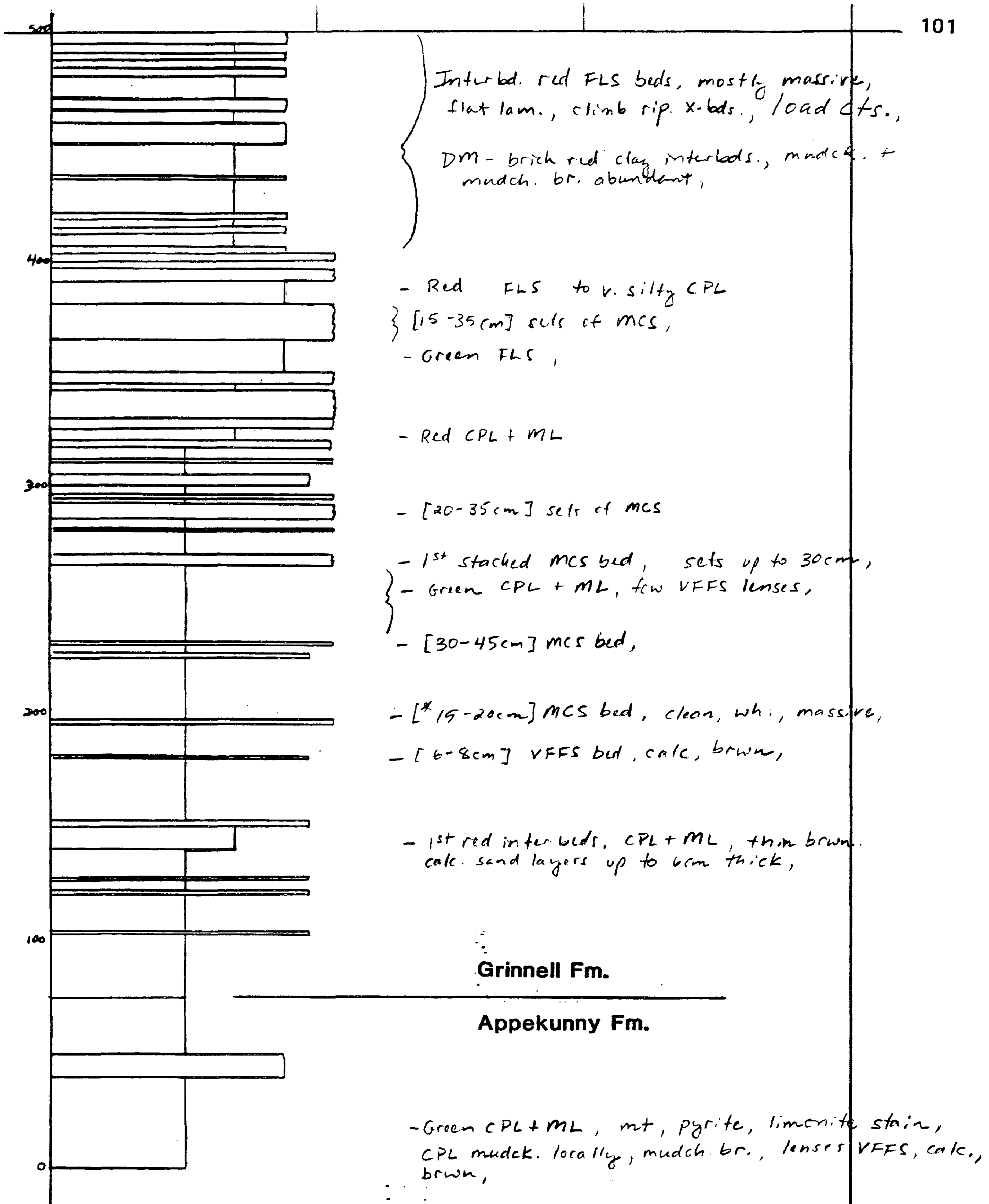
- Abbreviations used in section notes (Cont.)

pk - pink
wh - white
grnd - grained

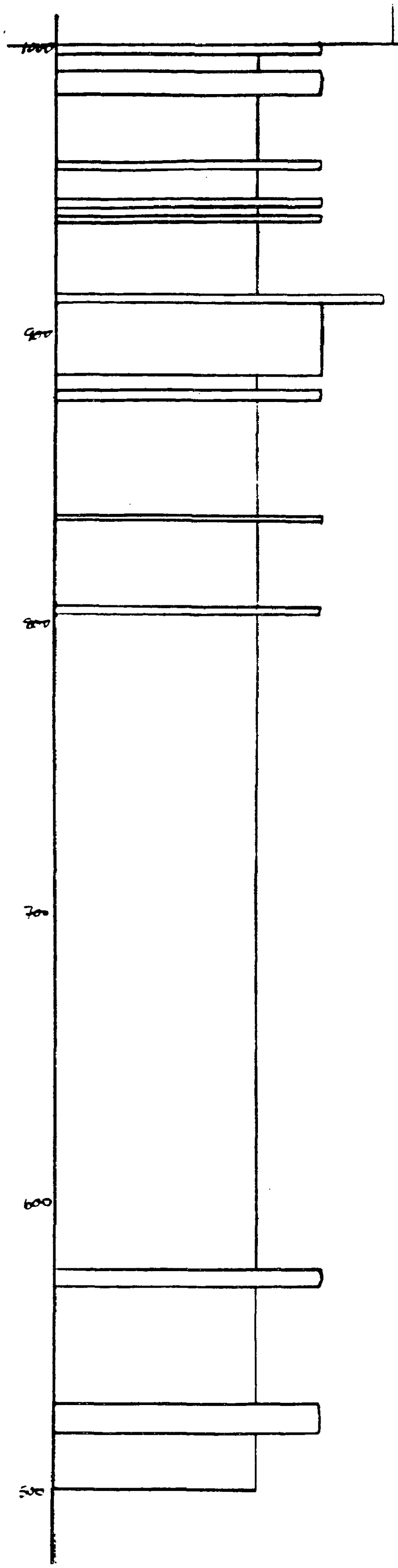
bd - bedding
bds - beds
low ∢ tang. - low angle tangential

(⅄) - used to indicate shrinkage cracks in a subaqueous setting

osc. ripples - oscillation ripples
acct. mudballs - accreted mudballs
flat lam. - flat-laminated
tab. planar - tabular planar cross-beds
otcp - outcrop
lim. - limonite



Mt. Henkel Section



- DM

- Dm

- 30cm bed MCS, low ∡ tang. x-bds

- Red to Pk FLS

- Dm

- DM

- Thin lenses MCS increase upsection [1-10cm] sets,

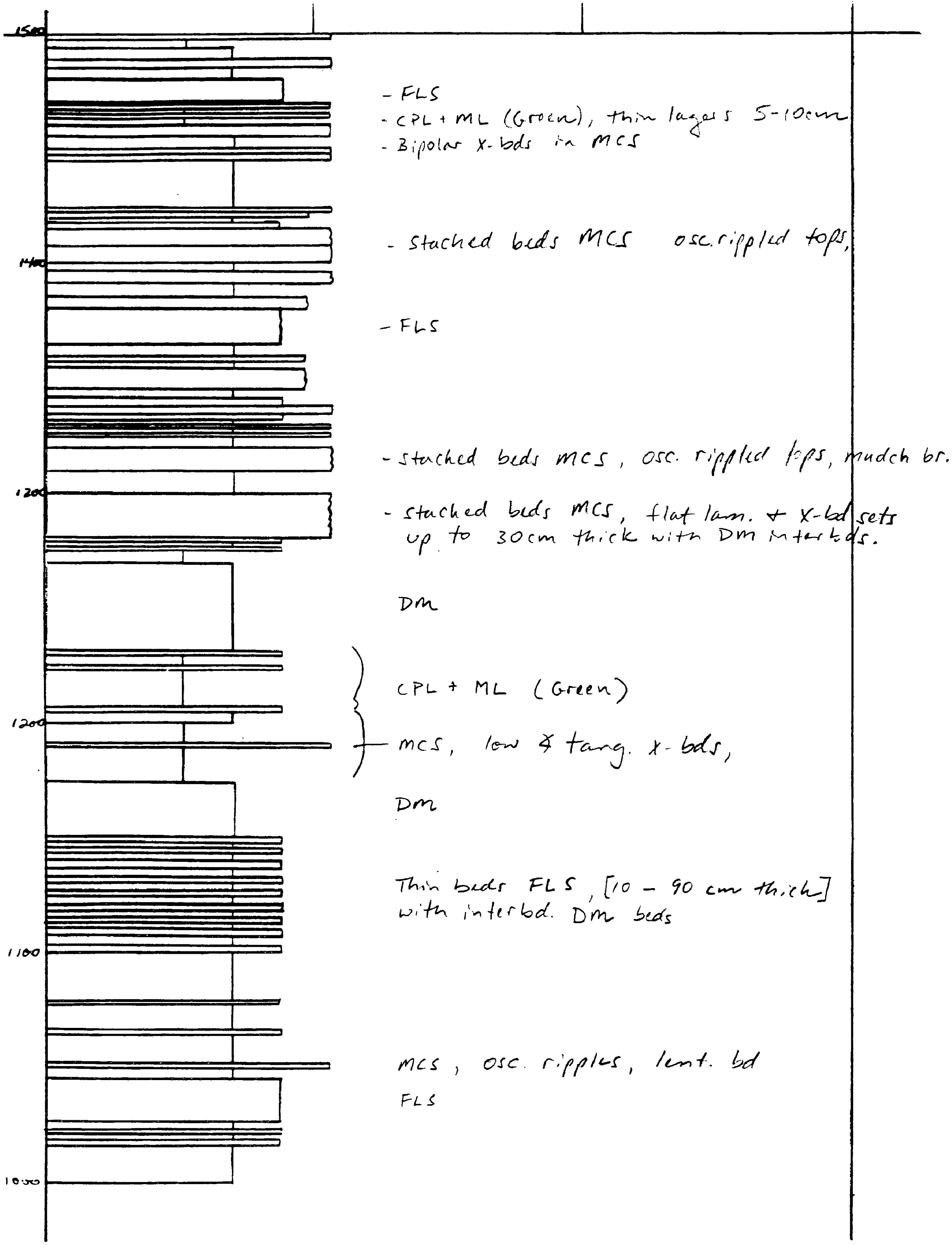
- DM, w/ thin, rare VFFS lenses often reduced to green [1-5cm], thin intervals ML,

- Red to Pk FLS,

- Dm

- Red to Pk. FLS,

- Dm w/ thin VFFS lenses reduced to green



- FLS
- CPL + ML (Green), thin layers 5-10cm
- Bipolar X-bds in MCS

- Stacked beds MCS osc. rippled tops,

- FLS

- stacked beds MCS, osc. rippled tops, mudch br.

- stacked beds MCS, flat lam. + X-bd sets up to 30cm thick with Dm interbds.

Dm

CPL + ML (Green)

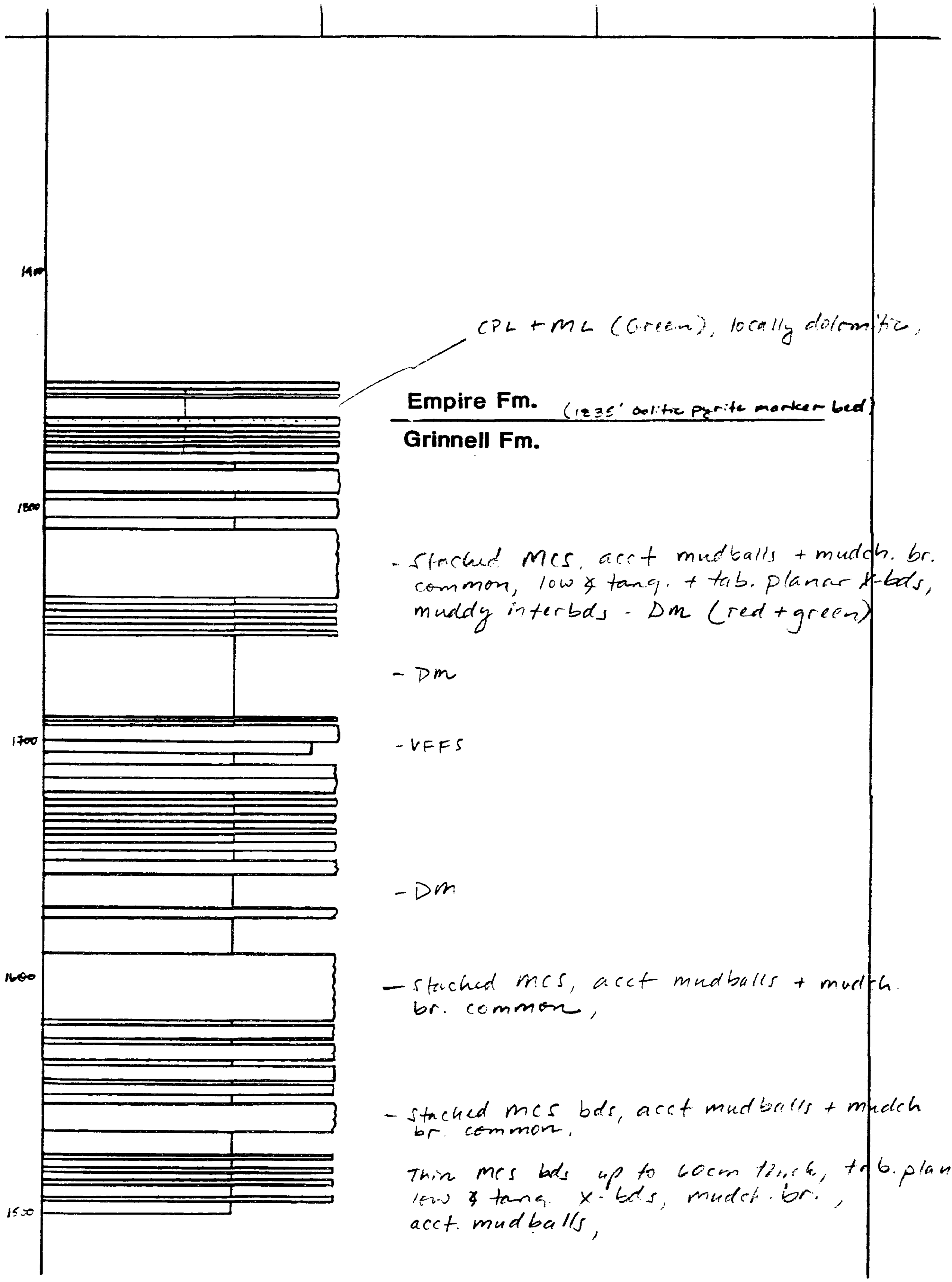
MCS, low & tang. x-bds,

Dm

Thin beds FLS, [10 - 90 cm thick] with interbd. Dm beds

MCS, osc. ripples, lent. bd

FLS



CPL + ML (Green), locally dolomitic,

Empire Fm. (1235' oolitic pyrite marker bed)

Grinnell Fm.

- Stacked MCS, acct mudballs + mudch. br. common, low ∡ tang. + tab. planar X-bds, muddy interbds - Dm (red + green)

- Dm

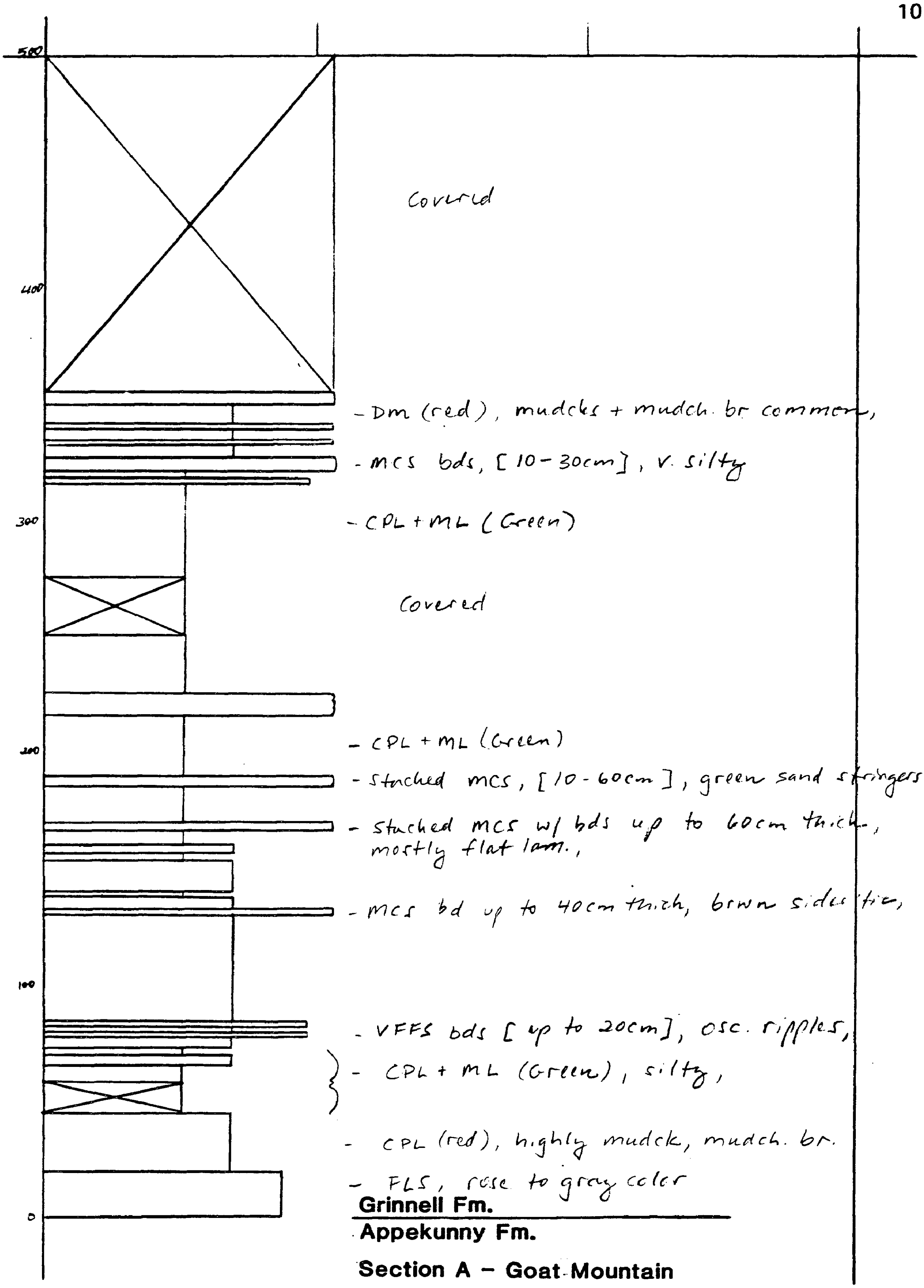
- VFFS

- Dm

— stacked mcs, acct mudballs + mudch. br. common,

- stacked mcs bds, acct mudballs + mudch br. common,

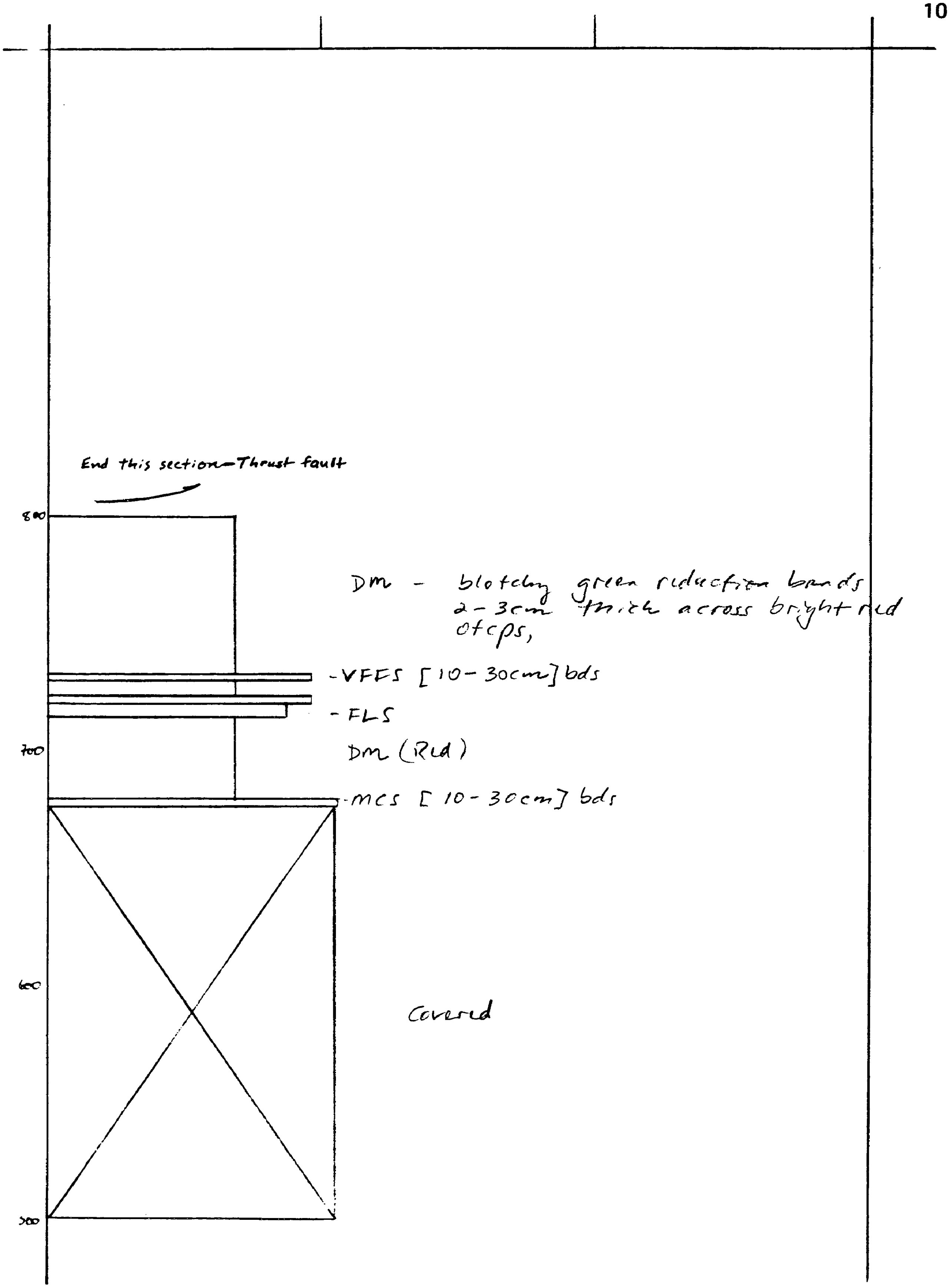
Thin mcs bds up to 60cm thick, tab. planar + low ∡ tang. X-bds, mudch. br., acct. mudballs,

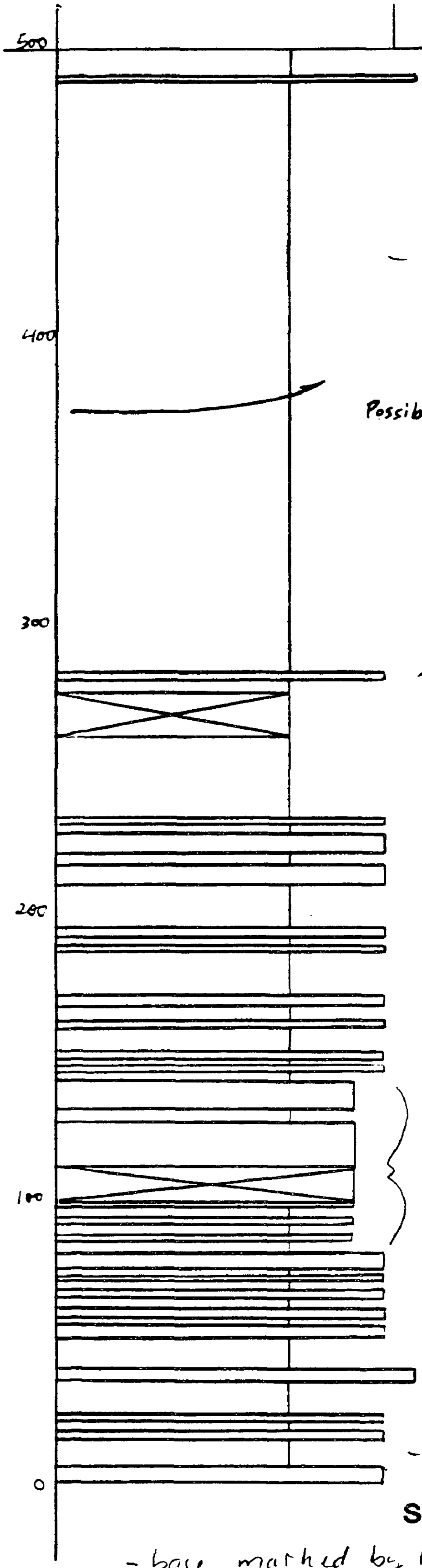


Grinnell Fm.

Appekunny Fm.

Section A – Goat Mountain


End this section—Thrust fault
800
DM - blotchy green reduction bands 2-3cm thick across bright red otcps,
-VFFS [10-30cm] bds
-FLS
700
DM (Red)
-mcs [10-30cm] bds
600
Covered
500



- Mostly DM, silty, rose to bright red color, greenish reduction bands follow thin [2-3cm] sand stringers,

Possible bedding plane thrust - 375'

- 2.5 m. thick mostly fn.-med. grnd sand bd., stacked bds [10-30cm]

- Dm,

Stacked VFFS, white to pink [10-30cm] mudch. br. common,

- Dm (red)

FLS (Rose to gray color)

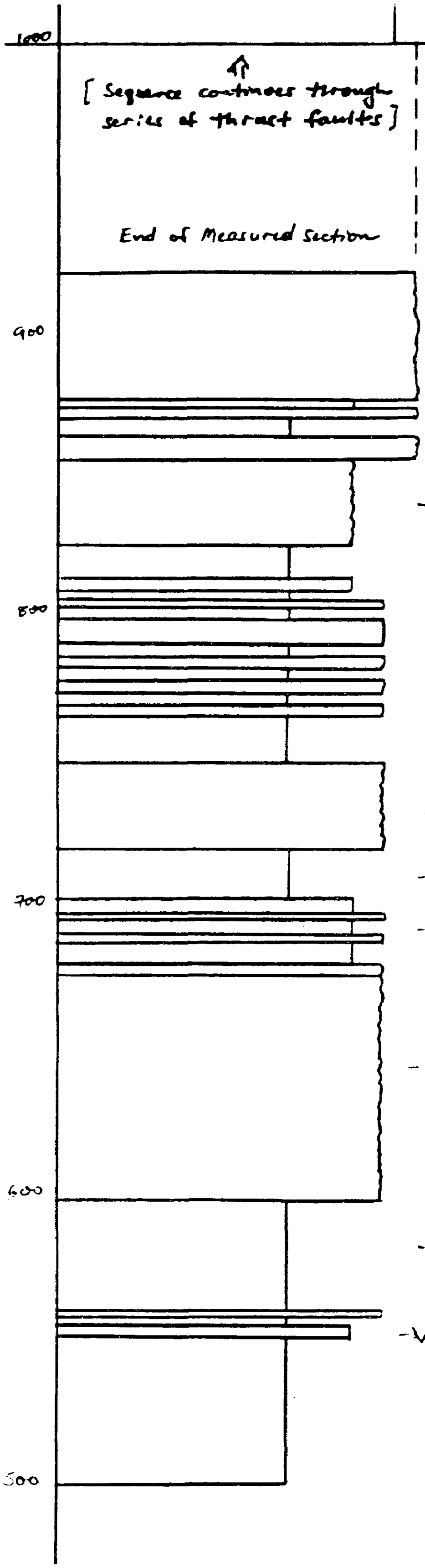
VFFS bds [10-30cm], mostly fn.-med. grnd,

- MCS bed [10-30cm]

- Interbds silty red Dm,

Section B – Goat Mountain (overlapping section)

- base marked by low ∠ thrust



- Stacked MCS [10-90cm] bds, low & tang. x-bds, common, mudch. br. + acct. mudballs common, osc ripples,

- stacked VFFS [10-30cm] bds, low & tang. x-bds, common, osc. ripples,

- Dm

- Stacked MCS [10-90cm], mudch. br.'s + acct mudballs common, low & tang. x-bds rare,
- Dm

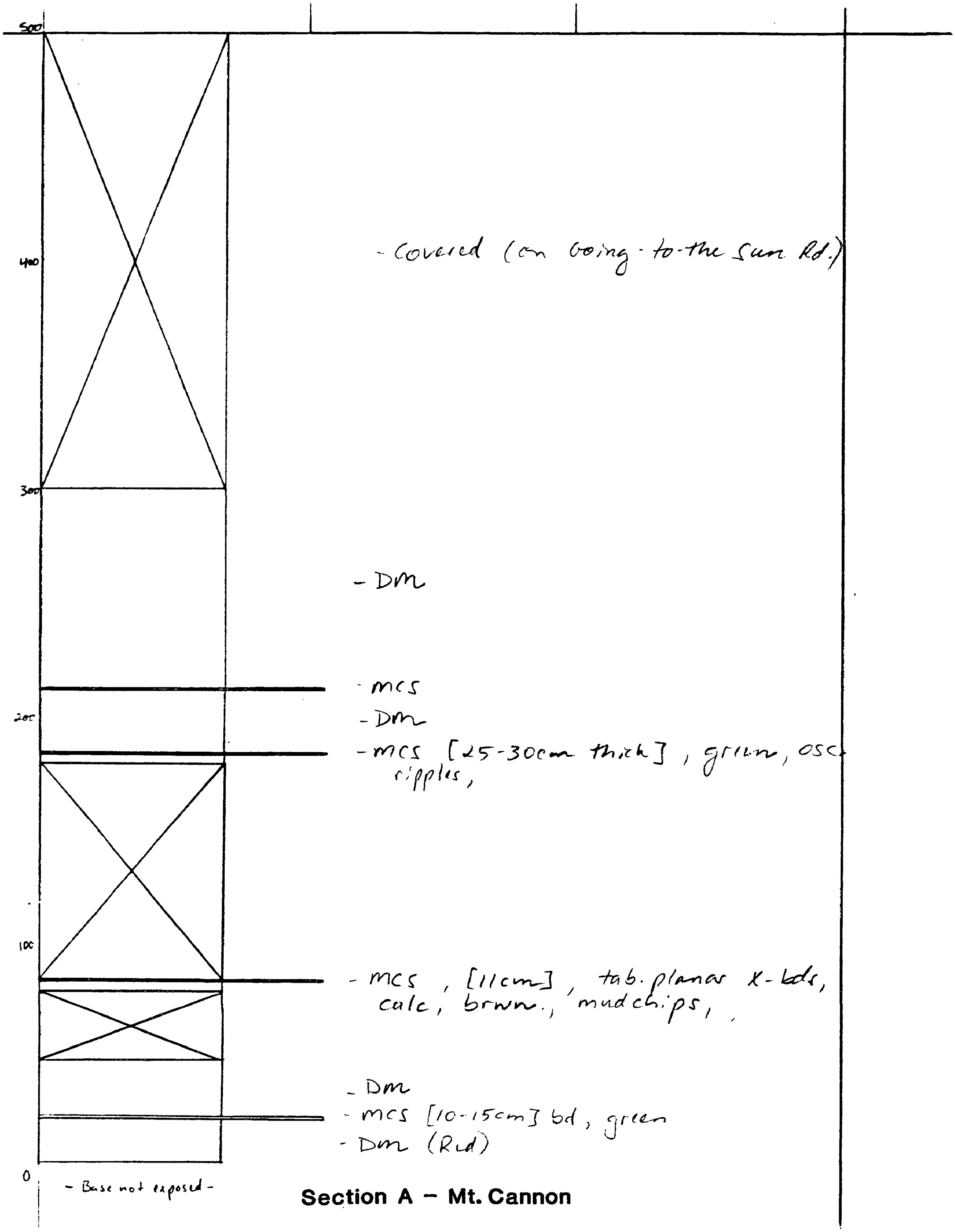
- FLS, massive w/ MCS Mfcs bds,

- Stacked MCS bds [10-90cm], mudch. br.'s + acct mudballs common, mostly flat lam.,

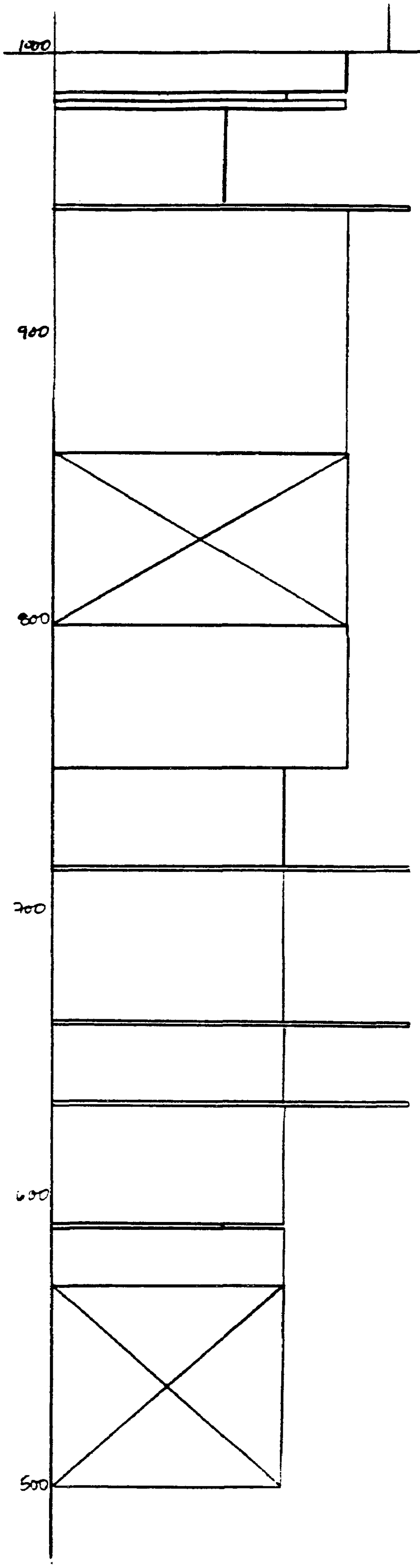
- <u>DM</u> - mudch. br.'s increase in frequency upsection

-VFFS, [10-30cm] bds, clean, white,

<u>DM</u> - m-cs floating sand increases upsection
↑



Section A – Mt. Cannon



- FLS, green to tan-weathering,

- Green CPL + ML, massive siltier interbds,

- MCS [20-30cm thick], green,

- FLS, pink to gray color, thin 5-6 cm lenses of MCS,

- covered

- FLS, rose to gray color, muddy, load casts, climb ripp. x-bds,

- Dm

- MCS [30cm thick] pk to white color,

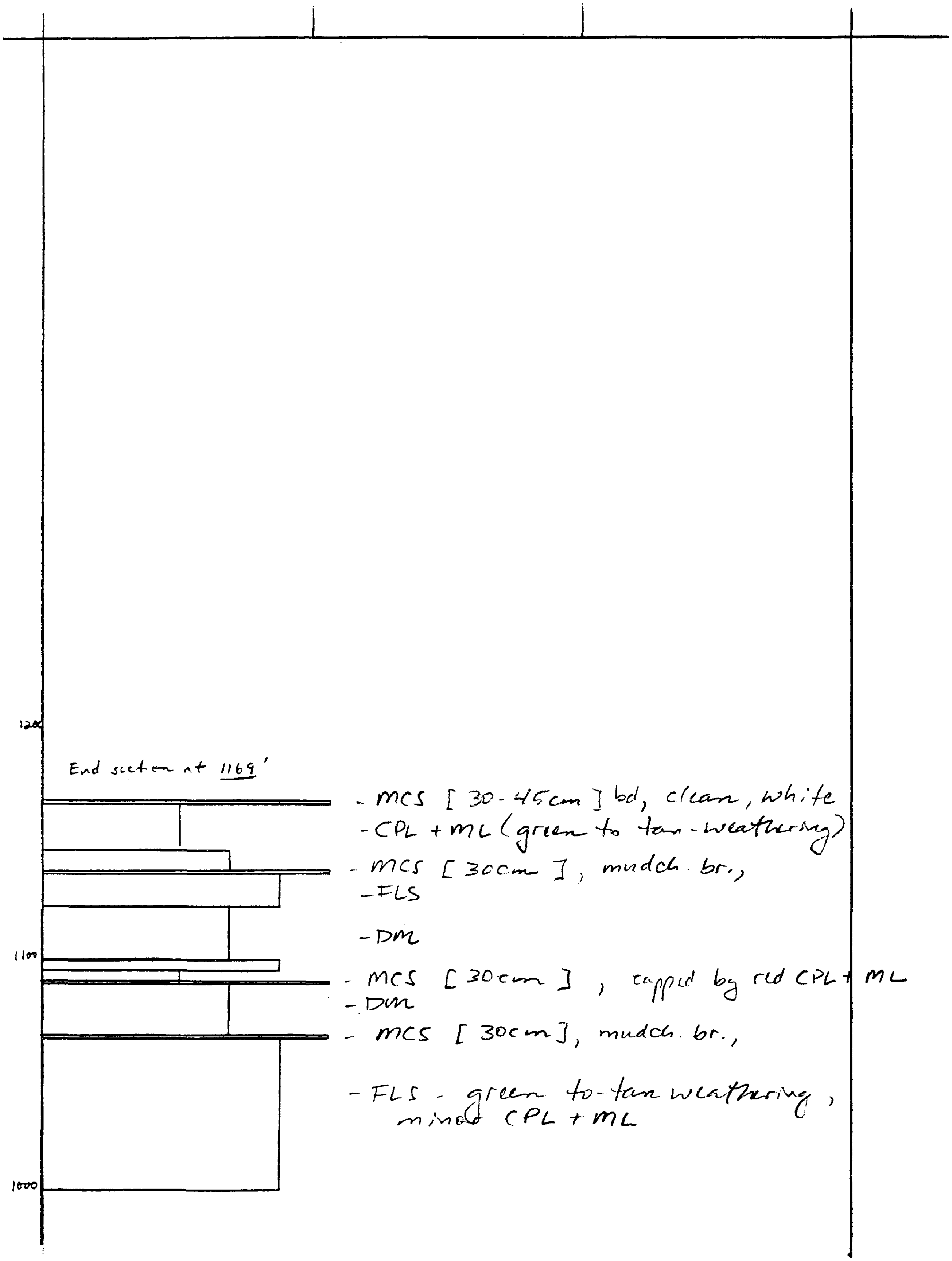
- Dm

- MCS [30cm thick]

- MCS [30cm thick], red to pk color,

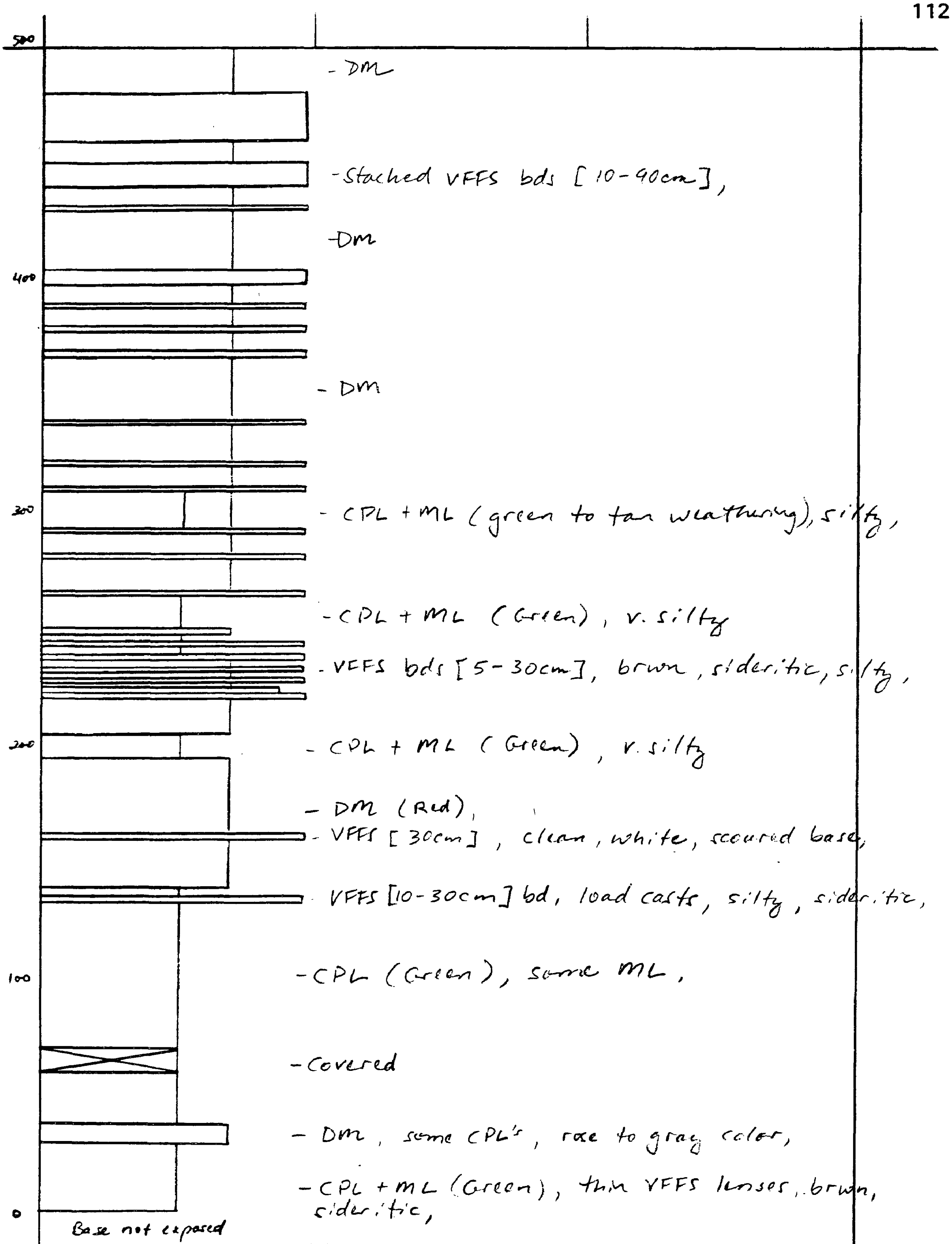
- Dm

- Covered

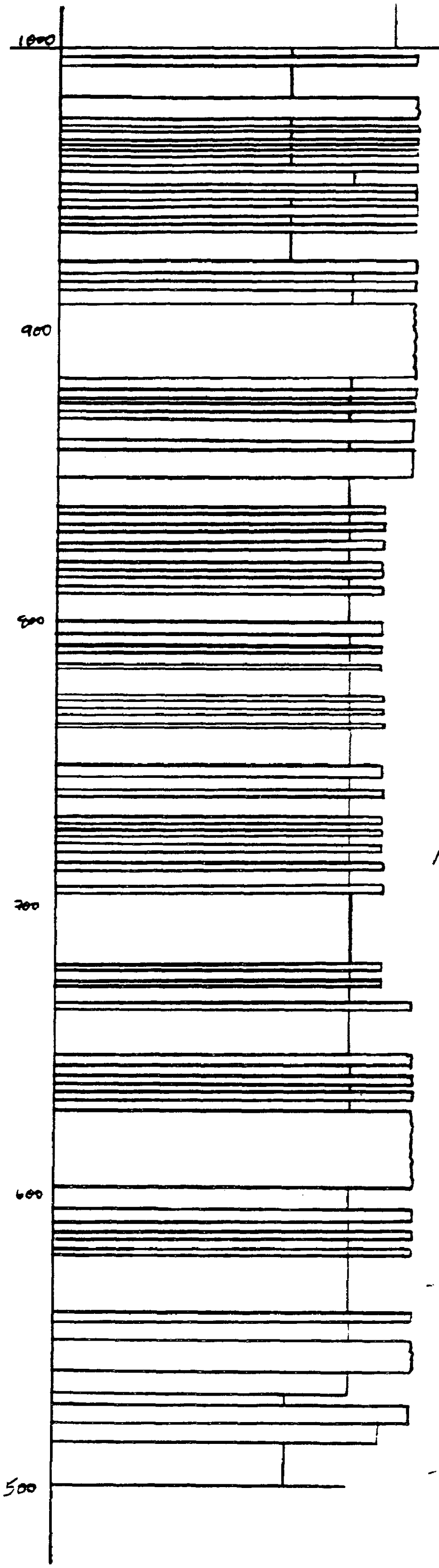


End section at 1169'

- MCS [30-45cm] bd, clean, white
- CPL + ML (green to tan-weathering)
- MCS [30cm], mudch. br.,
- FLS
- DM
- MCS [30cm], capped by red CPL + ML
- DM
- MCS [30cm], mudch. br.,
- FLS - green to-tan weathering, minor CPL + ML



Section B – Mt.Cannon
(near Going – to – the – Sun Road)



-Dm

-FLS

- Dm

- Begin stacked MCS bds [10-90cm], dirty siderite, tab. planar x-bds, acct. mudballs, mudch. br.,

- Mostly VFFS bds [10-60cm], w/ FLS interbds, tab planar x-bds 3-4cm, beds pk to white, clean, well sorted,

- FLS, muddy silt, pk-purple, massive, mudcks,

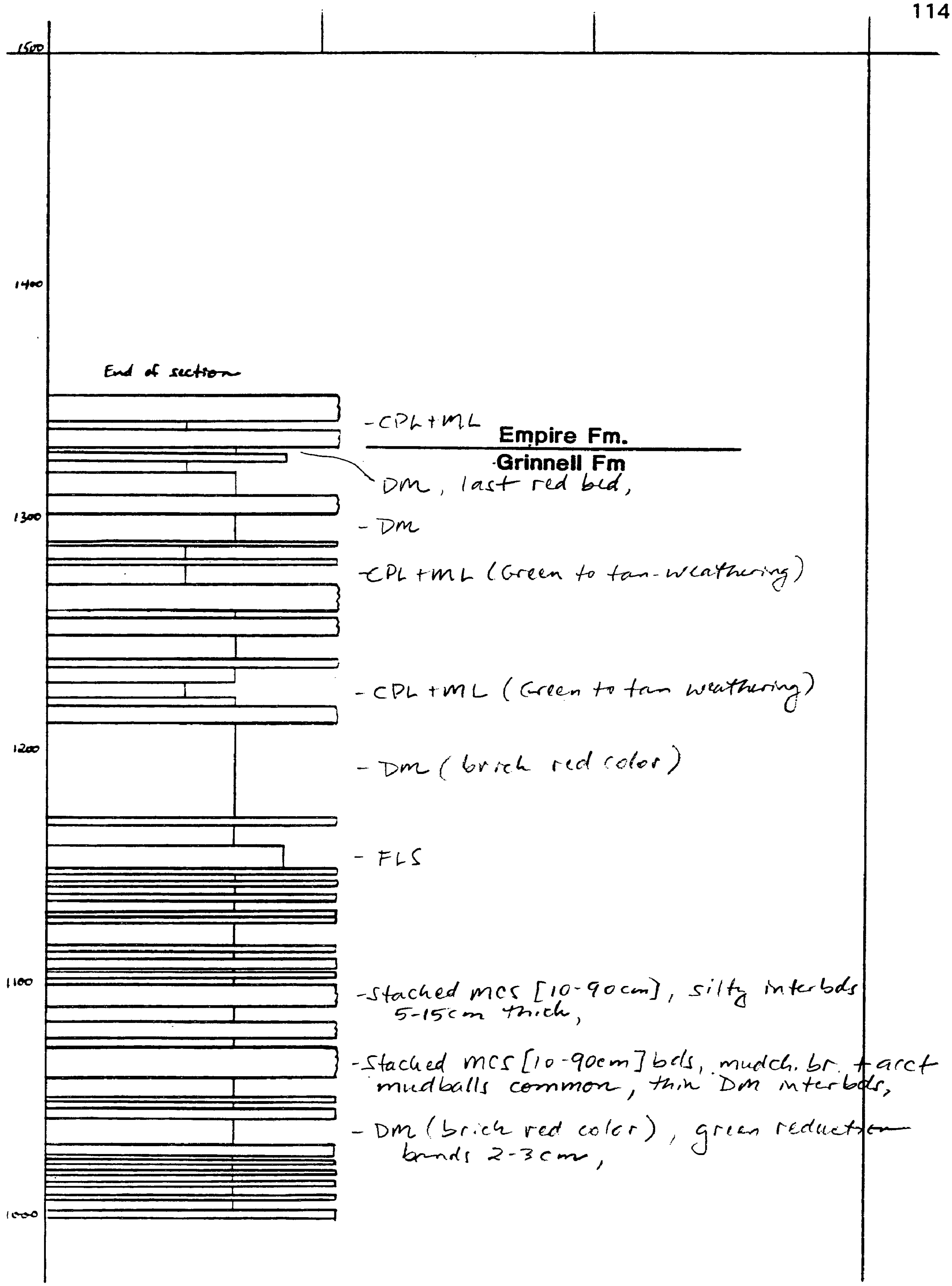
- FLS, muddy silt, pk-purple, massive, mudcks,

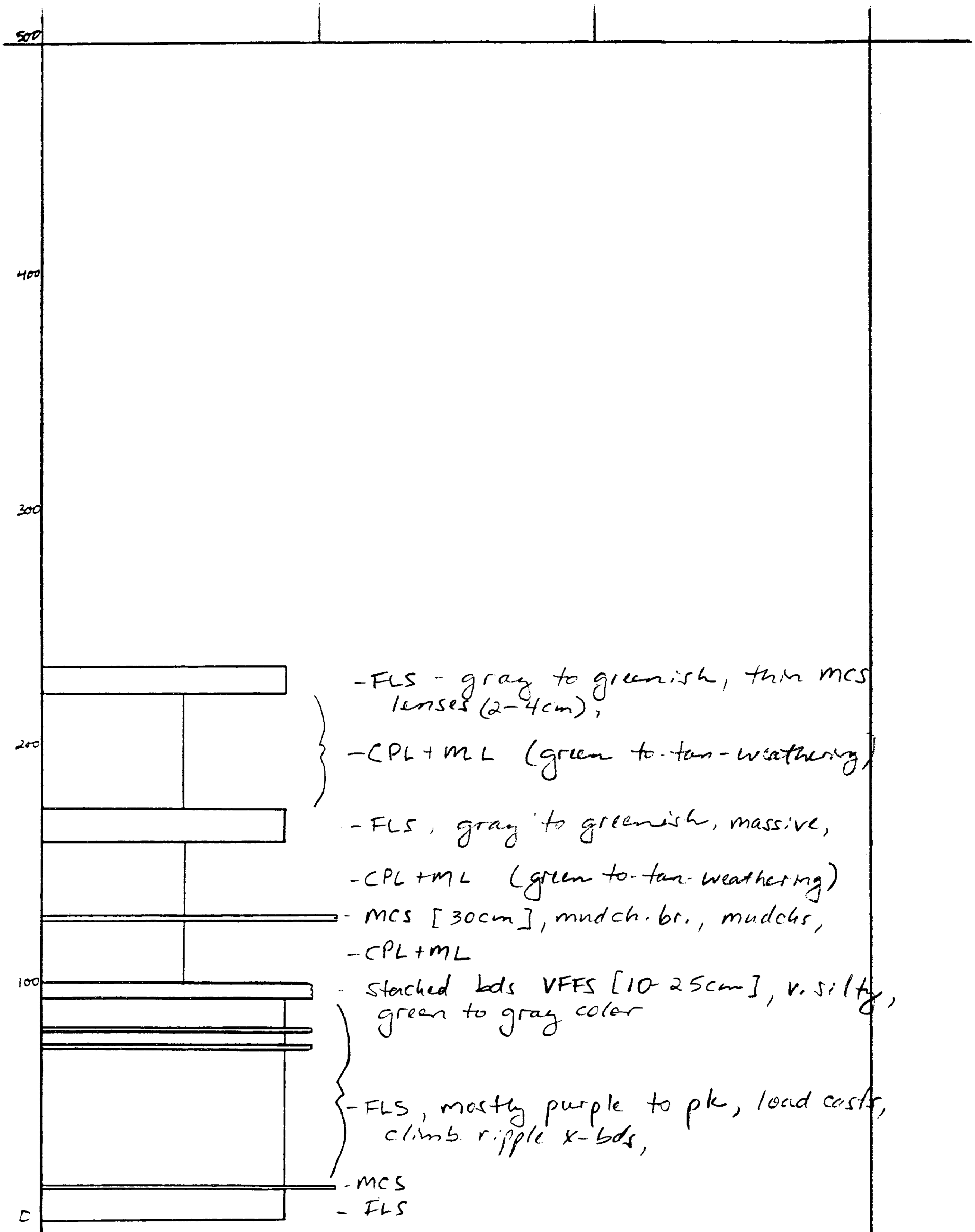
stacked MCS [10-90cm] bds, mudch. br, acct. mudballs, low ∡ tang. x-bds,

- FLS, some MCS "floating stringers",

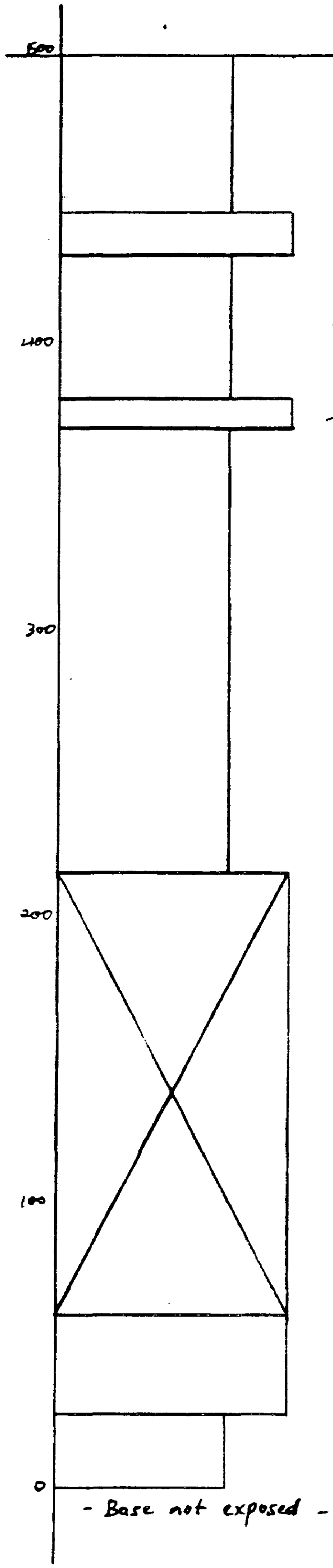
stacked MCS [10-90cm] bds, tab. planar x-bds, sand white to pk color,

- Dm, pink to purple color, wispy mcs sand lenses, 3-4cm thick,


1500
1400
1300
1200
1100
1000
End of section
-CPL+ML
Empire Fm.
Grinnell Fm
DM, last red bed,
- DM
-CPL +ML (Green to tan-weathering)
- CPL +ML (Green to tan weathering)
- DM (brick red color)
- FLS
-Stacked MCS [10-90cm], silty interbds 5-15cm thick,
-Stacked MCS [10-90cm] bds, mudch. br. + arct mudballs common, thin DM interbds,
- DM (brick red color), green reduction bands 2-3cm,



Section C – Mt.Cannon
(near Avalanche Lake)



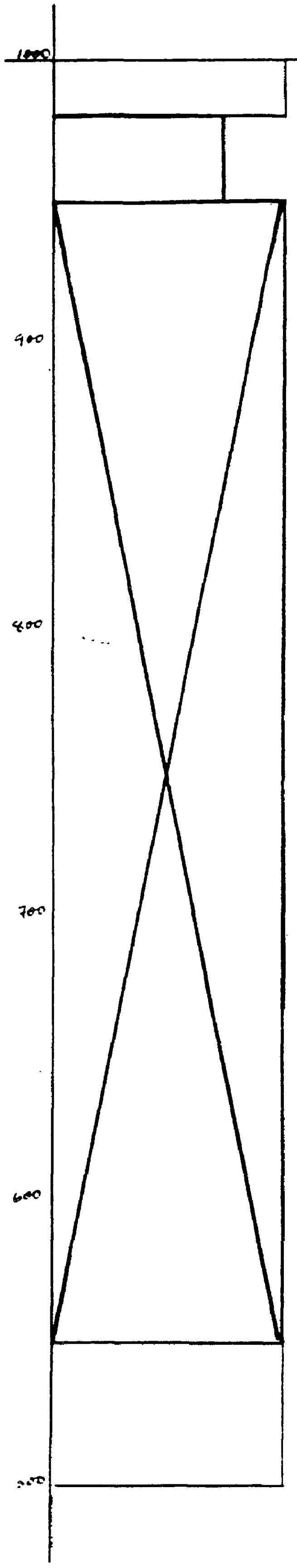
- Bright green, CPL + ML,
- Purple, mostly CPL
- Bright green CPL + ML, pervasive orange limonite stain,
- FLS, rose
- Variagated purple + green bds, mostly CPL + ML fluid esc. + mudch. br.'s common, some bds distinctly bright green w/orange limonite stain,

Covered

- Purple-rose color, bds mostly CPL, fluid esc., mudcks, mudch. br., some ML's,
- Variagated purple + green bds, CPL + ML, fluid esc., mudch. br.,

- Base not exposed -

Upper Whitefish Lake – Whitefish Range Section

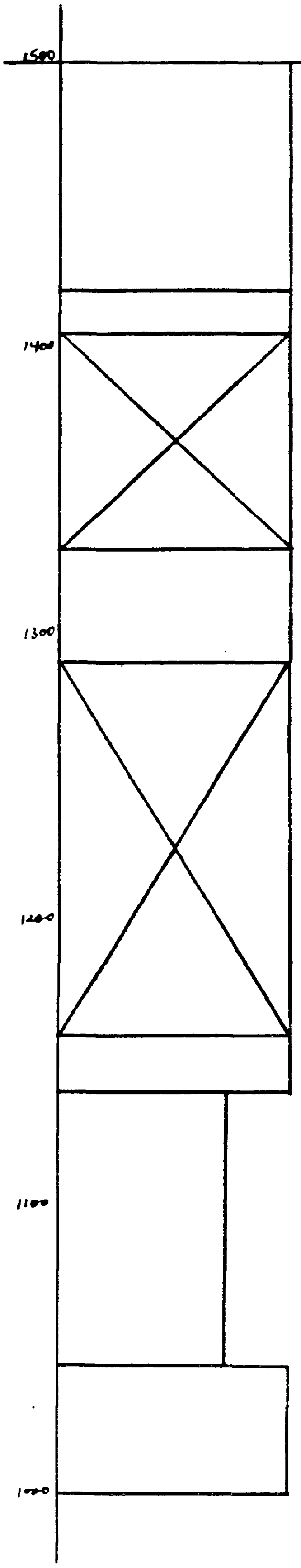


- Purple CPL, mudch. br.'s + mudcks common,

- Bright green, CPL + ML, orange limonite stain, shrinkage cracks ? (-'-)

Covered

Purple, motly CPL, mudch. br. + mudcks common,



- Purple CPL, mudch. br., mudchs common

- Purple CPL, mudch. br., mudchs,

- Covered

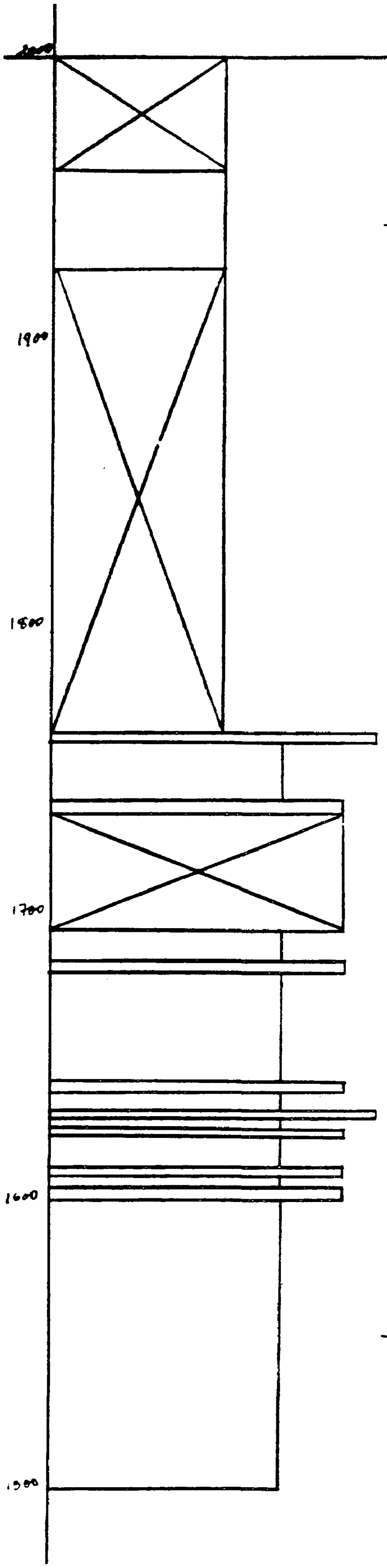
- Mostly purple CPL + ML, w/ thin green ML beds,

- Covered

- Purple CPL, fluid esc's, mudchs common

- Bright green CPL + ML, rare purple CPL interbds, shrinkage cracks? (/'_)

- Purple, CPL + minor grayish ML, mudch. br. + mudchs common,



- Covered

- Bright green, CPL + ML, orange lim. stain, shrinkage cks ? (☺)

Covered

- VFFS [10-15 cm]

- FLS, dark gray color, load casts, climb ripp. x-bds,

- FLS - Interval covered by snow, FLS observed in earlier reconn.,

- FLS, gray

- Dm, silty, highly desiccated,

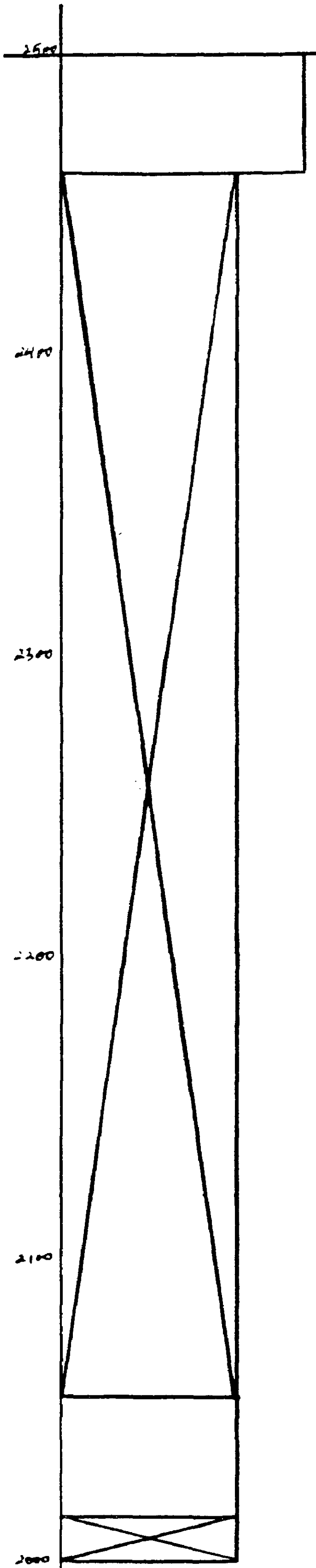
- VFFS [10-15 cm lenses]

- Dm, highly desiccated,

- FLS, gray - rose color, climb ripp. x-bds,

- DM ?

- Variagated purple + green, CPL + ML, becomes siltier upsection, fluid esc, mudcks common,

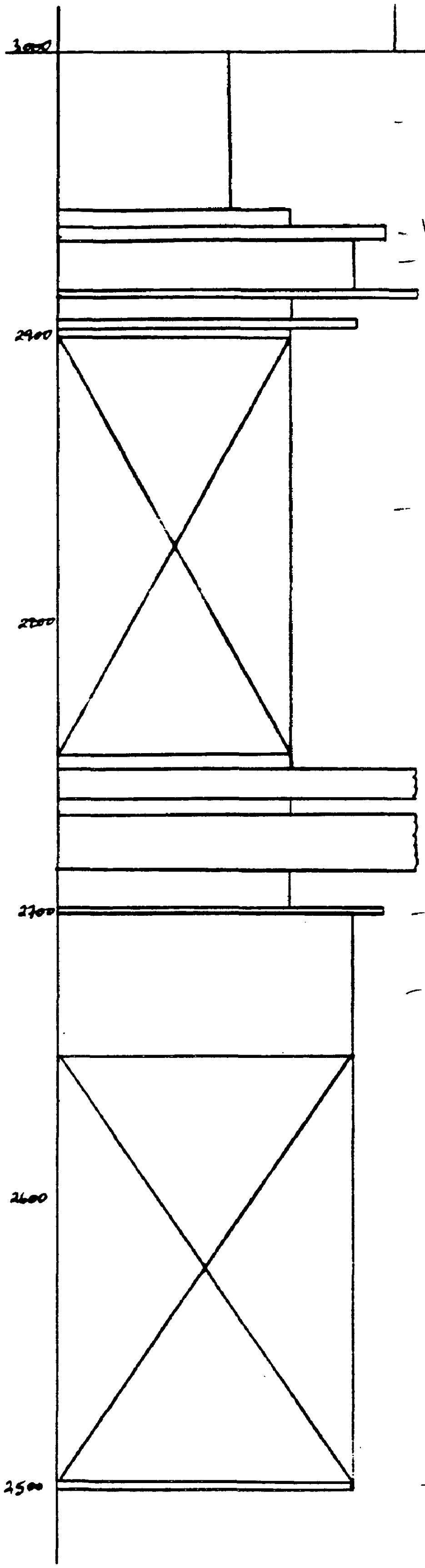


- Purple CPL + ML, mudcks + mudck br.? common, small-scale load casts,

-Covered

-Green CPL + ML, shrinkage cks ? (⊥), orange lim. stain,

- Covered



- Bright green to tan weathering CPL + ML, pervasive orange lim. stain

- VFFS

- FLS

- mcs [10-30cm], bds lense out across otcp., v. silty, mudch. br., acct. mudballs,

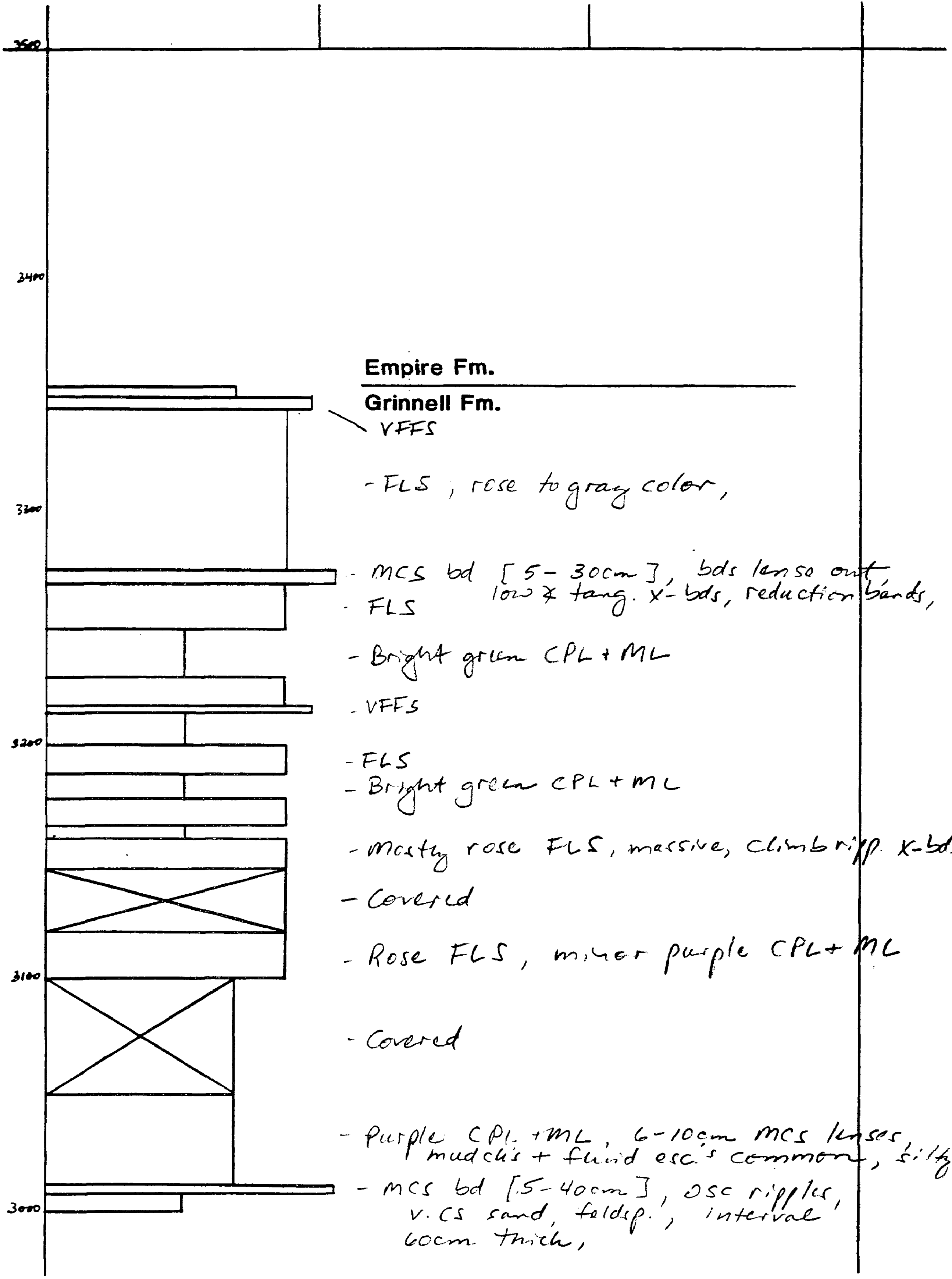
- Covered

stacked mcs [10-60cm], low & tang. x-bds, mudch. br., + acct mudballs common,

- VFFS [15-30cm]

- FLS, rose-gray color w/ interbd purple CPL, thin lenses VFFS, (up to 5cm); acct. mudballs 2-3cm diam.,

- FLS, rose color, w/ thin purple CPL + ML, climb ripp x-bds + load casts in silt, liesegang bds,

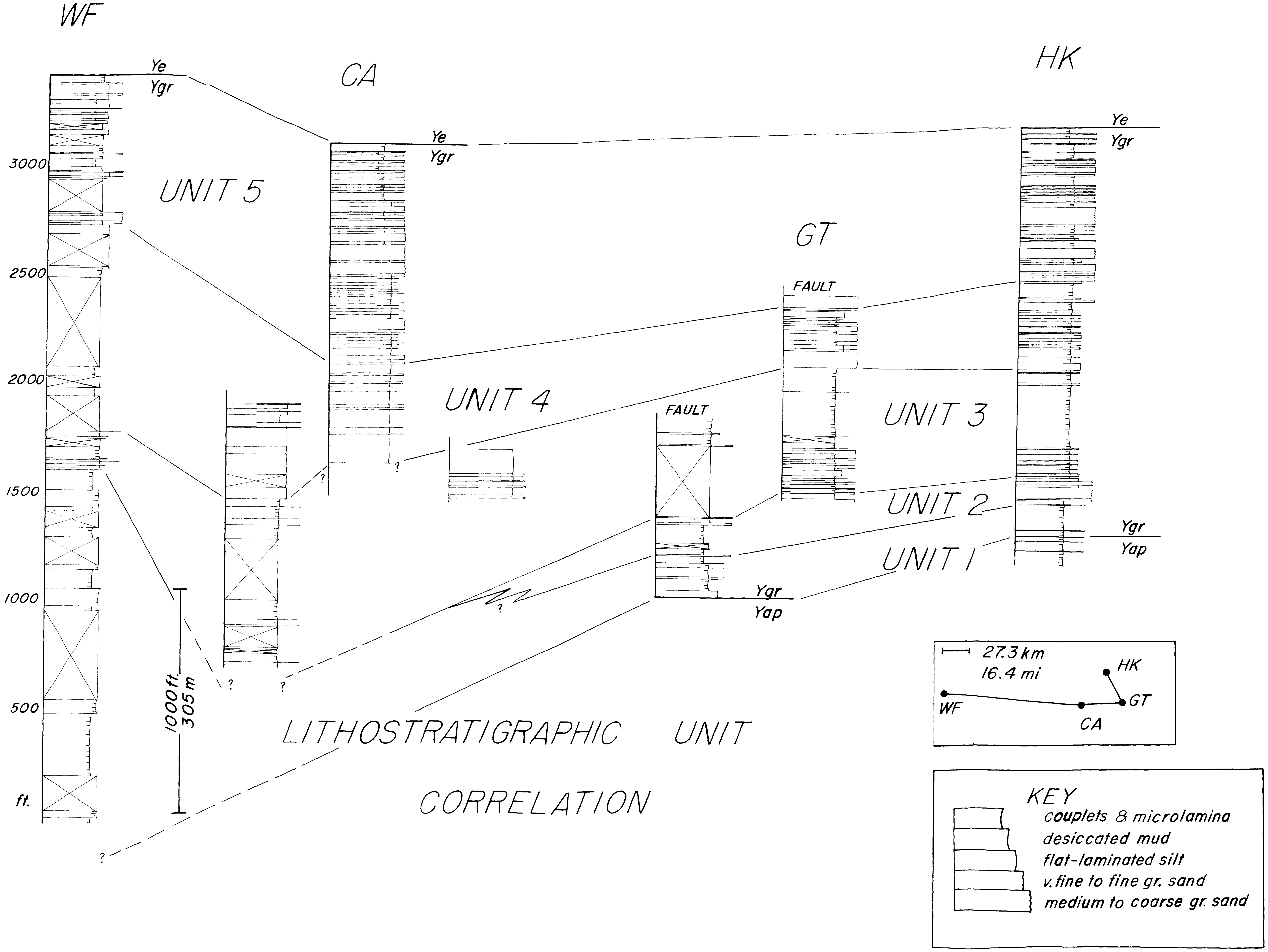


Empire Fm.

Grinnell Fm.

VFFS

- FLS, rose to gray color,
- MCS bd [5-30cm], bds lense out low ∡ tang. x-bds, reduction bands,
- FLS
- Bright green CPL + ML
- VFFS
- FLS
- Bright green CPL + ML
- Mostly rose FLS, massive, climb ripp. x-bds,
- Covered
- Rose FLS, minor purple CPL + ML
- Covered
- Purple CPL + ML, 6-10cm MCS lenses, mudck's + fluid esc.'s common, silty
- MCS bd [5-40cm], osc ripples, v. CS sand, feldsp.', interval 60cm. thick,


LITHOSTRATIGRAPHIC UNIT CORRELATION

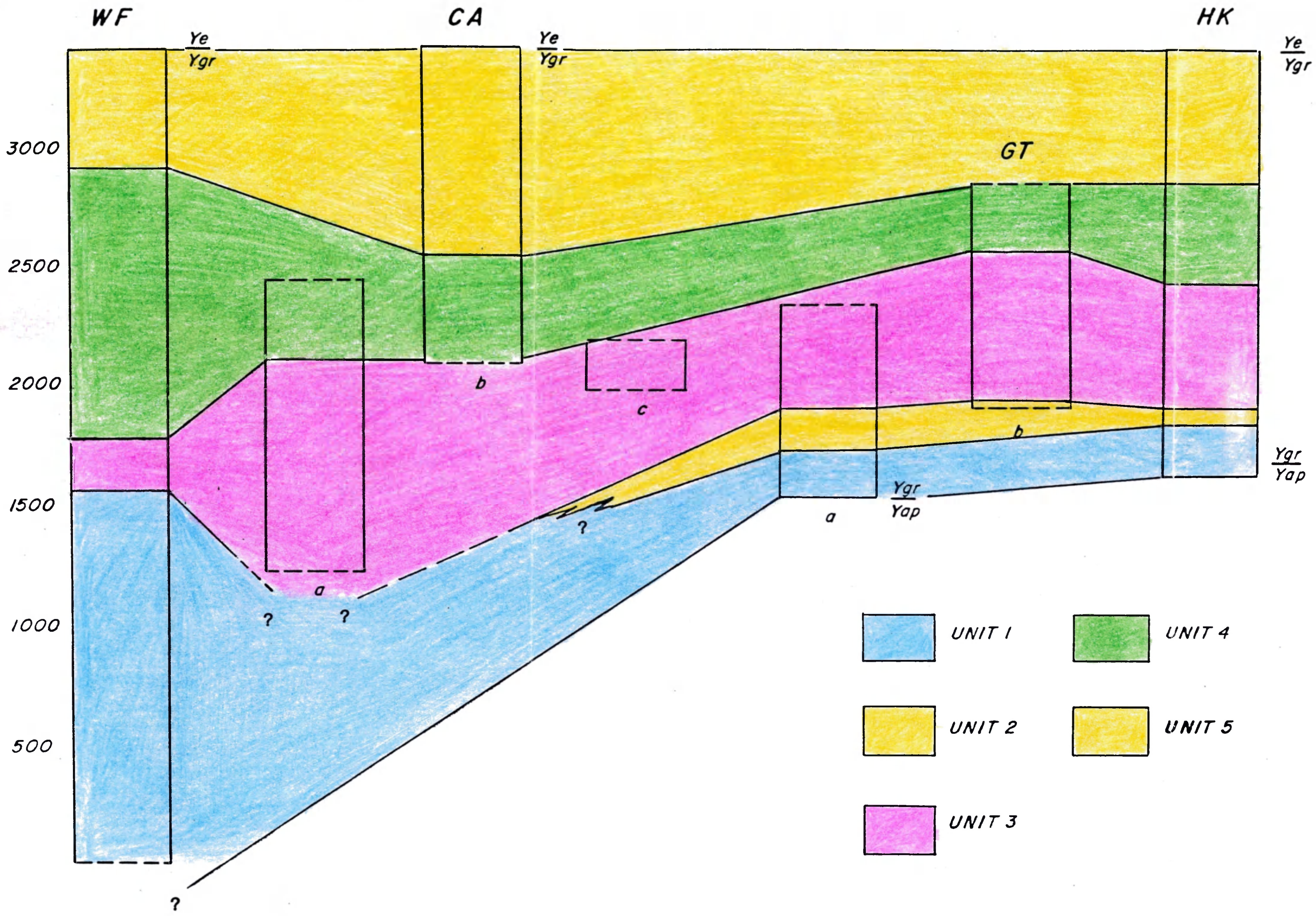


Figure 4-1: Generalized lithostratigraphic unit correlation.
Correlation of the Grinnell Formation from Glacier National Park to the Whitefish Range, Montana. WF: Whitefish Range section, CA: Mt. Cannon sections (a,b,c), GT: Goat Mountain sections (a,b), HK: Mt. Henkel section. Dashed lines on columns indicate incomplete sections.