Depositional subenvironments in a closed basin: the Shepard Formation (Middle Proterozoic Belt Supergroup) Southern Mission Swan and Lewis & Clark Ranges Montana

Marvin O. Woods
The University of Montana

Follow this and additional works at: https://scholarworks.umt.edu/etd
Let us know how access to this document benefits you.

Recommended Citation
https://scholarworks.umt.edu/etd/8962

This Thesis is brought to you for free and open access by the Graduate School at ScholarWorks at University of Montana. It has been accepted for inclusion in Graduate Student Theses, Dissertations, & Professional Papers by an authorized administrator of ScholarWorks at University of Montana. For more information, please contact scholarworks@mso.umt.edu.
COPYRIGHT ACT OF 1976

THIS IS AN UNPUBLISHED MANUSCRIPT IN WHICH COPYRIGHT SUBSISTS. ANY FURTHER REPRINTING OF ITS CONTENTS MUST BE APPROVED BY THE AUTHOR.

MANSFIELD LIBRARY
UNIVERSITY OF MONTANA
DATE: 1980
Depositional Subenvironments In A Closed Basin: The Shepard Formation
(Middle Proterozoic Belt Supergroup), Southern Mission, Swan,
and Lewis & Clark Ranges, Montana

by

Marvin O. Woods

B.S., University of California at Davis, 1982

Presented in Partial Fulfillment of the Requirements for the Degree of
Master of Science
UNIVERSITY OF MONTANA
1986

Approved by:

Chairman, Board of Examiners

Dean, Graduate School

Date
Sedimentation in a Closed Basin: The Shepard Formation (Middle Proterozoic Belt Supergroup), Southern Mission, Swan, and Lewis & Clark Ranges, Montana (215 pp.)

Director: Donald Winston II

The calcareous and argillaceous Shepard Formation, sandwiched between prograded alluvial fan/sandflat deposits of the Snowslip Fm. below and the Mount Shields Fm. above, represents a relatively high stand of the Belt "sea." Whether this "sea" was marine or non-marine has long been debated, but this study concludes that the Shepard was deposited in and around a large, shallow, enclosed sea or lake. Based on 9 measured sections, 7 distinctive sediment types are recognized. Correlation of sediment type packages reveals an internal stratigraphic framework composed of 8 units. Based on process interpretations of the sediment types, their lateral relationships as revealed by the stratigraphic framework, and comparison to marine tidal flat and playa/lacustrine deposits, a marine interpretation is rejected and a playa/lacustrine interpretation adopted. The following depositional model is proposed.

Episodic sheetfloods from inferred surrounding alluvial aprons brought fine sand and mud across a broad sandflat and into a large, shallow lake. Each flood caused the lake to expand, temporarily flooding its broad, nearly flat margins. Distal parts of the sandflat are recorded as flat-laminated to climbing-ripple or wave-ripple crosslaminated beds of the flat-laminated sand sediment type. More typical floods brought only silty mud as far as the lake margin, some of it settled out of ponded water as cm-scale, graded even couplets that became exposed and desiccated as the lake contracted, forming the mudcracked even couplet sediment type. In the broad, shallow reaches of the lake, gentle waves worked silty mud into cm-scale couplets composed of rippled silt layers capped by clay, forming the lenticular couplet sediment type, and where sand supply was sufficient, the ripple crosslaminated sand sediment type. Offshore, thin, graded mud layers formed the continuous even couplet sediment type where silty mud influx was sufficient. Farther offshore, where terrigenous influx was low, mm-scale laminae of dark, clay-rich mud accumulated, forming the microlamina sediment type. Many microlaminae intervals are stromatolitic, and some are further marked by loadcasted, fine sand lenses, gutter casts, and minor scour surfaces, probably reflecting the influence of occasional storms that swept over the lake. Calcite at times precipitated directly from the water over broad areas to form the carbonate mud sediment type.
# TABLE OF CONTENTS

Abstract.................................................ii
List of Illustrations.............................................iv

Introduction.......................................................1
  Regional Stratigraphic Setting.................................2
  Purpose Of This Study..........................................9
  Study Area......................................................10
  Methods.........................................................11

Lithologic Classification of the Shepard Formation: "Sediment Types"........13

  Flat-laminated Sand Sediment Type
    Description..................................................14
    Interpretation...............................................16

  Ripple Crosslaminated Sand Sediment Type
    Description..................................................19
    Interpretation...............................................20

  Mudcracked Even Couplet Lithofacies
    Description..................................................28
    Interpretation...............................................31

  Continuous Even Couplet Lithofacies
    Description..................................................33
    Interpretation...............................................33

  Lenticular Couplet Lithofacies
    Description..................................................35
    Interpretation...............................................38

  Microlamina Lithofacies
    Description..................................................41
    Interpretation...............................................47

  Carbonate Mud Sediment Type
    Description..................................................50
    Interpretation...............................................51

  Stratigraphic Framework....................................53
  Stratigraphic Correlation....................................54
  Sediment Type Distribution: Lithostratigraphic Units........57
  Summary of Lateral Sediment Type Relationships............63
LIST OF ILLUSTRATIONS

Figure 1. Index map of Belt basin................................. 3

Figure 2. Index map of study area................................. 4

Figure 3. Formal subdivision of the Belt Supergroup in the study area.............. 5

Figure 4. Flat-laminated sand with pillow structure.................. 17

Figure 5. Ripple crosslaminated sand.............................. 17
Figure 6. Ripple crosslaminated sand lens within lenticular couplets.................................21
Figure 7. Ripple crosslaminated sand..................................................21
Figure 8. Straight-crested, symmetrical ripples.................................22
Figure 9. Straight-crested, symmetrical ripples.................................22
Figure 10. Ladderback ripples.........................................................23
Figure 11. Ladderback ripples.........................................................23
Figure 12. Ladderback ripples with truncated crests.................................24
Figure 13. Dolomitic mudchips and accreted mudballs.................................24
Figure 14. Accreted mudballs in fine sand........................................29
Figure 15. Mudcracked even couplets..............................................29
Figure 16. Mudcracked bedding surface............................................30
Figure 17. Mudchip layer among mudcracked even couplets.......................30
Figure 18. Continuous even couplets and microlaminae............................34
Figure 19. Dolomitic lenticular couplets...........................................34
Figure 20. Lenticular couplets and microlaminae..................................37
Figure 21. Dolomitic, clay-rich lenticular couplets................................37
Figure 22. Green microlaminae.......................................................44
Figure 23. Green microlaminae.......................................................44
Figure 24. Photomicrograph of microlaminae......................................45
Figure 25. Sawed slab of microlaminae with shrinkage cracks.....................45
Figure 26. Photomicrograph of mudcracked microlaminae..........................46
Figure 27. Fine sand lens with loaded base within microlaminae interval..........46
Figure 28. Gutter cast enveloped by microlaminae.................................47
Figure 29. Stratigraphic cross section, showing distribution of sediment types........58-59
INTRODUCTION

Recent studies have shown that the Middle Proterozoic Belt Supergroup was deposited in a basin that subsided largely in response to high angle faults that cut the crust (Harrison et al., 1974a; Wallace et al., 1976; Hawley et al., 1982; Godlewski & Zieg, 1984; Winston et al., 1984; Winston, 1986c,d; Schmidt & Garihan, 1986; see Fig. 1). However, the paleogeographic and sedimentologic interpretation of the basin has been debated for nearly a century (Winston et al., 1984). Some workers have proposed that the basin was a marine embayment (Harrison, 1972; Harrison et al., 1974a; Harrison & Reynolds, 1976); whereas others contend that it was intracratonic, occupied by a landlocked, essentially tideless, shallow sea (Walcott, 1914; Smith, 1963; Winston et al., 1984; Winston, 1986b,c,d). This study examines in detail the stratigraphy and sedimentology of the Shepard Formation, an important argillaceous interval of the Missoula Group (upper Belt Supergroup). The Shepard records a relatively high stand of the Belt "sea;" the Shepard's muddy, subaqueous deposits provide for the most valid test of the marine and lacustrine hypotheses. Analysis of Shepard sedimentary rocks within their stratigraphic framework is the most direct means by which depositional subenvironments and thus paleogeography may be inferred.

The Shepard Formation is dominated by thinly bedded and thickly laminated fine-grained sandstone and argillite (slightly metamorphosed mudstone), commonly with mudcracks and rippled surfaces. Such sediments have been ascribed by many authors to marine tidal flats (de Raaf & Boersma, 1971; Weimer et al., 1982). Other authors have pointed out
that nearly identical deposits characterize continental playas and relatively shallow lakes (Picard & High, 1972; Fouch & Dean, 1982). This study will show that, in the Shepard, the weight of the evidence supports a continental, playa/lacustrine interpretation. This conclusion is reached by way of the following analytical steps:

1) recognition of seven distinctive, recurring "sediment types," each of which is interpreted in terms of hydrodynamic processes, with reference to similar deposits described in the literature;

2) recognition of a clearly defined stratigraphic framework built from physical lithocorrelation through nine measured sections; the correlations reveal important lateral relationships among the seven sediment types.

3) comparison of Shepard sediment types and their stratigraphic arrangement to modern and ancient tidal sequences and lacustrine sequences;

4) based on the results of such comparisons, incorporation of steps 1 and 2, above, into a coherent, hypothetical depositional model for the Shepard sediments.

**Regional Stratigraphic Setting**

The stratigraphic relationship of the Shepard Formation to other Belt formations in the study area (Fig. 2) is depicted schematically in Figure 3. The Shepard Formation was defined by Willis (1902) at Shepard Glacier, in north-central Glacier National Park. (Willis actually named the unit the Sheppard [sic] quartzite, emphasizing the relative
Figure 1. Regional extent of Middle Proterozoic Belt Supergroup, with present study area outlined. After Harrison (1972).
Figure 2. Index map of study area, showing locations of measured sections and major structures. Area shown corresponds roughly with the Choteau 1° x 2° sheet. Structures after Mudge et al. (1982). Note 2-letter abbreviations of section names.
Figure 3. Formal stratigraphic nomenclature of the Belt Supergroup in the study area. All units shown in right-hand column are formally formations. After Mudge et al. (1982).
sandiness of the Shepard in northern Glacier Park and the Whitefish Range to the west; see Whipple et al., 1984). In the type locality Willis placed the base of the Shepard at the top of the Purcell Lava, and he placed the top where calcareous and dolomitic argillite grades up into red argillite and quartzite of the lower Mount Shields Formation (= Kintla argillite of Willis, 1902). Beyond the extent of the Purcell Lava, however, the original criterion for the base of the Shepard is lost. Childers (1963, p. 144), in naming the Snowslip Formation near Marias Pass, placed the Snowslip-Shepard contact where "dull-red medium-grained quartzites grade into the calcareous shales and argillites of the Shepard." The argillite at this lowest Shepard level is also marked by scattered, small coarse-grained quartzite lenses and local stromatolites. The sum of these criteria can be applied quite consistently wherever the Snowslip and Shepard are mapped. However, based on these criteria, the Shepard at the type locality would include the Purcell Lava as well as approximately 30 meters of black, green, and red argillite below the basalt which Willis (1902) had included in the uppermost Siyeh limestone. The contact as defined by Childers (1963), besides being consistently mappable throughout most of the Belt basin, is also a sound choice on sedimentologic grounds, as it appears to reflect a fundamental change in depositional conditions. Horodyski (1983), working in Glacier National Park, and McGill & Sommers (1967) and Mudge et al. (1974), working in the Lewis & Clark Range south of the Park, are some of the workers who have mapped the Snowslip/Shepard contact as defined by Childers. However, Whipple et al. (1984) and Earhart et al. (1984), mapping in the Park and areas to the west and
south, have placed the Snowslip/Shepard contact above minor red argillite beds that Childers (1963) had included in his lower Shepard, apparently using the highest red beds, rather than the lowest green, calcareous beds, to mark the Snowslip/Shepard contact. In the present study area, Childers's criteria were found to be most applicable. In his outline of the history of formal Belt stratigraphic nomenclature, Winston (1986a) summarizes usages pertaining to the Shepard Formation throughout the Belt basin (see his Sheet 2).

The Shepard Formation consists predominantly of laminated green, dark grey, and minor red terrigenous argillite; tan-weathering, dolomitic argillite; and subordinate fine-grained quartzite. It lies above the Snowslip Formation and below the Mount Shields Formation, both of which consist largely of quartzite and red argillite. The Shepard reportedly attains a maximum thickness of about 900 m in the Swan Range (Mudge et al., 1982), where it is dominated by wavy-laminated, dolomitic silty argillite, with minor dark grey muddy argillite. The Shepard extends eastward as far as the Montana overthrust belt, where it is approximately 70 m thick at Slategoat Mountain (Mudge, 1972). Eastern outcrops are characterized by dark argillite and shale, but are sandy high and especially low in the formation. The Shepard extends as far south as Lost Creek in the southern Flint Creek Range, though it appears to be cut out by a thrust fault at Flint Creek Hill (Winston & Wallace, 1983). Northward, near Marias Pass, the Shepard is 472 m thick and Childers (1963) subdivided it into two, equally thick units: 1) a lower unit of calcareous green and grey shale, fine-grained green and red quartzite, and silty grey micrite and dolomicrite; and 2) an upper unit
of tan—weathering grey silty micrite and dolomicrite. The Shepard thins northward into southern British Columbia [formally "Sheppard" Formation in Canada, after Willis' (1902) original spelling] (Price, 1964; Höy, 1984; McMechan, 1981), and extends formally as far west as the Cabinet Mountains of Montana (Harrison et al., 1974b; Lemoine, 1979; Lemoine & Winston, 1986). Lemoine (1979), Winston (1984) and Lemoine & Winston (1986) have shown that west of the Cabinet Mountains, in the Coeur d'Alene Mountains of northern Idaho, the Shepard passes into rocks mapped as upper Wallace Formation (Harrison et al., 1974b; Harrison, 1984; Winston, 1984). At Clark Fork, Idaho, according to Lemoine & Winston (1986), black argillite of the lower Shepard is continuous with the upper part of Wallace informal member 3 of Harrison & Jobin (1963). Calcareous argillite of the middle Shepard, and another thin, black argillite interval at the top of the Shepard are continuous with Wallace informal members 4 and 5, respectively.

As described here, the Shepard rests on the Snowslip Formation, the uppermost part of which is a fine-grained, northwestward-thinning sand wedge (Winston, 1984, 1986a,b,d). However, the upper Snowslip sand pinches out before reaching northern Idaho; there, the Shepard equivalent Wallace 3 (upper), 4 and 5 rests on red and green, mudchip-bearing argillite of the Snowslip equivalent Wallace 3 (lower) (Lemoine, 1979; Lemoine & Winston, 1986). The Shepard is overlain by red, mudchip-bearing argillite of Mount Shields Formation informal member 1 (= lower Striped Peak of northern Idaho), over which rests the northwestward-thinning sand wedge of Mount Shields member 2 (Winston,
1977, 1978, 1986a,b,d; Winston & Jacob, 1977; Lemoine, 1979; Lemoine &

Purpose Of This Study

Winston (1977, 1978, 1984, 1986b,d) and Slover & Winston (1986) have proposed that the red argillite and overlying sand wedge of the Mount Shields Formation represent a vast prograded alluvial apron and adjoining sandflat. The sand wedge high in the Snowslip Formation may represent a similar prograded sequence, though it has been studied in much less detail (Winston, 1986a). If Winston's alluvial interpretation is correct, these sandy deposits, though they limit interpretational possibilities for the Shepard Formation, accumulated marginally to the Belt "sea" per se and thus do not speak directly to the marine vs. non-marine question of the Belt "sea." The possibility of finding the answer in the more "basinal" deposits directed my attention to the argillaceous Shepard Formation, which, with respect to the Snowslip and Mount Shields formations, clearly must represent a relatively high stand of the Belt "sea."

Beyond its description as a mapped unit (e.g., Mudge et al., 1982; Harrison et al., 1974b; Whipple et al., 1984) and as a stratigraphic unit widely correlated in terms of its gross lithologic characteristics (e.g., McGill & Sommers, 1967), the Shepard has been the focus of few sedimentologically oriented studies. Lemoine (1979), Horodysky (1983), and Lemoine & Winston (1986) are the only previous workers to report and interpret sedimentologic and internal stratigraphic details of the Shepard. Although the Shepard is mapped and is often generally
described simply as an argillite and calcareous argillite interval (e.g., Mudge et al., 1982), its deposits are in fact quite heterogeneous and contain enough diagnostic sedimentologic features to clearly reflect variations of the hydrodynamic and bathymetric conditions within and along the margins of the Belt "sea." It is through a thorough sedimentologic analysis of the Shepard deposits within their detailed stratigraphic framework that I propose that the Shepard Formation represents shallow lacustrine and marginal-lacustrine deposition.

**Study Area**

The area in which detailed stratigraphic sections were measured (Fig. 2) comprises the southern Mission Range, the Jocko Mountains, the southern Swan Range, and the southern part of the Lewis and Clark Range, those mountains along and east of the continental divide. The study area was chosen because of its relatively minor structural complications, and the relative abundance of Shepard outcrops. Unfortunately, good exposures are separated by large expanses of heavily forested terrain, through which units cannot be physically traced. Because of this, some stratigraphic correlations (Plate 1) are less certain than others. Within the constraints imposed by the distribution of suitable outcrops, the cluster of measured sections was chosen with the objective of attaining broad enough regional correlations to have some basinwide relevance, while securing enough local detail to document interfingering of lithic packages (Fig. 29).

Figure 2 shows most of the known major structures which may affect stratigraphic reconstructions, though none are believed to cause great
distortion. The straight, north-northwest trending Swan fault is mostly
dip-slip (Mudge et al., 1982; Crosby, 1984), while the west-northwest
trending faults shown are part of the right-lateral oblique-slip St.
Marys fault system. The St. Marys fault extends to the west-northwest,
where it clearly displays right-lateral movement (Harrison et al.,
1974b) and is one of several faults that coalesce with the Osburn fault,
each of which contributes to the Osburn's 26 km right-lateral offset in
the Coeur d'Alene district of northern Idaho (Harrison et al., 1972).
Thus, while the absolute amount of strike-slip movement on the St. Marys
fault in the present study area is uncertain (Mudge et al., 1982), it
must be significantly less than 26 km. The two easternmost measured
sections are separated from the rest of the sections by the Hoadley and
related thrust faults. Lateral displacement across this fault zone is
probably less than 30 km (McDonough, 1985). [Total displacement in the
entire eastern thrust belt, with respect to the craton, is about 50 km
(Sears, 1986)]. Thus, with the exception of the easternmost two
sections, all the sections lie on a single thrust slab (Sears, 1986).
Therefore, it was not deemed necessary to palinspastically construct the
cross section (Fig. 29), since the amount of lateral tectonic transport
along the St. Mary and Hoadley faults appears to be proportionately
small compared to the size of the study area.

Methods

Nine sections through the Shepard Formation were measured, using a
Jacob's staff and Brunton compass. Most sections were marked with tape
at 5-foot intervals to insure accuracy and were then sketched and
described at a scale of 1:120 in as much detail as that scale would allow. These sections are illustrated at that scale in Appendix II. They are also displayed and correlated at a vertical scale of 1:1200 (Plate 1) and 1:4800 (Fig. 29). My preliminary reconnaissance of Shepard rocks had shown that they could be adequately described in terms of only a handful of Winston's (1984, 1986b,d) "sediment types" (discussed below). The "sediment type" classification readily and consistently allowed precise discrimination among the range of mudrocks that comprise the Shepard. Because the classification emphasizes sedimentological features, it was favored over more cumbersome, less precise descriptions built around the term "argillite."

Though the sections were measured in great detail and record fine interbedding of the various sediment types (Appendix II and Plate 1), most intervals are dominated by a single sediment type. Accordingly, prominent lithostratigraphic units, dominated by a particular sediment type, are recognized (Fig. 29), the lateral relationships of which are constrained by the physical litho correlations between the measured sections (Plate 1).
LITHOLOGIC CLASSIFICATION OF THE SHEPARD FORMATION: "SEDIMENT TYPES"

The muddy sedimentary rocks of the Shepard Formation are referred to by most workers as "argillite," a term whose original definition indicated slightly metamorphosed mixtures of silt and clay (Twenhofel, 1937). As such, argillite is an apt rock term, though it would properly apply to essentially the entire Shepard formation and thus, while useful as a mapping term, has limited classification value within a muddy unit such as the Shepard. However, the term's original definition has become somewhat muddied since 1937 (cf. Harrison & Campbell, 1963) such that it is not always clear what a particular author intends by "argillite."

Traditionally, argillite of the Shepard Formation (and of the Belt Supergroup in general) has been subdivided according to its color (i.e., red, green, black, or tan-weathering), but because color most directly reflects diagenetic processes, the relationship between color and the conditions of primary sedimentation is often ambiguous.

For sedimentological studies, a classification scheme based on lamination style and other sedimentary structures would surely be much more viable than one based on mapping terms and rock color. Winston (1984, 1986b,d) has developed such a classification scheme for Belt rocks, and as mentioned previously, his scheme proved readily applicable to Shepard rocks. Winston's scheme, which emphasizes lamination style, texture, and inferred original composition, distinguishes among thirteen "sediment types" ranging from gravel to carbonate mud. Of Winston's several sediment types, the following five characterize the Shepard: the even couplet (with mudcracked and non-mudcracked varieties),
lenticular couplet, microlamina, carbonate mud, and flat-laminated sand sediment types. The first four sediment types comprise the bulk of the Shepard (the "argillite"), and the flat-laminated sand sediment type is volumetrically minor. For purposes of this study, explicit discrimination is made between mudcracked even couplets and non-mudcracked (continuous) even couplets. Specific to the Shepard Formation is one additional, volumetrically minor sediment type, defined for the purpose of the present study: the ripple crosslaminated sand sediment type. Thus, the Shepard Formation is treated here in terms of seven sediment types (Table 1), all of which are described and interpreted below.

It is important to note that the Shepard's sediment types are the elements of a purely descriptive classification, and are not in any sense genetic. Only to the extent that Winston's (1984, 1986b,d) classification is based partially upon "inferred original composition" is his scheme genetic. However, for the purpose of the present purely sedimentologic and stratigraphic study, only textures and sedimentary structures are significant, and mineralogic composition of the argillite and sandstone is of minor concern. Only the composition of the Shepard's micritic and dolomicritic "carbonate mud sediment type" and calcareous and dolomitic varieties of the other muddy sediment types is significant in this study.

FLAT-LAMINATED SAND SEDIMENT TYPE

Description -- The flat-laminated sand sediment type consists of flat-laminated to ripple crosslaminated fine-grained sandstone in tabular
<table>
<thead>
<tr>
<th>SEDIMENT TYPE</th>
<th>SCHEMATIC DEPICTION</th>
<th>DESCRIPTION</th>
<th>SEDIMENTARY PROCESSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat-laminated Sand</td>
<td></td>
<td>mudchip-bearing, flat-laminated fine sand passes up to unidirectional and/or bidirectional climbing ripples, capped by desiccated mud drape; tabular beds 10-50 cm thick.</td>
<td>episodic, waning sheetflows over flat, desiccated surface; ephemeral ponding of water; wave working of some bed tops; suspension settlement of mud; desiccation.</td>
</tr>
<tr>
<td>Ripple Cross-laminated Sand</td>
<td></td>
<td>mudchip- and accreted mudball-bearing, cross-laminated fine sand; cross-laminae show opposed foresets, offshoots; tabular beds &amp; lenses 10-15 cm thick capped by symmetrical ripples.</td>
<td>mostly wave working, with some unidirectional current transport, in shallow water; sticky mudchips agglutinated and rolled about on the wave-washed surface, forming accreted mudballs.</td>
</tr>
<tr>
<td>Mudcracked Even Couplet</td>
<td></td>
<td>paired, graded, silt- &amp; fine sand-to-clay laminae, 0.3-3 cm thick; laminae are parallel &amp; even, laterally extensive, bear mudchips, cut by mudcracks; tend to be red.</td>
<td>episodic, waning sheetflows over flat, desiccated surface; ephemeral ponding of water; suspension settlement of mud; desiccation.</td>
</tr>
<tr>
<td>Continuous Even Couplet</td>
<td></td>
<td>paired, graded, silt-to-clay laminae, 0.3-3 cm thick; laminae are even &amp; parallel, laterally extensive.</td>
<td>episodic, turbid influxes, resulting mostly in suspension settlement onto perennially submerged surface.</td>
</tr>
<tr>
<td>Lenticular Couplet</td>
<td>ripple lenses and layers of silt to fine sand alternate rhythmically with clay, forming couplets 0.3-3 cm thick; ripples tend to be symmetrical; mudcracks common.</td>
<td>mostly wave, with some unidirectional current, working of silt &amp; sand in shallow water; alternating with suspension settlement of mud in calm water; occasional desiccation.</td>
<td></td>
</tr>
<tr>
<td>Microlamina</td>
<td>very thinly (&lt;3 mm) laminated fine, dark mud; some laminae graded, silt-to-clay; mudcracks rare; occasional scours, &quot;gutter casts,&quot; fine sand lenses with loaded bases.</td>
<td>episodic, small terrigenous influxes, resulting in suspension settlement onto perennially submerged surface; rare currents scoured mud, and some deposited sand lenses.</td>
<td></td>
</tr>
<tr>
<td>Carbonate Mud</td>
<td>tan-weathering, impure very fine-grained dolomite &amp; limestone; terrigenous mud &amp; sand significant, but faint laminae generally rare; commonly cut by &quot;molar-tooth structure.&quot;</td>
<td>direct precipitation of calcium carbonate from water, combined with terrigenous mud influxes.</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Summary of Shepard sediment types, with brief descriptions and hydraulic process interpretations.
beds 10–50 cm thick. The beds have sharp to slightly scoured bases and commonly have thin mud drapes, and are typically stacked to form intervals up to about 5 m thick (Fig. 4). The mud drapes are locally mudcracked, and some are dolomitic. Also, some sandstone beds are separated by one or more even or lenticular couplets rather than by a simple clay drape. Internally, the sand beds tend to be mostly flat-laminated, and in some cases flat laminae pass abruptly up to erosional-stoss and/or depositional-stoss (Jopling & Walker, 1968; Allen, 1973; Ashley et al., 1982) climbing current- and/or wave-ripple crosslaminae. Some bedding surfaces display well-formed symmetrical ripples and thus are indistinct from those of the ripple crosslaminated sand sediment type (described below). Some thick sand beds display large, pillow-like load structures (Fig. 4).

Grain size of most sand beds in the flat-laminated sand sediment type ranges from very fine to fine. Sorting tends to be moderate to good, and the sands tend to be quite clean. The sand consists mostly of quartz grains, with less than 7 or 8 percent feldspar grains, and commonly small, angular mudclasts. The grains are cemented mostly by quartz overgrowths but in some cases by calcite and/or dolomite cement or neomorphosed micrite. Sandstone beds are mostly light grey to light tan. Occasional dolomitic sand beds weather a richer, yellowish tan, and a few slightly muddy sand beds are reddish.

Interpretation — Given that, for fine sand, there is no lower flow regime plane bed phase (Harms et al., 1982), the prominent flat lamination of these sands must represent the upper regime plane bed
Figure 4. Large pillow-like load cast in thick sand bed indicates rapid sand deposition; flat-laminated sand sediment type. Tabular beds of flat-laminated sand with climbing ripples at the top record unconfined, waning sheetflows. Staff is 5 ft long. DR 594

Figure 5. Ripple cross laminated sand sediment type. Ripple "foreset" laminae drape across two or more ripple bundles. This type of crosslamination is interpreted to be wave-generated in shallow water. RB 156
phase, while the climbing current ripples represent lower regime flow (Harms et al., 1982, fig. 2-4). Thus, where upper regime flat laminae pass upward to climbing current-ripple crosslaminae that are in turn capped by a desiccated mud drape, the most plausible explanation is a waning unidirectional flow that terminated in ephemeral standing water. With the exception of mud drapes, these beds are virtually identical to those produced experimentally by waning flows in flumes (Ashley et al., 1982). There is no evidence to constrain the depth of flow, but peak flow velocity had to have been greater than about 60 cm/sec, according to experimental data (Harms et al., 1982, fig. 2-4). Furthermore, besides the fact that mud drapes are commonly mudcracked, mudchips incorporated within the sand beds may represent broken, transported mudcrack polygons, which implies that the flows occurred over subaerially exposed, desiccated surfaces. The broad, tabular aspect of the beds indicates further that the depositional surfaces were at least equally broad and relatively flat. Thus this depositional surface can reasonably be termed a "sandflat," in the most generic sense of the word, and because the flows apparently occurred over subaerially exposed surfaces, they are correctly termed "floods."

Where the upper parts of flat-laminated sand beds are oscillation-ripple crosslaminated and capped by a desiccated mud drape, the bed records the following sequence of events: 1) upper-regime unidirectional flow, 2) shallow-water wave reworking of the top sediment, 3) settling of suspended mud from quiet water, and 4) exposure and desiccation of the deposit. Angular mudchips incorporated within some such beds suggest that the initial flow occurred over a desiccated
surface, and thus that the flood culminated in ephemeral standing water. Pillow-like load casts in some flat-laminated sand beds indicate rapid deposition of new sediment over relatively incompetent existing deposits (Reineck & Singh, 1980).

Flat-laminated, tabular sand beds capped by climbing ripples and desiccated mud are reported mainly from some braided stream deposits (Cant, 1982; Robinson & Love, 1986) and continental deposits interpreted as alluvial sandflat/mudflat/playa sequences (Smoot, 1983; Hubert & Hyde, 1982; Tunbridge, 1984).

RIPPLE CROSSLAMINATED SAND SEDIMENT TYPE

Description — The ripple crosslaminated sand sediment type consists mostly of various forms of ripple crosslaminated sandstone in tabular beds and lenses 10-15 cm thick with sharp to slightly scoured bases (Figs. 5, 6, & 7). Bedding surfaces commonly display well-formed, straight- and sharp-crested to bifurcating, symmetrical ripples (Figs. 8 & 9); rarely, they display interference ripples (Fig. 10), and ladderback ripples (a straight-crested ripple train with smaller ripples, roughly orthogonal with respect to the larger ripples, confined to the larger ripple troughs; Fig. 11), some with truncated ripple crests (Fig. 12). More rarely, ripples are more asymmetric and are straight to scalloped in plan, with regularly spaced, aligned cusps. All ripples observed are small, generally with heights of less than 1 cm and spacings of 8-10 cm (and thus with ripple index values of around 10). The sand is generally fine- to medium-grained, though rare lenses are coarse-grained. The sand consists mostly of quartz grains, with
rare glauconite grains and ooliths (especially in eastern sections), and occasional mudchips. The sand is generally well sorted and clean, cemented by quartz or, more rarely, calcite or dolomite. A very distinctive component of some ripple crosslaminated sand beds and lenses are occasional accreted mudballs, which consist of mudchips and sand grains accreted together in a sandy mud matrix to form spheroids on the order of 3-5 cm in diameter (Figs. 13 & 14).

Internal structure of the beds comprises a range of ripple crosslamination features. These include: 1) undulatory, unidirectional, and opposed crosslaminae in lenticular, bundle-like sets, with occasional foreset offshoots and continuous "drape" laminae over several bundles (Fig. 5 & 7) (Boersma, 1970; de Raaf et al., 1977); 2) nearly symmetrical, very steeply to vertically climbing ripple crosslamination (Fig. 6) (draped lamination of Ashley et al., 1982).

Interpretation — Ripple crosslaminated sand deposits record mostly bed load deposition, and in some cases combined bed load and suspension deposition, from turbulent water. Those with opposed laminae in bundle-like sets are the deposits of wave-formed ripples, formed primarily under oscillatory flow conditions (Newton, 1968; Boersma, 1970; de Raaf et al., 1977). However, Newton (1968) showed that wave-formed ripples in nearshore zones of the Baltic and North seas display internal structures essentially identical to those of many current-formed ripples. Thus, actual flow conditions responsible for many ripple crosslaminated sand deposits, such as those shown in Figure 7, are best regarded as indeterminate or possibly as combined (oscillatory with net
Figure 6. Fine-grained ripple crosslaminated sand lens within fine sandy lenticular couplets. The ripples climb nearly vertically, so that the symmetrical ripple form is well preserved. They record rapid deceleration of wave-generated flows (possibly asymmetric), with rapid settlement of suspended fine sand. LP 1285

Figure 7. Ripple crosslaminated sand, with prevalent irregular bounding surfaces, among red even couplets. Here, the form of the ripples is unclear, and sandstone above the main cut surface appears nearly flat-laminated. Flow character is uncertain, but may have been mostly unidirectional. BC 553
Figure 8. Straight, bifurcating, symmetrical vortex ripples capping a ripple crosslaminated sand bed. The ripples formed in shallow water, probably less than 4-5 meters deep, under the influence of gentle, wind-generated waves. Hammer is 38 cm long. Middle Dearborn River section.

Figure 9. Straight, bifurcating, symmetrical vortex ripples capping a ripple crosslaminated sand bed. Interpretation of ripples is as in Fig. 8. Scale is 30 cm long. LP 1470
Figure 10. Ladderback ripples, comprised of a primary set of strongly bifurcating symmetrical wave ripples and a secondary set of smaller, mostly symmetrical ripples, oriented roughly normal to the primary set and confined to the primary ripple troughs. Staff is 5 ft long. DR 270

Figure 11. Ladderback ripples, similar to those in Fig. 10, but with straighter primary ripple crests. Secondary ripples may have formed as shallow water drained off a wave rippled surface, or when wind and wave propagation direction abruptly shifted. Pen is 14 cm long. DR 270
Figure 12. Ladderback ripples with distinctly flat-topped primary ripples. Primary ripple crests were possibly truncated as very shallow water rapidly drained off a formerly shallowly submerged surface. Above Granite Park Chalet, near type Shepard section.

Figure 13. Dolomitic mudchips and accreted mudballs concentrated in the middle of a grey-green, medium-grained sand bed. The 15 cm-thick bed occurs within lenticular couplet deposits and is classified as ripple cross laminated sand sediment type. LP 241
the draped lamination present in some beds (Figs. 5 & 7) and dominating others (Fig. 6), however, does indicate settling of abundant suspended sand during a rapid slackening of flow, whether unidirectional or oscillatory (Ashley et al., 1982; Boersma & Terwindt, 1981; de Raaf et al., 1977). The flows would had to have been relatively strong to keep such a volume of sand suspended.

Preserved ripple trains on bedding surfaces should provide more direct evidence for flow conditions; however, the modern set of field and experimental data on symmetrical ripples and the flows responsible for them is scant compared to the corresponding data set for "current" ripples and unidirectional flows (Harms et al., 1982). Straight- and sharp-crested, bifurcating symmetrical ripples (vortex ripples) such as those shown in Figures 8 & 9 are produced essentially exclusively by velocity-symmetric, purely oscillatory flows; i.e. flows produced by waves (Harms et al., 1982). However, Amos & Collins (1978) related more round-crested symmetrical ripples to combined oscillatory and unidirectional flows. For a given sand size, ripple index (ratio of height to spacing) and ripple spacing of symmetrical ripples can be related to wave period and maximum flow velocity but not independently, and a wide range of combinations of values for wave period and maximum flow velocity may produce a particular ripple spacing or index value (Harms et al., 1982). Though Miller & Komar (1980) report that for small waves ripple spacing systematically equals the near-bottom wave orbital diameter times a coefficient of 0.65, Harms et al. (1982), summarizing the data from several authors, show a wide scatter of coefficient values. Furthermore, given the limited success (Harms et
al., 1982) of several authors to relate ripple spacing and index to water depth, using abundant data (e.g. Tanner, 1971; Clifton, 1976; Allen, 1979), there is no justification in attempting such a correlation here, since the appropriate measurements are sparse in this study. However, the few observed sets of asymmetric, straight ripples with regularly spaced cusps are virtually identical to those that form by the action of gently breaking waves on very shallow, gently sloping strand lines such as are found in Willapa Bay, Washington (1984 personal observation) and numerous other settings (Don Winston, 1984 personal communication).

Ladderback ripples in which both ripple sets are symmetrical apparently formed as waves, having formed one set, abruptly shifted their propagation direction by about 90 degrees and formed another, smaller set in the troughs of the existing ripples, without otherwise modifying the original ripple set. Furthermore, if this interpretation is correct, then the second generation of waves was only short-lived; otherwise, the original ripple set would eventually be completely reworked to conform to the later wave orientation. An approach to such conditions may be recorded in the more irregular interference ripples, but these may also represent either the intersection zone of two, coexistent, differently oriented wave trains, or the superposition of a wave-generated, symmetrical oscillatory flow and a unidirectional (though probably not steady) flow (Harms et al., 1982). Truncation of ripple crests, observed in the Shepard only twice, represents an abrupt, brief change in the strength and quality of the flow, from gentle (non-scouring) and oscillatory, to strong (erosive) and probably
unidirectional (Campbell, 1966). Such a sequence of events occurs commonly on modern tidal flats (both diurnal and wind tide flats) as water level drops during ebb flow (various authors in Ginsburg, 1975; Klein, 1977; de Raaf & Boersma, 1971; Miller, 1975; Lin & Wang, 1978). It may also occur during continuous oscillatory flow as water level drops due to sinking of water into the loose sand, causing the ripple phase to become unstable (Tanner, 1967). Truncated symmetrical ripples are reported in nearshore deposits of the lacustrine Pliocene Ridge Basin Group of California (Link & Osborne, 1978).

Accreted mudballs are composite clasts that record progressive, though not necessarily steady, agglomeration of apparently sticky, cohesive mudchips, sand grains and mud into sub-spherical balls. The ripple crosslaminated sand sediment type is not characterized by an abundance of individual mudchips, though it is most commonly interbedded with the mudcracked even couplet and lenticular couplet sediment types, both of which do have abundant mudchips. Thus, the mudchips contained in the accreted mudballs may not have been transported far. The balls' spherical shape, along with the tendency for mudchips to be roughly concentrically arranged within the balls, indicates that the mudballs rolled along the depositional surface, incorporating mudchips as they rolled. Since the mudballs occur in ripple crosslaminated sand deposits interpreted to have been wave-worked, the rolling motion of the growing mudballs was probably bi-directional, on a wave-washed surface.
MUDCRACKED EVEN COUPLETS SEDIMENT TYPE

**Description** -- The mudcracked even couplet sediment type consists of paired laminae, 0.3-3 cm thick overall, that characteristically extend across large outcrops with even to slightly wavy, parallel upper and lower boundaries. These couplets are repetitive, and commonly form continuous intervals up to several decimeters thick. Each couplet consists of a lower silt to very fine sand lamina, gradationally to abruptly overlain by an upper clay lamina (Fig. 15). Couplet bases are sharp. The proportional thickness of the silt and clay layers varies among individual couplets, as does the absolute thickness of the zone of silt-to-clay gradation. Other than grading, internal structure within the couplets is rarely apparent, though some lower silt half-couplets show flat lamination or ripple crosslamination. Sublayering within the clay laminae was never observed. Mudcracked even couplets are further characterized by the fact that they: 1) are commonly disrupted by silt-, sand-, and/or mudchip-filled mudcracks 1-2 cm wide that cut one or two couplets and outline irregular, centimeter- and decimeter-scale polygons (Figs 15 & 16); 2) typically bear abundant, angular mudchips a centimeter or two in length, commonly imbricated and concentrated in irregular layers and lenses (Fig. 17); and 3) are typically red. It is the combination of these features that serves to readily distinguish the mudcracked even couplet sediment type from the continuous even couplet sediment type (described below). Most mudcracked even couplet intervals are wholly terrigenous, and dolomitic intervals are fairly rare. Dolomitic even couplets weather tan, especially the upper clay laminae, in which most of the carbonate (mostly dolomicrite) is concentrated.
Figure 14. Large, dolomitic accreted mudballs in fine-grained sand bed. Not shown, but also present within the sand, are numerous individual mudchips. Accreted mudballs probably formed in shallow, wave-agitated water, as sticky mudchips adhered to each other to form a gradually growing ball. DR 41

Figure 15. Red, mostly thin, mudcracked even couplets. Note the one particularly thick red clay layer that is distinctly mudcracked. In upper third of photo, a few vague lenticular layers are present. Scale graduated in centimeters. LP 730
Figure 16. Typical mudcracked bedding surface in the mudcracked even couplet sediment type. The surface is bright light green, yet subaerial exposure is clearly indicated. Similar mudcracked surfaces can be seen in deposits of the lenticular couplet lithofacies. Scale is 14 cm long. LP 1100

Figure 17. Mudchip layer interbedded with mudcracked even couplets. Angular mudchips are crudely imbricate and represent transported broken mudcrack polygons. Large mudcracks are filled from above with silt and small mudchips, above scale and at top of photo. Low in the Shepard, between Jocko Lake and Turquoise Lake.
Interpretation — By the fact that mudcracked even couplets are graded fine sand- or silt-to-clay laminasets (Campbell, 1967), it is clear that they represent individual sedimentation events (Scheidegger & Potter, 1965), separated temporally by subaerial exposure and desiccation. The flat-lamination and/or ripple crosslamination, along with angular, imbricate mudchip layers in some couplets indicate traction transport, and the gradationally overlying clay layers record settling of suspended clay-rich mud from standing or very slowly moving water. Because these deposits are generally desiccated and mudcracked, it is most probable that the mudchips present are transported mudcrack polygons. If this is accepted, then the flows which produced the even couplets represent floods over a desiccated muddy surface. Furthermore, since the couplets are laterally very extensive (typically stretching across cliff outcrops for at least several tens of meters), it can be reasonably inferred that the depositional surface was flat and broad. Thus, the surface upon which the mudcracked even couplet sediment type was deposited can be reasonably termed a "mudflat," in the most generic sense of the word. Depth of flow over the mudflat cannot be reliably determined, though frequent subaerial exposure implies standing water of no great depth. However, just as the laterally extensive even couplets imply a broad, flat depositional surface (mudflat), they also imply a broad, unconfined, sheet-like flow that transported fine sand, silt, and mudchips as bed load as well as fine silt and clay as suspended load. The abundant desiccated surfaces further suggest that flood events were episodic and were separated by relatively prolonged periods of exposure. An alternative, probably less likely, is that flood events were more
frequent and regular, but under an extremely arid atmosphere. (There are no observed evaporites in the Shepard, nor is there evidence for their former existence.) Since carbonate mud, when present, is generally concentrated in the upper clay layers of the even couplets, I infer that fine-grained calcium carbonate (micrite) was precipitated mostly from the ephemeral standing water coevally with the settling terrigenous clay. Though other Shepard sediments show clear evidence of wave working in shallow water (cf. lenticular couplet sediment type), post-sedimentation currents at the sediment/water interface apparently never exceeded the critical shear velocity for the initiation of mud transport prior to initial mud consolidation and eventual desiccation (Terwindt et al., 1968; Terwindt & Breusers, 1972; Amos & Mosher, 1985). Thus the mud consolidated quickly or currents within the ephemeral standing water were very weak or non-existent.

Desiccated muddy deposits similar to those described here are reported by numerous authors, from modern continental playas (Hardie et al., 1978; Handford, 1982), to ancient sequences interpreted as lacustrine and/or playa deposits, including the Wilkins Peak Member of the Eocene Green River Formation (Smoot, 1983), the Upper Triassic Blomidon Formation (Hubert & Hyde, 1982), the Devonian Trentishoe Formation (Tunbridge, 1984), the Middle Triassic Edderfugledal Member (Clemmensen, 1978), and the Lockatong Formation and other units of the Triassic-Jurassic Newark Supergroup (e.g. Van Houten, 1964; Klein, 1969; Hubert et al., 1978; Suchecki et al., 1985). They also form on some marine supratidal mudflats and their ancient equivalents, though those
deposits tend to be more crudely laminated (e.g. Reineck, 1972; several authors in Ginsburg, 1975; Frey & Basan, 1978; Weimer et al., 1982).

CONTINUOUS EVEN COUPL ET SEDIMENT TYPE

**Description** -- Even couplets of the continuous even couplet sediment type have essentially the same textural and dimensional qualities as those of the mudcracked even couplet sediment type, although they tend to be somewhat thinner and slightly wavy (Fig. 18). More significantly, however, they also characteristically bear fewer mudchips and lack mudcracks. The mudchips that do occur tend to come in relatively distinct layers and are generally smaller and more rounded than those of the mudcracked even couplet sediment type. Only very rarely do the lower silt half-couplets display such sedimentary structures as flat lamination: on the whole they show only grading, with sharp bases. Continuous even couplets occur rhythmically in continuous intervals up to several decimeters thick. Argillite of this sediment type has a strong tendency to be light to medium green in color, which is more typical of the Shepard than red. Some continuous even couplet intervals are dolomitic and weather tan.

**Interpretation** -- The fine-grained, graded mud layers of the continuous even couplet sediment type probably represent mostly suspension settle-out from discontinuous turbid influxes of fine sediment in a standing body of water (Kuenen, 1966; Reineck & Singh, 1972; Sturm & Matter, 1978). The occasional flat lamination within the lower silt layers of the couplets provide only equivocal evidence for
Figure 18. Interlaminated light green, thin, continuous even couplets and microlaminae. Also present are two thick clay layers (number is on lower one), and a few very thin lenticular couplets. RB 41

Figure 19. Dolomitic variety of the lenticular couplet sediment type, with minor scours (arrows). Only the clay layers weather tan. These couplets record alternating turbulence (mostly wave-generated) and quiescence in shallow water. Number is on loose rock fragment. RB 485
traction transport: it is at least equally likely that such lamination records settling of suspended very fine sand and silt (Reineck & Singh, 1972). However, the occasional small, rounded mudchips were most probably transported as bed load. They may be distal, more eroded variants of the larger, more angular ones more abundant in the mudcracked even couplet sediment type. Alternatively, they may have been generated as soft, pasty rip-ups by periodic scour of adjacent muddy lenticular couplet deposits (Terwindt et al., 1968; see below). Carbonate mud incorporated within some continuous even couplets may have been precipitated directly from the water column (Last, 1982). Absolute depth of water is indeterminate, but the lack of desiccation features attests to continuous submergence and the lack of observed scour features suggests deposition below normal wavebase. There is no evidence to indicate frequency of sediment influx, but at least the textural grading effectively negates the possibility that the couplets represent seasonal varves.

Continuous even couplets are similar to the graded "rhythmites" reported from a variety of lacustrine, marine tidal, estuarine, and deep marine subenvironments, of numerous authors (e.g. Piper, 1970, 1972; Stow & Bowen, 1978; Biggs, 1978; Reineck & Singh, 1980).

LENTICULAR COUPLET SEDIMENT TYPE
Description -- Lenticular couplets consist of rhythmic alternations of undulating to lenticular, generally ripple crosslaminated very fine sand to silt laminae, and relatively structureless silty clay laminae. All laminae boundaries are sharp and some basal silt lamina boundaries are
scoured (Fig. 19). The combined lamina pairs range in aggregate thickness from 0.3 to 3 cm, extend across large outcrops, and lie stacked repeatedly atop each other, typically forming pure, continuous intervals up to 2 m thick, and dominating major intervals up to 300 m (1000 ft) thick (see Fig. 29, unit 5). Though rarely observed, bedding surfaces display small, straight crested, symmetrical ripples with somewhat rounded crests. The ripples tend to be less than 0.5 cm high with spacings of 5-8 cm. Many of the silt laminae consist of thinly connected to isolated, generally symmetrical and crosslaminated lenses, with 0.2-1 cm maximum thickness and with regular, 5-8 cm spacings (Figs. 19, 20, & 21). Other silt layers, though generally ripple crosslaminated, are more irregular to undulatory, and are commonly somewhat thicker (Figs. 19 & 20). Commonly, however, crosslamination in the silt layers is not apparent, regardless of degree of regularity of the lamina. Clay-rich mud laminae, sharply overlying the silt layers, generally appear massive and non-graded. Though some silt layers are discontinuous, clay layers are consistently continuous across outcrops. A particular clay layer tends to maintain a constant thickness along its lateral extent, undulating slightly over the lenticular silt layer below it. Fine sand- and silt-filled mudcracks, frequently observed on bedding planes and in cross sections, commonly disrupt one or two couplets. In cross section, they are generally crinkled, apparently from compaction. Mudcracks and mudchip layers are as common in some lenticular couplet intervals as they are in the mudcracked even couplet sediment type. Lenticular couplets most commonly occur in various shades of light green, but are rarely red. In some cases, red mudchips
Figure 20. Green, thin lenticular couplets interlayered with microlaminae. The deposit is transitional between the lenticular couplet and the microlamina sediment types and probably accumulated where sediment influxes and wave energy were limited. Lower Shepard, between Jocko Lake and Turquoise Lake.

Figure 21. Tan-weathering, dolomitic, clay-rich lenticular couplets. Laminae may be present within thick, tan-weathering portions, but are masked by the thin weathering rind covering the outcrop; this sample is a close approach to the carbonate mud sediment type. LP 1753
are incorporated within otherwise green lenticular couplets. In the upper part of the Shepard, tan-weathering, dolomitic lenticular couplets are very common; in these, most of the carbonate is concentrated in the clay layers, which consequently tend to weather more tan than the silt layers.

In cross sectional views of lenticular couplets, internal sedimentary structures within the silt layers are commonly only faintly visible, if visible at all, and thus tend to be non-photogenic. Where crosslamination is discernable, however, it displays, on a much smaller scale, many of the features that characterize the ripple crosslaminated sand sediment type. The ripple foreset laminae tend to occur in small, upward-curved bundles, some with offshoots that pass through the trough and up onto the adjoining ripple flank, thus creating opposed crosslaminae. Other lenticular silt layers show unidirectionally oriented foreset laminae, even though the lenses themselves are generally symmetrical. Lenticular couplets are thus very similar to the "lenticular bedding" of Reineck & Wunderlich (1968, especially bottom of fig. 4), but do not include amalgamated silt or sand lenses as Reineck & Wunderlich (1968) illustrate in the middle part of their figure 4.

Interpretation — Lenticular, ripple crosslaminated silt layers represent preserved ripple trains and record active migration of ripples across the depositional surface, with minimal sediment aggradation (Harms et al., 1982). Massive, ungraded clay layers record settling of suspended clay-rich mud from quiet standing water. Mudcracks in some intervals record subaerial exposure and desiccation of the depositional
surface. The internal features of some crosslaminated silt layers (e.g., upward-curved bundles of laminae, some of which extend across ripple troughs and up onto the adjacent ripple flank) are characteristic of wave-generated symmetrical ripples (Newton, 1968; Boersma, 1970; de Raaf et al., 1977). The unidirectional crosslaminae within other symmetrical lenses are somewhat ambiguous in that such crosslamination can occur both within ripples produced by unidirectional flows and those produced by oscillatory flows (Newton, 1968; de Raaf et al., 1977). Although formation of these layers by unidirectional flows is a possibility, the symmetrically lenticular profile of these layers, and of the even less informative internally structureless lenticular layers, lends support to the "wave-generated" alternative. Many flows may have been oscillatory with net translation. There is very little evidence to constrain hydraulic qualities of the flows, however. As noted in the section on the ripple crosslaminated sand sediment type, determination of water depth based on ripple form parameters is still largely a speculative business, given the paucity of good data (Harms et al., 1982). The mudcracks present in some intervals imply that at least those lenticular couplets formed in relatively shallow water. Since all lenticular couplets are essentially similar, the shallow water interpretation may apply generally, though this cannot be confirmed.

It is very significant that the ripple crosslaminated silt layers, formed in turbulent water, alternate rhythmically with clay layers, formed in quiet water. Flume experiments attest to these basic requirements (e.g. Terwindt & Breusers, 1972). For those silt layers which possibly record a unidirectional current, the complete lenticular
couplet apparently records a pulse of lower regime flow, transporting very fine sand and silt, followed by settling of suspended clay from quiet water. Notwithstanding possible mudcracks within such couplets, there is no indication of relative water depth. A reasonable possibility, however, would be a shallow, fairly low velocity flow such as the kind typical on modern tidal flats (both intertidal and subtidal), where the incoming and outgoing tides generate relatively brief unidirectional currents, and the slack-water periods allow for settling of suspended mud (de Raaf & Boersma, 1971; Ginsburg, 1975; Clifton, 1983). However, since most of the crosslaminated silt layers record oscillatory flows (waves), an alternative set of processes is indicated—one in which the depositional surface was alternately affected by waves and calm water. Conceivably, these conditions could be attained three different ways: 1) gentle waves are maintained more or less constantly but water level rises and falls, alternately placing the depositional surface above, then below, wavebase; 2) water level remains essentially steady, but wavebase rises and falls according to the size of the waves (which varies with stormy and fair-weather conditions); 3) in relatively shallow water, gentle waves exist only periodically or sporadically, and alternate with essentially absolute calm (essentially an extreme case of alternative 2). The conditions outlined in alternative 1 characterize many modern tidal flats, and various types of lenticular bedding characterize modern, and interpreted ancient tidal flat deposits (Weimer et al., 1982). They also characterize some modern playa deposits (Hardie et al., 1978), and ancient sequences interpreted as playa or lake deposits (see references
cited at the end of the "mudcracked even couplet sediment type" section). Some shallow marine successions appear to have been affected largely by the conditions outlined in alternative 2 (e.g. de Raaf et al., 1977), producing wave-generated flaser, lenticular, and wavy bedding (Reineck & Wunderlich, 1968). The conditions of alternative 3, though conceivable, probably do not occur on a spatially and temporally significant scale. (This, however, does not strictly preclude the possibility that such conditions were significant in the Proterozoic).

MICROLAMINA SEDIMENT TYPE

Description — The microlamina sediment type consists of very thin (< 3 mm, commonly paper-thin), discontinuous to laterally persistent laminae of dark, clay-rich mud (Figs. 22 & 23). The mud laminae are generally graded, from silt up to clay, but because microlaminae are generally so thin and fine-grained, grading, where it exists, is apparent only in thin section. More rarely, the mud is dominated by fine silt, and the thin lamination is defined by very thin cryptalgal (?) laminae or thin, wispy layers of dark organic material (Fig. 24). Microlaminae form relatively pure decimeter- to meter-scale intervals in most sections and dominate a continuous, 300 m (1000 ft) interval in the Evans Peak measured section (Plate 1; Figure 29, unit 3E). Fine details are difficult to observe because microlamina intervals tend to be recessive in outcrop and the laminae commonly split apart, making sample retrieval difficult. Microlaminae are commonly dark green or dark grey, and some intervals are black and carbonaceous (Lemoine, 1979). The black variety tends to be particularly fine-grained and fissile.
Occasional horizons of small, weathered pyrite crystals and molds occur within intervals of black and dark grey microlaminae. Other levels may be merely stained rusty orange. As with the other sediment types, microlaminae in some intervals contain a moderate amount of dolomicrite, causing those intervals to weather to a greyish tan color. Mudcracks and possible fluid escape structures disrupt some microlaminae deposits, but these features are generally observable only in sawed slabs and thin sections (Figs. 25 & 26). A few thin intervals were observed in which clay-rich mudstone appears essentially massive.

Occasional small scour surfaces cut through microlaminae intervals, generally with only a few centimeters of relief and traceable for only one or two meters. These are remarkable in that they are immediately overlain not by coarser material such as sand, but merely by more microlaminae with the same appearance as those below the scour. The overlying microlaminae simply drape over the truncation surface. The microlamina sediment type is also frequently host to small penecontemporaneous deformational structures such as centimeter-scale, tight chevron folds, and more rarely, decimeter-scale slump folds and tiny soft-sediment faults.

Stromatolites occur more commonly in contact with microlaminae than with any of the other sediment types; where this occurs, the microlaminae adjacent to the stromatolites tend to be locally red. The stromatolites vary considerably in form and degree of development: from vague, irregular algal crusts; to small, poorly developed, sparse vertically stacked heads up to 20 cm in diameter; to large, well developed, laterally linked hemispheroids forming irregular beds up to
40 cm thick. They range in composition from largely terrigenous (dark) to largely calcareous (pinkish). Small mudchips and fine sand partially fill the spaces between some well-formed heads, but otherwise the stromatolites generally sharply overlie and underlie microlaminae or lie at the contact between intervals of the microlamina and lenticular couplet sediment types.

Some microlamina intervals are punctuated by numerous small lenses of fine-grained sand and silt. These are generally no more than 10 cm thick, usually on the order of one or two meters in length. Only rarely do they approach 30 to 40 cm in thickness and five or six meters in length. The bases of many lenses are distinctly scoured and/or loaded down into the microlaminae below (Fig. 27). Internally, the lenses generally appear structureless, though some display faint flat laminae or low-angle crosslaminae.

Fine sand also occurs within some microlamina intervals in the form of narrow, squat, rather bulbous lenses. These distinctive lenses commonly occur together with the more broad, low-profile lenses noted above. Where outcrop surface relief is sufficient, they prove to be fairly flat-topped, semicircular (up to 20 cm in diameter) in transverse section, but long, slender, essentially tubular (at least several decimeters long) in longitudinal section. Though most appear internally structureless, a few are flat-laminated (Fig. 28), with the laminae terminating abruptly, squarely against the wall of the structure. Structures apparently identical to these were termed "pseudochannels" by Lemoine (1979), who reported them from black and green argillite intervals of the Shepard in the Cabinet Mountains. The structures
Figure 22. Green microlaminae. Most laminae are continuous and less than 1 mm thick. Visible in center of photo is a single relatively thick, discontinuous lamina (arrow), here the only evidence for current activity. BC 472

Figure 23. Green microlamina sediment type. LP 250
Figure 24. Microlaminae defined by thin, wispy layers of dark organic material which enclose isolated silt grains. The layers are possibly cryptalgal laminae, though they may represent "dead oil" injected into microfissures. Plain light; bar = 1 mm. DR 70

Figure 25. Green microlaminae disrupted by shrinkage (desiccation ?) cracks or fluid escape structures (?). If they are desiccation cracks, these microlaminae, as well as those in Fig. 26, may have formed in a very shallow, nearshore setting. Scale in centimeters. DR 70
Figure 26. Brown, abruptly graded microlaminae, cut by mudcrack filled with silt from above. Mudcracks such as these are generally not observed in outcrop. Dark, wispy organic layers cross the crack and thus must be post-depositional features. Plain light; bar = 1 mm. DR 70

Figure 27. Green, sharply loaded and/or scoured fine-grained sand lens within crumbly microlamina deposits. The sole structures are linear and curved and may be load-accentuated rivulet fill. Other, similar appearing occurrences, however, are clearly simple load casts. DR 395
Figure 28. Gutter cast enveloped by microlaminae. Many workers believe such structures to record ephemeral subaqueous rivulets scoured into the substrate by storm-generated bottom currents. Flat internal lamination (upper-regime plane lamination ?) would be consistent with such an interpretation. BC 50

appear similar to the "gutter casts" described by Whitaker (1973) from the Llandoverian (earliest Silurian) of southern Norway, and also reported by Tunbridge (1984) from the Middle Devonian of North Devon, and by Soegaard & Eriksson (1985) from the Middle Proterozoic Ortega Group of New Mexico.

Interpretation -- The microlamina sediment type represents settling of suspended fine mud out of mostly quiet water. For those microlaminae observed to be graded, a seasonal varve interpretation is unrealistic (Reineck & Singh, 1980, p. 127; Dickman, 1985); these most likely record
small, discrete sediment influxes, the frequency of which is indeterminate. For those in which internal grading is unobserved, the time duration represented by each microlamina is also indeterminate. The depth of water in which microlaminae accumulated may have been quite variable. Rare mudcracks appear to be desiccation cracks (Figs. 25 & 26) and thus suggest relatively shallow water. Occasional scour surfaces indicate erosive bottom currents, which, if wave-generated, would indicate a depth at least shallower than storm wavebase, and if tide-generated, would suggest a similar order of depth. However, both mudcracks and scours are fairly rare features of the microlamina sediment type, and thus most microlaminae appear to have accumulated under quiet water that was either deeper than wavebase, or shallow and protected from currents and waves.

In the black, carbonaceous variety of microlaminae, the carbon is evidence for organic production in the water column (e.g. algal blooms) and/or on, and probably in, the sediment substrate. Preserved carbon and pyrite layers indicate reducing conditions within the sediment, probably resulting from uptake of all available oxygen by decaying organic material (Krauskopf, 1979).

In addition to the stromatolite mounds that grew atop microlaminated mud surfaces, algae and bacteria may have formed more extensive rubbery films or thin mats, which would have served to bind the top layer of sediment (Grotzinger, 1981; Smoot, 1983), protecting it from fairweather current or wave scour. The apparent shallowness and local extent of scour surfaces, as well as occasional small chevron folds, may reflect either relatively weak scouring currents or the
relative cohesiveness of microlaminated mud in the shallow subsurface. The fact that such scours in microlaminae are directly overlain by more microlaminae suggests that the erosive currents were barren or underladen. They perhaps emanated from offshore, muddy parts of the basin. The centimeter-scale, chevron-shaped soft-sediment folds may have developed very near the surface as the shear imposed by bottom currents or waves rumpled the rubbery top sediment layer (Grotzinger, 1981; Smoot, 1983). Decimeter-scale soft-sediment folds may have formed during compaction and dewatering. Though both the centimeter- and decimeter-scale folds reported here could also have formed in response to slope instability, independent evidence for slope deposition is lacking: microlamina beds are concordant with surrounding strata, and there are no graded beds or any other beds suggestive of gravity-induced turbidity flows.

The broad, relatively thin lenses of fine sand record episodic delivery of sand to a setting clearly dominated most of the time by mud settling from suspension in quiet water. Because some lenses appear to have scoured bases, traction transport of the sand is suggested though not definitely indicated. Massive internal textures in many such lenses provide no clue, and flat laminae may represent either upper regime flow (Harms et al., 1982) or settling from suspension (Reineck & Singh, 1972). Occasional low-angle crosslaminae provide some evidence for relatively high-velocity, large-period oscillatory flow with both traction and suspension transport of the sand (Walker, 1979; Harms et al., 1982). Regardless of particular flow conditions, fairly rapid deposition of the sand over structurally weak, water-rich microlaminated
mud is indicated by the common presence of load casts at the bases of lenses.

With regard to the Shepard "gutter casts," it is noteworthy that several authors (Whitaker, 1973; Goldring & Aigner, 1982; Soegaard & Eriksson, 1985) regard the structures as recording episodic, subaqueous helicoidal currents, probably generated by storms. In the views of these authors, gutter casts form as small, relatively stationary subaqueous rivulets that are progressively filled with fine sand and silt during dominantly unidirectional storm surges in normally subwavebase water.

The carbonaceous variety is strikingly similar to oil shale such as that which characterizes parts of the Eocene Green River Formation of Wyoming (Bradley, 1931; Culbertson, 1969; Surdam & Wolfbauer, 1975; Surdam & Stanley, 1979; Smoot, 1983). Microlaminae in general are similar to some "rhythmites," interpreted to form in a variety of lacustrine, marine tidal, estuarine, and deep marine subenvironments, of numerous authors (e.g. Piper, 1970, 1972; Stow & Bowen, 1978; Biggs, 1978; Reineck & Singh, 1980).

CARBONATE MUD SEDIMENT TYPE

Description — As previously noted, all of the muddy Shepard sediment types vary in composition from wholly terrigenous to dolomitic. Where dolomite content is quite high, the resulting tan weathering of the rock surface generally obscures all signs of lamination and sedimentary structures; this is the carbonate mud sediment type of Winston (1984, 1986b,d). It is the only sediment type in the Shepard defined on the
basis of composition, and is reasonably viewed as an end member of a compositional spectrum, ranging from completely siliceous, through mixed siliceous/dolomitic, to mostly dolomitic. Notwithstanding its textural gradation with the other clay-rich sediment types, the carbonate mud sediment type commonly occurs as distinct beds 5-20 cm thick. Though the beds are characteristically massive, faint lamination, vague silt-to-clay couplets, and fine sand ripple lenses are visible within some beds. The mud itself consists of varying proportions of quartzitic silt and terrigenous clay, with abundant (up to about 50%) dolomicrite, dolomicrosparite, and very fine-grained calcite (neomorphosed micrite).

**Interpretation** — In terms of a hydraulic interpretation, the carbonate mud sediment type offers little evidence short of its gross muddy texture. As noted, some sedimentary structures are faintly visible within carbonate mud beds, but the paucity of these structures on the whole makes consistent sedimentologic interpretation of this sediment type essentially impossible. Therefore, given the textural similarity with other muddy sediment types, and the fact that in general the carbonate mud sediment type differs from the others only in composition, it seems reasonable to give it a hydraulic interpretation equivalent to that given to whatever terrigenous muddy sediment type it happens to be interbedded with.

In terms of its mineral composition, however, the carbonate mud sediment type warrants its own interpretation. The source of the carbonate is a first order concern. Throughout the Shepard, there is no evidence for detrital carbonate grains entering the basin. Therefore,
only two other alternatives exist: 1) The carbonate is entirely
diagenetic, and was deposited as carbonate-charged ground water
percolated through the Shepard deposits. This could have happened at
any time prior to complete lithification. 2) The calcium (and magnesium
?) and carbonate existed as dissolved ions in Belt "sea" water and
precipitated from the water under particular conditions. As noted
previously, where the various Shepard couplets are dolomitic, the
carbonate is concentrated in the clay layers, and the sandy and silty
layers are relatively carbonate-free. Furthermore, the carbonate mud
sediment type itself is very fine-grained and contains a significant
proportion of terrigenous mud, but generally little sand. These
observations cast some doubt on the veracity of a totally diagenetic
interpretation, since many more pore-volumes of potentially carbonate-
precipitating ground water would flow through the relatively coarse
silty and sandy layers than their less permeable muddy counterparts.
However, a systematic petrographic analysis of Shepard rocks was not a
part of this study, so the diagenetic history of them is uncertain.
Therefore, a diagenetic origin for the carbonate cannot be ruled out.

The second alternative, that the carbonate was precipitated from
Belt "sea" water, is viable for the same reasons that the first
alternative is presumably not. If the carbonate mud sediment type
proper is genetically the same as the carbonate generally concentrated
in the various couplets' clay layers, then it seems reasonable to infer
that the carbonate mineral (whatever the original mineral was)
precipitated directly from the water, admixing and settling with the
hydraulically equivalent terrigenous clay that was then settling from
suspension. Winston (1986b,d) proposes this same hypothesis regarding the carbonate mud sediment type, but offers little evidence in support of it other than Eby's (1977) observation of halite crystal casts in carbonate mud beds of the Helena Formation. This observation suggests that the precipitation of carbonate may have been stimulated by evaporative concentration, a mode of precipitation also reported by other authors in modern sediments and other rocks (Bissell & Chillingar, 1962; Driese, 1985). However, besides the mudcracks in the mudcracked even couplet and lenticular couplet sediment types, there is no independent evidence for highly evaporative or hypersaline conditions in the Shepard. Alternatively, if Belt "sea" water was sufficiently concentrated with respect to calcium carbonate, precipitation of carbonate may have been stimulated by photosynthetic utilization of carbon dioxide (Jones & Bowser, 1978), as in Lake Manitoba, Canada (Last, 1982). Certainly, the stromatolites common to many of the Shepard's microlamina deposits, many of which are also carbonaceous, attest to the presence of algae and bacteria in relative abundance.

**STRATIGRAPHIC FRAMEWORK**

Having described the seven sediment types of the Shepard—the flat-laminated sand, ripple crosslaminated sand, mudcracked even couplet, lenticular couplet, continuous even couplet, microlamina, and carbonate mud sediment types—it is important to document and describe their geometrical relationships to one another. In this section I discuss the method and rationale for stratigraphic correlations, and recognize eight lithostratigraphic units, each dominated by one particular sediment
type, that display lateral interfingering relationships.

**Stratigraphic Correlation**

Plate 1 records the measured sections and shows lithocorrelations (see Appendix II for more detailed measured sections). Note that the spacing between columns is to scale (see inset map on plate). Detailed physical lithocorrelation (i.e. based solely on lithology) of relatively widely spaced stratigraphic sections is an uncertain undertaking at best (Miall, 1985, p. 80). Lithocorrelation of the Shepard Formation as a single unit across most of the Belt basin is widely agreed upon (McGill & Sommers, 1967; Mudge et al., 1974, 1982; Horodyski, 1983; Wallace et al., 1984). On a much larger scale—if, say, one had several closely spaced sections within a 20 square kilometer area—the Shepard's internal stratigraphic intervals presumably could be correlated in extreme detail with a high degree of confidence. The situation in this stratigraphic study is intermediate between those extreme cases, and a pragmatic approach to lithocorrelation was taken, correlating only on as fine a scale as seemed reasonable. In making the correlations shown, the following considerations were made, approximately in the order listed:

1) Where the base and/or the top of the Shepard Formation is included in the measured section (true in all cases except the Jocko Lake section, Plate 1), these boundaries were correlated across the study area.

2) Within this overall context, some distinctive sequences of sediment
types occurring at approximately equivalent stratigraphic levels (e.g., 30% up from the base of the Shepard) in adjacent sections were correlated based on direct match. Such distinctive sequences do not occur frequently in the Shepard, so presumably where they do occur, even at apparently different stratigraphic levels, they are probably physically continuous. As an example of this type of correlation, on Plate 1, LP 250-310 matches BC 150-260 (stromatolitic microlamina passing up to partly dolomitic lenticular couplets, capped by flat-laminated sand), and since this sequence also lies at approximately the same stratigraphic position, there is good justification for correlation.

3) Where relatively pure intervals of a particular sediment type occur in adjacent sections at approximately equivalent stratigraphic levels, they are probably correlative, using the framework provided by the correlation of sequences described above as a guide. The simple assumption was made that, the thicker a particular sediment type interval is in a given section, the greater its lateral extent is likely to be, and thus the greater the likelihood that it extends to an adjacent section. For example, stromatolitic microlaminae comprise nearly the entire EP 180-1000 interval (Plate 1), with only minor occurrences of the lenticular couplet and carbonate mud sediment types. A virtually identical thick interval comprises DR 100-480. Based on this identity and similarity of stratigraphic position, the intervals are deemed to correlate.
4) As a consequence of the kinds and levels of correlation listed above, certain non-matching intervals, sandwiched between intervals that correlate on the basis of lithologic identity, are implied to correlate as well. For example, the lower 100 feet of the Dearborn River section (Plate 1) consist of the flat-laminated sand, ripple crosslaminated sand, and mudcracked even couplet sediment types. The lower 180 feet of the adjacent Evans Peak section consist primarily of the microlamina sediment type, with two flat-laminated sand units, each less than 10 feet thick. Both of these intervals rest above red quartzite and argillite of the Snowslip Formation and lie below the thick microlamina interval mentioned above. Thus, despite their extreme lithologic contrast, they necessarily correlate. The two different lithosomes apparently interfinger somewhere in the region between Evans Peak and the Dearborn River. Similarly, in the interval overlying the thick microlamina unit described above, lenticular couplets with lesser amounts of microlaminae at Evans Peak (EP 1000-1160) apparently pass to continuous even couplets and minor microlaminae at Dearborn River (DR 480-610).

The previous discussion outlines the basis for the lithocorrelations. By using the four criteria in the order listed, the precision of correlation increased step-wise. There is no way to verify the accuracy of the correlations, but nor is there any way to refute them. It is certainly possible that some of the thinner intervals are miscorrelated, but unlikely that the broader correlations are incorrect. Ideally, there should be many more measured sections positioned between
the ones shown. This certainly would tend to increase the level of confidence. However, the lack of continuous outcrop across the field area precludes that situation.

**Sediment Type Distribution: Lithostratigraphic Units**

Figure 29 illustrates the generalized distribution of the Shepard sediment types across the study area. Generalization is necessary because stratigraphic correlations, though at least grossly accurate, do not support the precise depiction in a lateral sense of small, pure sediment type intervals. Indeed, all occurrences of the ripple crosslaminated sand and carbonate mud sediment types are too thin to depict explicitly on the cross section (Fig. 29). However, most ripple crosslaminated sand beds are interbedded exclusively with the lenticular couplet sediment type with the remaining few distributed as interbeds among intervals of the mudcracked even couplet and flat-laminated sand sediment types. The carbonate mud sediment type and dolomitic varieties of the other sediment types are distributed broadly, primarily in the upper half of the Shepard (see Plate 1). Only the principal occurrences of the flat-laminated sand sediment type (units up to 5 m thick) are shown in Figure 29. Most minor flat-laminated sand beds are closely associated with the mudcracked even couplet sediment type. The stratigraphic sections illustrated in Figure 29 are faithful, albeit scaled down and simplified, reproductions of the columns illustrated on Plate 1 and thus represent data gathered in the field. All other graphical information is interpretive but is based on the stratigraphic lithocorrelations worked out and displayed on Plate 1. Other than the
Figure 29. Stratigraphic cross section, showing the generalized distribution of terrigenous sediment types in the Shepard Formation in a north-south line from the Jocko Mountains to the Mission Range, and from there in an east-west line through the Swan Range to the Lewis & Clark Range. Based on Plate 1.
degree of lithologic generalization, the principal difference between
the two types of diagrams is that Figure 29 pictorially depicts inferred
interfingering lateral relationships explicitly, while Plate 1
schematically shows only interpreted lines of correlation.

As shown in Figure 29, the Shepard has been subdivided into eight
distinct lithostratigraphic units, each of which is dominated by one
particular sediment type. The units are defined principally to
facilitate discussion of fundamental stratigraphic relationships and the
depositional history.

Unit 1 -- Unit 1 is fairly heterolithic, but consists mostly of the
lenticular couplet sediment type, with a thin interval of the mudcracked
even couplet sediment type at its base (uppermost Snowslip Formation ?)
and minor intervals of the microlamina, flat-laminated sand, and
mudcracked even couplet sediment types in the middle. The unit extends
from Crazy Fish Lake northward to Turquoise Lake. From there it
thickens eastward to Blind Canyon and beyond, where it passes to and is
split by a western tongue of unit 3E. Unit 1 is overlain by continuous
even couplets and microlaminae of unit 3Wa.

Unit 2 -- Unit 2 is predominantly a northwestward-pinching wedge of
the flat-laminated sand sediment type, extending from Blowout Mountain,
where it consists almost solely of sand with abundant mud interbeds, to
Dearborn River, where it consists of a sequence consisting of the
mudcracked even couplet sediment type at the base, passing upward
through the flat-laminated sand, mudcracked even couplet, and finally to
the lenticular couplet sediment type at the top. Two discrete bedsets of flat-laminated sand extend northeastward to Evans Peak, but otherwise the sequence totally loses its sandy character to the northeast, passing into the microlamina sediment type low in unit 3E at Evans Peak. Unit 2 is entirely overlain by continuous even couplets and microlaminiae of unit 3E.

Unit 3 — Unit 3 is a major lithosome consisting mostly of the microlamina sediment type, with subordinant intervals of the continuous even couplet sediment type. The unit predominates eastern Shepard sections (where the unit is labeled 3E). Two major tongues extend westward to Turquoise Lake and Red Butte, and from there southward to Crazy Fish Lake. The lower tongue (labeled 3Wa) is 200 ft thick at Blind Canyon and Leota Peak, but thins to only 10 ft at Turquoise Lake, generally maintaining that thickness to Crazy Fish Lake, where continuous even couplets are also present at the base. The upper tongue (labeled 3Wb) is consistently thin and tabular, except where it gradually thickens from Turquoise Lake to Crazy Fish Lake, where, like unit 3Wa below it, it has continuous even couplets at its base. Unit 3E interfingers westward with lenticular couplets of units 1, 4, and 6 and to the east is progressively overstepped by unit 6. Unit 3Wa lies above lenticular couplets of unit 1 below, and units 3Wa and 3Wb envelop unit 4. Where intervals of the continuous even couplet sediment type occur in unit 3, they are as minor tongues and lenticles either at the base of the unit (above lenticular couplets of units 1, 2, and 4) or as westward-extending tongues passing to lenticular couplets of unit 4 high.
in the easternmost sections. Most of the Shepard's stromatolite beds occur in unit 3.

Unit 4 — Unit 4 is dominated by the lenticular couplet sediment type, with two lenticles of the mudcracked even couplet sediment type and several discontinuous bedsets of the flat-laminated sand sediment type. It overlies unit 3Wa, interfingers with unit 3E to the east, and passes upward and southward to microlaminae and continuous even couplets of unit 3Wb.

Unit 5 — Unit 5 is very similar to unit 4, but is thicker and more extensive. Although dominated by the lenticular couplet sediment type, it contains several thin, discontinuous bedsets of the flat-laminated sand sediment type, as well as a lenticle of the mudcracked even couplet sediment type, and five of the microlamina sediment type. The unit is thickest at Leota Peak and thins eastward to Evans Peak, where it passes to microlaminae and continuous even couplets at the top of unit 3E. Unit 5 passes westward to Red Butte and southward to Jocko Lake and Crazy Fish Lake, where it envelops units 6 and 7. At Red Butte and Leota Peak, unit 5 essentially envelops unit 8 as well, but only a thin sheet of lenticular couplets, the uppermost Shepard beds, overlies unit 8.

Unit 6 — Unit 6 is a small lithosome consisting solely of the mudcracked even couplet sediment type. It extends from Crazy Fish Lake to Jocko Lake, beyond which it passes to lenticular couplets and
microlaminae of unit 5. Unit 6 overlies the southern extension of unit 5 and passes upward to unit 7.

Unit 7 -- Unit 7 is represented at Jocko Lake by the continuous even couplet sediment type, which passes southward to the microlamina sediment type at Crazy Fish Lake. The continuous even couplet interval at Jocko Lake interfingers northward with lenticular couplets and minor microlaminae of unit 5.

Unit 8 -- Unit 8 is the uppermost distinctive unit of the Shepard and consists mostly of the mudcracked even couplet sediment type, with flat-laminated sand at Red Butte in the middle of the unit and at its abrupt boundary with overlying lenticular couplets of the uppermost Shepard. The unit extends eastward from Red Butte to Leota Peak, where it is split into two tongues and interfingers with lenticular couplets at the top of unit 5. Unit 8 presumably extends southward from Red Butte, but apparently not as far as Jocko Lake.

Summary of Lateral Sediment Type Relationships

Figure 29 reveals significant lateral relationships among the various sediment types. Even allowing for some inaccuracy in some of the finer correlations, the gross relationships are still evident. Probably most obvious is the major zone of interfingering between lenticular couplets of units 1, 4, and 5, and microlaminae of unit 3E around Leota Peak and Blind Canyon and at Evans Peak. Also apparent is the general association of continuous even couplets with the microlamina
sediment type (e.g. upper parts of eastern sections). In many places on the diagram, continuous even couplets appear intermediate between lenticular couplets and microlaminae (e.g. the lenticular couplet—continuous even couplet—microlamina sequences at the unit 1/unit 3Wa transition (Leota Peak and Crazy Fish Lake) and the unit 4/unit 3Wb transition (Crazy Fish Lake). Mudcracked even couplets are either enveloped by or pass laterally to lenticular couplets in all cases except at Jocko Lake, where continuous even couplets directly overlie mudcracked even couplets. As noted earlier, most ripple crosslaminated sand beds lie within lenticular couplet intervals. Finally, all of the thin subunits of the flat-laminated sand sediment type are enclosed either by lenticular couplets or by mudcracked even couplets.

From the combined observations noted above, the following coherent scheme of lateral relationships is apparent: flat-laminated sand passes laterally to mudcracked even couplets; both of these pass to lenticular couplets and interstratified ripple crosslaminated sand beds, which in turn pass either to continuous even couplets or to microlaminae. The carbonate mud sediment type is most commonly interbedded with both lenticular couplets and microlaminae (see Sheet 1). Obviously, however, those are the Shepard's most voluminous sediment types, and carbonate mud beds are also associated with both mudcracked and continuous even couplets, but only rarely with flat-laminated sand (Sheet 1).
SEDIMENTOLOGIC SYNTHESIS

The Depositional Surface

Up to this point, the only sedimentologic interpretations have been those relating hydraulic processes to the seven sediment types. Those interpretations were made simply by applying widely accepted sedimentologic principals developed by experimentalists, theorists, as well as myriad field sedimentologists. Thus, conclusions drawn were based on direct outcrop-scale observations of the rocks, classified into one of seven sediment types. Establishment of the stratigraphic framework into which the sediment types fit on a regional scale allowed recognition of the basic lateral relationships among the sediment types, noted above. It is now fairly straight-forward to conceive of the overall depositional surface on which the various Shepard sediment types accumulated, and thus infer the average distribution of hydraulic conditions across that surface during any particular short period of time.

Recall the basic lateral relationships among the major sediment types; i.e., flat-laminated sand passes laterally to mudcracked even couplets, both of which pass to lenticular couplets and associated ripple crosslaminated sand, which in turn pass either to continuous even couplets or to microlaminae. Then recall the fundamental hydraulic processes inferred for each sediment type; i.e., the flat-laminated sand and mudcracked even couplet sediment types represent sheet-like, unidirectional flows culminating in shallow standing water, followed eventually by subaerial exposure and desiccation; ripple crosslaminated sand represents wave working of sand in relatively shallow water;
lenticular couplets record mostly alternating wave working and quiescence in fairly shallow water, sometimes followed by subaerial exposure and desiccation; and continuous even couplets and microlaminae both record generally calm, quiet-water conditions. Furthermore, recall that the fine layering of all of these deposits (except some cases of ripple crosslaminated sand) is extensive and even across large outcrops. Therefore, the conceptual model of deposition necessarily involves a broad, low-relief, gently sloping depositional surface on which up to four broad, roughly parallel zones can be recognized: 1) a mostly subaerially exposed, sandy zone; 2) a similarly exposed, but more muddy zone; 3) a broad, frequently wave-washed, and occasionally exposed, shallow-water silty/muddy zone; and 4) a more quiescent, perennially submerged muddy zone. Thus, basinward and landward directions can be inferred with respect to the sediment types deposited on this surface, with the conclusion that the Shepard sediment types thin and fine basinward.

Comparable Modern Environments and Deposits

Modern mud-dominated depositional environments that have depositional surfaces with the combined features outlined above are few. Attention naturally turns to low-energy, muddy marine tidal flats as one possibility. Numerous authors have investigated the processes and deposits of modern tidal flats (de Raaf & Boersma, 1971; various authors in Ginsburg, 1975; Klein, 1977; Boersma & Terwindt, 1981; Yeo & Risk, 1981; Clifton, 1982; Weimer et al., 1982), and many of these and others have described and interpreted ancient sequences as tidal deposits.
Virtually the only other type of environment, however, that warrants comparison with the Shepard is that represented by continental playas and shallow lakes with playa-like margins. In contrast to the copious literature on tidal deposits, only a few authors have published on modern continental playas and playa-lakes (e.g. Hardie et al., 1978; Eugster & Hardie, 1979; Handford, 1982), though several have described the details of ancient lacustrine and playa sequences (Clemmensen, 1978; Link et al., 1978; Hubert et al., 1978; Allen, 1981; Hubert & Hyde, 1982; Smoot, 1983; Tunbridge, 1984; Sullivan, 1985).

**Tidal flats and related deposits** — Factors influencing the quality and appearance of modern tidal flats include the tidal range, degree of wave activity, and texture of available sediment (Weimer et al., 1982). Features which characterize macrotidal flats include an extensive intertidal mudflat, generally crossed by numerous small tidal creeks, and a muddy subtidal zone dominated by large tidal channels (Reineck, 1972, 1975; Weimer et al., 1982). On the intertidal mudflat, mixed wave and current activity alternating with high-tide slack water forms lenticular, wavy, and flaser bedding (Reineck & Wunderlich, 1968). However, meandering tidal creeks on the intertidal flat and particularly lateral-accretion channel fill in the subtidal tidal channels ultimately makes channel deposits the "most important tidal facies" (Weimer et al., 1982, p. 193). Moreover, the subtidal deposits in particular are the ones "most likely to be preserved" in a prograding tidal flat sequence (ibid., p. 191). Prograded tidal flat deposits form distinct fining-
upward sequences, from generally bimodally crossbedded sand at the base, followed by flaser bedded muddy sand, then wavy and lenticular bedded sand and mud, and finally more irregularly bedded (typically bioturbated), often desiccation-cracked mud deposited in the high intertidal zone (Reineck, in Ginsburg, 1975; Weimer et al., 1982). The high intertidal ("supratidal") deposits appear to be virtually the only ones to become desiccated and mudcracked.

Meso- and microtidal flats display most of the same features noted above, but at a correspondingly smaller scale (Weimer et al., 1982). Furthermore, as tidal influence decreases, wave influence increases proportionately, so that microtidal strandlines tend to be characterized by sandy beaches and barrier islands, cut by tidal pass channels, seaward of the intertidal mudflat (McCubbin, 1982).

Although some of the Shepard's sediment types—particularly the lenticular couplet sediment type—are very similar to some of the deposits formed on tidal flats, many deposits and features characteristic of tidal tidal flats are totally absent in the Shepard. Notably absent are virtually any deposits that could be in any way related to a channel (with the possible exception of the Shepard's "gutter casts"), though both mud and sand channel-fill deposits are characteristic (if not diagnostic) of tidal sequences. One of the Shepard's stratigraphic characteristics is a very low tendency for regular sequential arrangement of the sediment types, while prograding tidal flats produce discrete, fining-upward sequences, and the deposits of transgressive tidal flats tend to not be preserved (Klein, 1977). Finally, major sand deposits of beaches, barrier islands, and tidal pass
deltas, while often a significant element of tidal flat sequences, are absent from the Shepard. Thus, in light of these shortcomings, a marine muddy tidal flat does not provide a suitable depositional model for the Shepard Formation, and a marine tidal flat interpretation of the Shepard is rejected.

Playa-lakes and related deposits — Lakes and their deposits vary widely and are thus difficult to characterize (Picard & High, 1972). However, the apparently great lateral extent of desiccated muddy deposits in the Shepard makes comparison to ephemeral lakes (playas) and lakes with broad, ephemerally submerged margins reasonable. Although sedimentological details of such modern settings are not widely described in the literature, Hardie et al. (1978, p. 20) summarize their observations on many active playa mudflats, and recognize two basic types of active mudflats surrounding saline lakes: sheetwashed mudflats and ponded water mudflats. They state:

Deposition on sheetwashed mudflats would occur when thin sheets of sediment-charged stormwaters stream off the sandflats and across the mudflats en route to the central saline lake. The essential process here would be very shallow, unchannelled flow (hence fine-grained sediment but upper flow regime bedforms). The resulting layering probably would be graded, with traction load, flat lenticular sandy or silty laminae capped by a fine mud (clay sized sediment) drape deposited when the flow waned. These mud drapes, as well as the finer-grained lenticular lamination, would become mudcracked (centimetre-scale) on drying out; such small shallow mudcracks should be beautifully preserved when the next flood washes sandy sediment over the bottom and into the old surface cracks. Deposition in ponded (standing) water on mudflats occurs during storm flooding when the saline lake temporarily expands outward over the fringing mudflat subenvironment. Under these conditions the sediment-charged sheetwash off the sandflats should rapidly decelerate as it enters the expanded lake and quickly deposit its load. We envisage that deposition would take the form of a graded thin
bed or thick lamina deposited (a) from the sheetwash that entered the shallow standing lake water as a waning turbid underflow (turbidite) or (b) from the mixed inflow-lake water body as a simple settle-out. After deposition these graded layers could be reworked by wind waves to produce either coarse silt-fine sand lenses and muddy drapes or, if the layer is thick enough, simple surface rippling. Finally, as the lake waters recede by evaporation the mudflats are exposed once more and mudcracking will disrupt the layering.

Hardie and co-authors (1978) were rightly cautious in their generalization of the relationship between processes and deposits, given the paucity of observations of sheetfloods on modern continental mudflats. Yet their somewhat speculative discussion is supported by numerous apparently equivalent ancient deposits. Similar mudflat facies are reported in the Recent sediments of Bristol Dry Lake, California (Handford, 1982). Other descriptions of appropriately broad and shallow modern lakes and their fringing mudflats are virtually non-existent, but several ancient large, unequivocally lacustrine sequences, many with mudflat facies similar to those of the Shepard, are thoroughly described in the literature. These include several Tertiary deposits in the western United States, such as: the Green River and Uinta formations, Wyoming/Colorado/Utah (Bradley, 1964; Eugster & Hardie, 1975; Fouch, 1975; Surdam & Wolfbauer, 1975; Surdam & Stanley, 1979; Smoot, 1983), and the Ridge Basin Group, California (Link & Osborne, 1978; Link et al., 1978). Mudflat and lacustrine facies are well represented in the Jurassic-Triassic Newark Supergroup, eastern United States (Van Houten, 1964; Klein, 1969; Hubert et al., 1976, 1978; Hubert & Hyde, 1982; Demicco & Kordesch, 1986) and the Middle Triassic Edderfugledal Member, East Greenland (Clemmensen, 1978).
Principal facies in these deposits generally record alluvial plain or sandflat, delta, subaerially exposed mudflat, shallow-water nearshore, and open lacustrine environments (Fouch & Dean, 1982). The presence or absence of particular facies, and the extent to which they are developed, depend upon the paleohydrology and tectonic style of the basin (including climate and whether the basin was closed or open), chemical composition of the water supplied to it, and dominant texture of the terrigenous sediment supplied to it, all of which tend to vary with time in a long-lived basin (Hardie & Eugster, 1970; Fouch & Dean, 1982; Smoot, 1985). Alluvial plain facies include trough crossbedded and/or flat-laminated sand deposited in ephemeral to perennial streams and/or on ephemeral sheetflood sandflats (e.g., Hubert & Hyde, 1982; Smoot, 1983; Tunbridge, 1984). Deltaic deposits include interbedded trough-crossbedded channel sand and laminated mud overbank and marsh deposits, and/or large-scale planar crossbeds (Gilbert-type delta foresets) (Fouch & Dean, 1982; Smoot, 1985). Normally or frequently exposed mudflat deposits are typified by graded even to lenticular laminae of silty to sandy mud, generally disrupted by desiccation cracks (Ryder et al., 1976; Fouch & Dean, 1982). Normally submerged nearshore deposits consist of thin beds of ripple crosslaminated fine sand to clay-rich mud, with bedding surfaces showing straight-crested, symmetrical ripples, occasionally with truncated crests (Fouch & Dean, 1982; Link & Osborne, 1978). Some shallow-water nearshore deposits are very thinly laminated clay-rich, carbonaceous and calcareous mud, with occasional desiccation cracks, that apparently formed in relatively protected zones away from significant terrigenous clastic influx sources.
(Fouch & Hanley, 1977; Fouch & Dean, 1982). Deposits very similar to these, without the desiccation cracks but with occasional patches of convolute bedding, apparently accumulated offshore on the quiet lake floor (Link & Osborne, 1978; Fouch & Dean, 1982; Smoot, 1983). These deposits in particular have attracted the attention of many of the workers cited here, for they tend to be rich in kerogen and often form significant "oil shale" deposits (Bradley, 1931; Fouch & Hanley, 1977; Fouch & Dean, 1982; Smoot, 1983). Additional open lacustrine deposits include even, typically graded laminae of silty mud, which in some modern lakes are deposited by turbidity currents (Sturm & Matter, 1978). Apparently depending on the chemistry of the lake water (Eugster & Hardie, 1979), many of the above facies range from purely terrigenous in composition to highly calcareous/dolomitic, and significant evaporite deposits occur in some sequences (Eugster & Hardie, 1975; Smoot, 1983).

Except for some lake deposits that display meter-scale terrigenous-to-carbonate cycles (Van Houten, 1964), the facies listed above are generally packaged within formations not as rhythmic sequences but rather as a set of extensive, broadly interfingering lithosomes in which the preserved facies distribution in cross section roughly parallels the original landward-to-basinward distribution across the depositional surface (Fouch & Dean, 1982, fig. 69; Smoot, 1983, figs. 16 & 17; Handford, 1982, fig. 13). However, because closed basin lakes expand and contract with climatic shifts (i.e., balance between water inflow and evaporation and downward seepage), alluvial facies at times prograde far out into the basin, while open lacustrine facies at other times
transgress up onto the basin margins (Smoot, 1985), and these shifts are
recorded in the stratigraphic framework.

Despite some differences, the overall striking similarity of the
Shepard Formation to many ancient playa-lake sequences, as well as of
parts of the Shepard to described modern playa mudflats, makes a
conceptual correlation between the two very appealing. Not only are the
individual facies similar, but equally importantly, the stratigraphic
arrangement of those facies is very similar to many lacustrine
sequences. The differences are generally attributable to natural wide
variability among lakes and lacustrine deposits (Picard & High, 1972).
There are no Shepard deposits that could reasonably be interpreted as
deltaic (Miall, 1979; Coleman & Prior, 1982), but on the other hand most
playa-lake deposits also lack significant delta deposits (e.g. Smoot,
1983; Tunbridge, 1984). The Shepard also lacks trough-crossbedded
stream channel sand deposits, but these are also absent in the more
distal alluvial sediments of the same sequences lacking delta deposits.
Finally, though a large percentage of the Shepard's sediment volume is
dolomitic (like many lake deposits), it is apparently lacking in saline
evaporite minerals. Eugster & Hardie (1979) point out, however, the
broad hydrochemical spectrum of modern arid-region lakes, including many
that are not saline at all, but only calcareous. Therefore, of the two
modern environments (marine tidal flats and continental playa-lakes)
explored as being potentially comparable to the Shepard, only the playa-
lake system appears generally valid. A generalized playa-lake model is
thus accepted and adopted as a working depositional model for the
Shepard Formation in the study area.
Paleogeographic Setting of the Shepard Formation

The prograded alluvial fan and sandflat deposits of the underlying Snowslip Formation (Winston, 1986a) and overlying Mount Shields Formation (Winston, 1978, 1986a,b; Slover, 1982; Slover & Winston, 1986) place limits on the paleogeographic setting for accumulation of the muddy Shepard Formation. Winston (1984, 1986b) has proposed that the alluvial facies retreated before the Shepard transgression and returned with the basal Mount Shields, and that view is adopted here. Thus, the Shepard deposits are here regarded as being essentially the distal equivalents of an alluvial depositional system similar to that of the Mount Shields.

The Playa-Lake Model As It Applies To The Shepard Formation

The six terrigenous sediment types that comprise the bulk of the Shepard Formation each formed under distinctive circumstances in generally distinctive sub-environments (Fig. 30). The carbonate mud sediment type formed more generally across much of the depositional surface; its development depended more upon water chemistry than on hydrodynamic conditions in the lake. The flat-laminated sand sediment type, composed of sheet-like beds of flat-laminated, fine-grained sand with climbing-ripple and wave-ripple crosslaminated tops and thin, mudcracked mud drapes, formed as sheetflood deposits on the broad sandflat fringing the lake margin. Wave-ripple crosslaminated bed tops attest to ephemeral, shallow residual ponds following a flood event, or possibly actual flood-induced expansion of the lake up onto the sandflat. No channel-fill deposits suggestive of perennial streams are
Figure 30. Block diagram of proposed Shepard depositional model, showing schematic, hypothetical distribution of Shepard sediment types. "Alluvial fan deposits" are entirely hypothetical. Base drawing modified from Peterson (1981).
recorded in this or any other Shepard facies; the flat-laminated sand sediment type records instead flashy, episodic sheetfloods. This facies is not extensively developed in the study area, though at times, portions of this sandflat prograded out over the lake margin proper, passing directly to shallow-water nearshore facies (the lenticular couplet and ripple crosslaminated sand sediment types). Normally, however, the sheetfloods carried only silt and mud as far as the lake margin, where some of it settled out of ponded flood water as even couplets. The ponding of water on the normally exposed mudflat was effected mostly by flood-induced expansion of the lake. The ponded water was only ephemeral, and with a return to subaerial exposure these even couplets usually became mudcracked, thus forming the mudcracked even couplet sediment type. The contraction of the lake was probably caused by combined evaporation and downward seepage (cf. Smoot, 1985).

The next sheetflood necessarily flowed over a desiccated, mudcracked surface, picking up broken mudcrack polygons and incorporating the mudchips within the new even couplet layer.

Sheetfloods also introduced much suspended sediment, as well as some mudchips, to the standing water of the mostly perennial, but shallow lake. In the broad, shallow nearshore margin, gentle waves worked the sediment to form lenticular couplets. The waves were strongest during the brief, relatively high stands resulting from lake expansion, during which time they suspended clay and worked silt and fine sand into discontinuous ripples or a rippled continuous layer. As water level again fell, waves were significantly attenuated and the clay settled from suspension, capping the rippled silt layer and thus forming
the lenticular couplet sediment type. By the time the next lake expansion occurred, the clay had become cohesive enough to resist resuspension; occasional small scour surfaces through mud layers suggest erosion of cohesive mud. Some parts of this broad, generally submerged mudflat were occasionally subaerially exposed, allowing some lenticular couplets to become desiccated and mudcracked.

During the occasional periods when the sandflat advanced over the exposed mudflat, fine sand was introduced directly into the shallow-water nearshore environment. This sand became worked by waves to form ripple crosslaminated beds and lenses with symmetrical ripple tops, thus forming the ripple crosslaminated sand sediment type. The waves that worked the sand appear to have been somewhat stronger than the average waves that formed lenticular couplets. These stronger waves resulted either from storms or from relatively higher water levels (allowing larger waves) associated with relatively greater lake expansions. (Floods capable of advancing the sandflat completely across the exposed mudflat were probably relatively large floods and caused a correspondingly greater expansion.) Mudchips introduced by floods and created directly on exposed lenticular couplet surfaces occasionally nucleated and agglomerated in the wave-washed shallow water, forming accreted mudballs. These composite clasts generally became incorporated within ripple crosslaminated sand lenses or beds.

Farther offshore, in the more stable open lacustrine environment, subaerial exposure of the lake bottom occurred only rarely. Where terrigenous mud influx was sufficient, graded silt-to-clay laminae accumulated, forming the continuous even couplet sediment type. Most
influxes were related to episodic flood events, but some may have originated from resuspended mud originally deposited as lenticular couplets. Some small, rounded mudchips occasionally incorporated in the continuous even couplets may be eroded desiccation-crack derived mudchips, though perhaps more likely they are intraclasts scoured from cohesive, submerged lenticular couplet deposits.

Across much of the offshore lake bottom, however, terrigenous clastic influx was minimal; small, episodic pulses of suspended mud formed the microlamina sediment type. Similar conditions existed in some relatively nearshore settings, and microlaminae accumulated there as well, occasionally becoming exposed and desiccated. Water was generally calm or deep enough for waves to have no effect on the bottom, and suspended mud simply settled to the bottom to form microlaminae. Many microlamina deposits are carbonaceous, attesting to algae and bacteria growing on and in the sediment, and possibly to planktonic algae in the water column. Also, stromatolites, though surviving well enough in most of the lake's subenvironments, thrived farther offshore, where microlaminae formed (i.e., away from significant clastic sediment influx). Occasional storms passing over the lake created wave currents strong enough to locally scour cohesive microlamina deposits and to sweep sand from the nearshore out into the offshore. Lake water was apparently saturated with respect to calcium carbonate much of the time, particularly during the latter half of Shepard deposition, and the carbonate apparently precipitated directly from the water, perhaps induced by photosynthetic uptake of carbon dioxide.
Despite the large size of the Belt basin, the evidence from the Shepard Formation supports the hypothesis that during Shepard deposition, at least part of the basin was hydrographically closed, occupied by a large, mostly shallow lake (Fig. 30). The closed-basin playa-lake model fits the observations presented here very well, and may also work well with other argillite units of the Belt Supergroup. Whether Belt rocks represent vast lacustrine or shallow marine deposition has been much debated. Winston et al. (1984) outlined the history of the marine vs. lacustrine controversy, and concluded that, though many individual sedimentary features in Belt argillites are similar to those formed in marine tidal flat settings, marine beach, barrier island, and tidal channel deposits are notably absent, and thus Belt sediments most likely accumulated in a shallow, tideless inland sea (i.e., a lake). They also outlined evidence for a major western sediment source terrane, in addition to the well-known eastern and southern basin margins, which further suggests a restricted, if not enclosed, basin.

HISTORY OF SHEPARD DEPOSITION

Besides providing important evidence for the depositional model, the stratigraphic cross section (Fig. 29), which is a simplified, more pictorial depiction of the correlation diagram (Plate 1), reveals much about the depositional history of the Shepard. Because there are no fossils or any widespread, reliably instantaneous marker beds in the Shepard, it is not valid to speak of particular intervals of "time" with respect to any correlated lithostratigraphic interval. Indeed, because
the Shepard as a whole represents a high stand of the Belt "sea" with respect to the Snowslip Formation below and the Mount Shields Formation above, it follows that the base of the Shepard represents a generally south-southeastward transgression over the Snowslip alluvial wedge (Winston, 1986b), and the base of the Mount Shields represents a generally north-northwestward progradation of a renewed alluvial wedge over the Shepard basinal deposits (Winston, 1986b; Winston & Slover, 1986). Thus, the Shepard contacts are clearly time-transgressive, though the rate of transgression or progradation is unknown. Certainly the transitional nature of each of the contacts, as well as other sedimentologic evidence (Winston, 1986b), including that presented in this study, suggests a low gradient depositional surface and probably rapid transgression and later progradation. Assuming that this is correct, time lines are probably not far from parallel to stratigraphic lines. While conservatism demands an avoidance of "time" terms in discussing the depositional history (except when limited to a particular vertical sequence), implicit in all previous discussion of "lateral relationships" of sediment types are time lines at least approximately envisioned. Thus, in the following discussion, no attempt is made to suppress such interpretation.

In the Shepard, the bulk of terrigenous sediment appears to have come from the south and west-southwest. Though one may reasonably conclude this based on the sediment type relationships depicted in the cross sections, more direct evidence lies south of the study area. On the northern edge of the Sapphire allochthon, approximately 25 km southeast of Missoula, the lower 300 meters of the 450 meter-thick
Shepard Formation consist of abundant quartzite and red argillite and siltite (Hunter, 1984). Below that interval lie 60 meters of quartzite clearly correlative with a similar, thick quartzite interval high in the Snowslip Formation in the Swan Range. The upper 150 meters of Shepard in the northern Sapphire Mountains consist mostly of green, slightly calcareous argillite (Hunter, 1984). This interval correlates well with the calcareous and dolomitic upper half of the Shepard in the Mission and Swan Ranges. Although Hunter (1984) assigned the sand and red argillite interval to the Snowslip Formation in his mapping, it is bounded by intervals which force its correlation with the lower half of the Shepard in the present study area. Thus the lower portion of the Shepard Formation appears to become considerably sandier to the southwest and implies a sand and mud source farther south or southwest.

[The Sapphire allochthon was tectonically transported from a more westerly position during the Cretaceous (Hyndman, 1980)]. Furthermore, the southward-thickening sand wedges of the overlying Mount Shields Formation (Winston, 1978, 1986a,b,c; Slover, 1982; Slover & Winston, 1986) and underlying Snowslip Formation (Winston, 1986a) indicate a southern source area and imply one for the Shepard as well.

Unit 1 records the onset of Shepard deposition in the vicinity of Turquoise Lake, Leota Peak and Blind Canyon. Broad development of the mudcracked even couplet sediment type, essentially vestigial remnants of the exposed Snowslip mudflat, gives way upward to lenticular couplets and, for a time, microlaminae. The mudflat recorded by unit 1 probably sloped gently to the northeast. Lenticular couplets prevail in this part of the basin, while fine-grained, muddy sand mostly of the flat-
laminated sand sediment type characterizes unit 2 in the easternmost sections. Such a sizable sand accumulation is rather anomalous for the Shepard; presumably the sand was derived primarily from the south-southeast, since the unit pinches out to the east-northeast. The sand passes upward and basinward through mudcracked even couplets to lenticular couplets, recording retreat of the distal sandflat and subaerially exposed mudflat. While exposed and shallow-water deposits of units 1 and 2 were forming, microlaminae of unit 3E were accumulating offshore, in a relative topographic depression centered around the site of Evans Peak. This site remained under similar conditions for much of the duration of Shepard deposition. Transgression begun early on culminated in relatively deep, quiet water spreading over the entire study area, laying down the extensive microlamina deposits represented by the combined units 3E and 3Wa. Regression then ensued, as shallow-water mudflats represented by unit 4 lenticular couplets abruptly displaced offshore microlaminae of unit 3Wa. These mudflats passed offshore to microlaminae of unit 3E; the nearshore/offshore transition zone long remained relatively stabilized in the vicinity of present-day Leota Peak and Blind Canyon. Subaerially exposed mudflats prograded into the line of section, represented low in unit 4 by subunits of the mudcracked even couplet sediment type at Leota Peak and Crazy Fish Lake. Because the lithosome at Leota Peak pinches out both east and west, it suggests that the direction of progradation was from the south, and that the exposed mudflat (and presumably the sandflat behind it) was lobate in plan, perhaps with a somewhat more focused sediment supply than is otherwise generally suggested by the diffuse sediment dispersal patterns
recorded in most of the Shepard. The mudcracked even couplet lithosome at Crazy Fish Lake pinches out to the north, suggesting that it prograded from the south.

After the regression recorded in unit 4, transgression again occurred, represented by a tongue (labeled 3Wb) of microlaminae of unit 3E apparently extending westward to Red Butte and southward to Crazy Fish Lake. Unit 3Wb is best developed around Crazy Fish Lake, where the transgression is well recorded by the upward passage from mudcracked even couplets to lenticular couplets (unit 4), to continuous even couplets and finally microlaminae of unit 3Wb. Thus, the site of Crazy Fish Lake was, for a time anyway, another mild topographic depression, receiving continuous even couplets and abundant quiet-water microlaminae.

Lenticular couplets of unit 5 abruptly overlie microlaminae of unit 3Wb and overstep microlaminae of unit 3E in the east, recording yet another phase of regression in the study area. Shallow-water mudflats prograded over nearly the entire area, bringing to a close the quiet-water conditions dominant for so long in the vicinity of Evans Peak. The virtually uninterrupted accumulation of the lenticular couplet sediment type at Leota Peak during the latter half of Shepard deposition attests to longlived extreme stability in shallow water conditions there, and apparently documents a firm balance between sedimentation and subsidence rates. A subaerially exposed lobate mudflat and sandflat prograded into the area of Blind Canyon, probably from the south, as it appears very similar to the one deposited in unit 4, discussed above. Between Red Butte and Leota Peak, minor deposits of the microlamina
sediment type record shortlived protected settings, probably not fully
"offshore." In the south at Crazy Fish Lake, an exposed mudflat well
represented by unit 6 mudcracked even couplets passes distally
(northward) to unit 5 lenticular couplets. Unit 6, however, is abruptly
overlain by continuous even couplets and microlaminae of unit 7,
recording a rapid reversal of apparent proximal and distal directions.
Such stratigraphic relations attest either to abrupt local subsidence
and/or an arrest of sediment supply; it is not clear why there is no
lenticular couplet interval intermediate between unit 6 mudcracked even
couplets and unit 7 continuous even couplets. In the east, conditions
alternated between quiet-water and wave-washed, as recorded in the
complex interfingering of unit 5 lenticular couplets with the
microlaminae of uppermost unit 3E. Microlamina deposits extend
completely to the easternmost section (Blowout Mountain); the continuous
even couplet lithosomes extending eastward from lenticular couplet
tongues of unit 5 would presumably extrapolate eastward to more
microlaminae if any more Shepard rocks were preserved there east of
Blowout Mountain. The regression begun in unit 5 culminated with
widespread development of a subaerially exposed mudflat and sandflat,
represented by the mudcracked even couplet and flat-laminated sand
sediment types of unit 8. Because unit 8 is well developed in the east-
west direction (passing eastward to lenticular couplets of uppermost
unit 5), but apparently pinches out to the south, the direction of
progradation into the study area seems to have been from the west. The
well developed mudcracked even couplet deposits of unit 8 high in the
Shepard herald the demise of the Belt "sea" in the study area and
progradation of the vast, exposed mudflat and sandflat represented by the lower Mount Shields Formation (Slover, 1982; Winston & Slover, 1986). Although unit 8 high in the Shepard may represent a progradational pulse from the west or southwest, the Mount Shields sediment wedge thins and fines to the north, recording progradation in that direction for the bulk of the Mount Shields (Winston, 1986a,b,c).

SUMMARY OF CONCLUSIONS

Shepard rocks are naturally divisible into seven sediment types. These are the flat-laminated sand, ripple crosslaminated sand, mudcracked even couplet, lenticular couplet, continuous even couplet, microlamina, and carbonate mud sediment types. These sediment type are distinct from one another on the bases of texture, lamination style and other sedimentary structures, and to a minor extent, color. Only the carbonate mud sediment type is defined on the basis of mineral composition, and sedimentary structures within it are largely obscure.

Each of the terrigenous sediment types represents distinctive hydraulic conditions within the Belt "sea." The flat-laminated sand sediment type represents sheetflood deposition of sand on a broad, mildly lobate sandflat surrounding the Belt "sea." The mudcracked even couplet sediment type represents sheetflood traction transport of fine sand, silt and mudchips, followed by mud settlement from suspension in shallow, ephemeral standing water, followed soon by subaerial exposure and desiccation. The lenticular couplet sediment type represents gentle wave reworking of silty mud alternating with quiet water mud settlement from suspension in broad expanses of shallow water. The ripple
crosslaminated sand sediment type indicates mostly wave working of fine sand in shallow water to form lenses and thin beds. The continuous even couplet sediment type represents mud settle-out in a sub-wavebase setting. These deposits, unlike those of the mudcracked even couplet sediment type, were not observed to be mudcracked, and thus were probably never subaerially exposed. The microlamina sediment type represents normally quiet-water settle-out of only the finest mud available to the Belt basin. Algae and bacteria often lived on and in these muds, resulting in the typical black shale appearance these deposits now have, and perhaps binding the mud to a certain degree. Discrete algal colonies formed stromatolites in all muddy parts of the basin, but thrived especially in or near microlamina deposits. Though normally quiet-water conditions prevailed where microlamina deposits accumulated, occasional scoured surfaces, current-generated (?) small soft-sediment folds, and quickly-deposited sandstone lenses with loaded bases all suggest occasionally turbulent conditions in the places where microlamina deposits formed.

The hydraulic process interpretation given to each sediment type is based on generally understood sedimentological principals founded on theory, experiments, and field observations of numerous authors. Only the carbonate mud sediment type is hydraulically ambiguous, since it displays virtually no sedimentary structures; accordingly, it plays a relatively insignificant role in the sedimentologic analysis.

The physical lithostratigraphic framework is based upon lithocorrelation through nine measured sections. Individual "key beds" are largely absent in the Shepard. Therefore, a pragmatic approach to
correlation is adopted in which four steps provide progressively finer (and probably somewhat less certain) correlations: 1) correlation of the lower and upper Shepard contacts provides a rough guide for further correlations within the Shepard; 2) matching of relatively thin, distinctive stratigraphic sequences at approximately equivalent stratigraphic levels provides a basic internal framework; 3) correlation of relatively pure sediment type intervals within the context of previous correlations; and 4) recognition of non-matching intervals that must necessarily correlate.

Vertical and lateral sediment type distribution is thus established, based on the lithocorrelations. Based on the lateral relationships among the several sediment types evident from the stratigraphic cross sections, it is apparent that flat-laminated sand passes laterally to mudcracked even couplets, both of which pass to lenticular couplets and generally associated ripple crosslaminated sand beds, which in turn pass to continuous even couplets or microlaminae.

Based on hydraulic interpretations of the various sediment types, and knowledge of their lateral relationships, the depositional surface must have been a broad, gently dipping slope characterized by four, roughly parallel zones (Fig. 30): 1) an alluvial sandflat (flat-laminated sand); 2) a subaerially exposed mudflat (mudcracked even couplet); 3) a broad, occasionally exposed, shallow-water zone (lenticular couplet and ripple crosslaminated sand); 4) a perennially submerged, quiet-water zone (continuous even couplet and microlamina). Such a depositional surface is only superficially similar to modern marine tidal flats, and lacks significant tidal channels, generally
considered to be the fundamental feature of tidal flats. Also lacking from the Shepard depositional surface are beaches and barrier islands, which are significant elements in some tidal flat systems.

The inferred Shepard depositional surface is, however, strikingly similar to many modern continental playa mudflats and associated shallow lake bottoms. Ancient deposits of such systems are very similar to Shepard deposits, both in terms of individual facies (sediment types) and how the facies are arranged stratigraphically. Based on this convincing similarity, a generalized playa-lake depositional system is offered as a viable working model to interpret and explain the sedimentary and stratigraphic features of the Shepard Formation.

The depositional history of the Shepard is interpreted in terms of this model, and is revealed by a stratigraphic cross section (Fig. 29) showing the sediment type distribution. The Shepard is dominated by exposed and shallow-water facies in the Swan and Mission ranges and the Jocko Mountains, and by submerged, quiet-water facies in the Lewis & Clark Range to the east. This relationship holds generally, except relatively major expansions of the lake deposited quiet-water microlaminae across the entire field area two separate times. At the top of the Shepard, exposed mudflat deposits (mudcracked even couplets) are widely developed, heralding the impending progradation of the major Mount Shields alluvial wedge over the area.

ACKNOWLEDGMENTS

I take this opportunity to thank the several people who assisted me in one way or another in this project. I thank my friend and wife,
Jessica Woods, for not only being patient and encouraging, but for being my primary field assistant. In that capacity she performed marvelously, sharing with me the often tedious task of measuring sections. I am also indebted to Mike McGroder for helping me complete the Jocko Lake section; and to Russ Axlerod for helping me measure the Red Butte section. Thanks go to Greg Byer for stimulating conversations about the Shepard and the philosophy of geology. I thank my committee members: Keith Osterheld, Johnnie Moore, and Don Winston. The debt I owe Don is immense and multifaceted. I thank him especially for the impetus after a false start, the invaluable help in the field, the many rewarding and encouraging conversations, the many other valuable opportunities he generously provided, and, in general, the many good times. A research assistantship under Don Winston provided much needed financial support, the funds for which were provided by National Science Foundation Research Grant EAR-8409507 and NSF-MONTS Research Grant ISP-8011449. Subsidiary funding for this project was provided by Sigma Xi, the Scientific Research Society.
REFERENCES


Amos, C. L., and Mosher, D. C., 1985, Erosion and deposition of fine-grained sediments from the Bay of Fundy: Sedimentology, v. 32, p. 815-832.


Bradley, W. H., 1931, Origin and microfossils of the oil shale of the


Horodyski, R. J., 1976, Stromatolites of the upper Siyeh Limestone (Middle Proterozoic), Belt Supergroup, Glacier National Park, Montana: Precambrian Research, v. 3, p. 517-536.


Höy, T., 1984, The Purcell Supergroup near the Rocky Mountain trench, southeastern British Columbia [abst.], in Hobbs, S. W., (ed.), The


Last, W. M., 1982, Holocene carbonate sedimentation in Lake Manitoba,
Canada: Sedimentology, v. 29, p. 691-704.


Miall, A. D., 1985, Principals of Sedimentary Basin Analysis: New York,


O'Connor, M. P., 1972, Classification and environmental interpretation of the cryptalgal organosedimentary "molar tooth" structure from the late Precambrian Belt-Purcell Supergroup: Journal of Geology, v. 80, p. 592-610.


Suchecki, R. K., Hubert, J. F., and Birney, C. C., 1985, Isotopic imprint of depositional and diagenetic environments on lacustrine and related terrestrial rocks of Triassic-Jurassic age in the Hartford, Deerfield, and Fundy rift-basins [abst.]: Society of Economic Paleontologists and Mineralogists Annual Midyear Meeting


APPENDIX I

An Early Diagenetic Feature: "Molar-Tooth" Structure

Many argillite intervals are highly disrupted by subvertical, crinkly, ribbon-like structures composed of pure, blue-grey, finely crystalline (<20 micron) blocky calcite, and subhorizontal pods composed of blue-grey silty limestone. These features, collectively called "molar-tooth" structure (Bauerman, 1885, p. 26; O'Connor, 1967, 1972; Smith, 1968), are common in the Shepard and occur extensively in the Helena Formation as well. The ribbons, < 1 cm thick and mostly on the order of a decimeter long, are cracks filled with calcite; while the pods, typically 1 x 3 cm, are nodule-like, envelop terrigenous silt and mud, and possibly record early carbonate cementation. Intervals as thick as two meters are affected by these structures, often so intensely that the host sediment type is not identifiable. The structures are well supported as very early diagenetic features by the following evidence: 1) The crinkly form of the ribbons and the fact that they often show slight displacement across breaks in kinks suggests that subvertical narrow cracks formed and were filled with calcite prior to sediment compaction. 2) Laminae within the small carbonate pods are comparatively uncompacted relative to the enveloping laminae. The pods were thus formed prior to compaction. 3) Occasional thin lag concentrations of molar tooth fragments lying on scoured surfaces indicate a very shallow depth of formation of the vertical ribbons. Apparently, the calcite that filled the newly formed cracks was not a soft ooze but was in fact rigid and crystalline.
Molar-tooth structure locally disrupts intervals of all the muddy sediment types, but especially the carbonate mud sediment type. The sandy sediment types and the edgewise conglomerate sediment type were never observed to be disrupted. Despite the constraints on timing of formation, interpretation of their genesis is rather speculative: few ancient and no modern analogs are known, and thus they seem to be enigmatic. In the Helena Formation, O'Connor (1967, 1972) interpreted the them as organosedimentary structures and related them to stromatolites. In the Shepard, no preferred association with stromatolites was observed. Smith (1968) also related their origin to biogenic activity, and calculated that vertical, sheet-like cracks formed and were filled with calcite within 1.3 m of the sediment surface, prior to folding and crinkling of the structures upon compaction. Horodyski (1976) proposed that the calcite filled voids of various origins, including synaeresis cracks, desiccation cracks, and liquid- and gas-filled voids formed by organic decay within the sediment and accompanying gas production. The fact that the structures themselves are pure calcite while the host rock is often dolomitic suggests that dolomitization may have occurred before the molar-tooth structure formed; i.e., pre-compaction. Otherwise, it is unclear why these early-formed structures would have escaped later dolomitization. Perhaps the formation of molar-tooth structure may even have been a consequence of the inferred early dolomitization, in that the volume reduction (i.e., density increase) resulting from the conversion of calcite to dolomite (Hurlbut & Klein, 1977) could conceivably manifest itself as sub-surface shrinkage cracks within a moist but cohesive mass
of muddy sediment. Interpretive analysis beyond this point would depend upon extensive petrographic and experimental work, which was not a part of this study.

**Edgewise Conglomerate: Not Quite a "Sediment Type"**

**Description** — Distinctive, isolated beds of edgewise conglomerate occur at only three positions within the Shepard Formation in the study area: at 70 ft in the Leota Peak section, 625 ft in the Evans Peak section, and 295 ft in the Dearborn River section (Plate 1). The latter two beds may be continuous. These distinctive deposits consist of large, plate-like intraclasts of dolomitic and terrigenous mudstone, up to 5 or 6 centimeters across and 1 centimeter thick, packed edgewise or imbricated at a high angle, with little sand and mud matrix, in isolated, massive beds up to about one-half meter thick (Fig. 31). The beds have sharp planar to undulatory bases, with undulatory to irregular tops. The plate-like intraclasts are flat to slightly curved, generally with rounded edges. Though roughly vertically oriented, no preferred azimuthal orientation is apparent. Imbrication of clasts commonly occurs in a variety of directions within a single bed. Though quite distinct from the other sediment types of the Shepard, edgewise conglomerate is so rare as to be best regarded as anomalous within the context of facies analysis. However, some readers may disagree with me on that point; thus its description and process interpretation is given here.
Figure 31. Edgewise conglomerate, as seen on bedding plane (above) and in cross section (below). The deposit consists largely of clast-supported, irregular plates and chips composed of dolomitic mud, with little sand matrix. Some plates lie horizontally but many others are steeply imbricate to vertical. Edgewise conglomerate forms irregular beds up to a half meter thick. DR 295
Interpretation -- The intraclastic composition of these beds implies that the fragments are either transported broken mudcrack polygons or are "rip-ups," eroded episodically from partially lithified surfaces (whether wet or dry) (Folk, 1962). In either case, the sharp, apparently scoured bases of beds and the tight packing of the intraclasts in a roughly imbricate to edgewise fabric indicates very energetic, turbulent conditions of deposition. The variability in the sense of imbrication of the clasts makes the possibility of unidirectional currents as the agent of deposition very unlikely. More likely, strong oscillatory flows washed the intraclasts back and forth vigorously, thus achieving the close packing, variable imbrication, and overall upright orientation of the clasts. If this interpretation is correct, then the clasts must have been fairly well indurated to withstand such reworking. It is not likely that mere desiccation of the mud layer from which the intraclasts were derived would provide the degree of induration apparently required (Germann, 1969). Therefore, the view preferred here is that the intraclasts represent partially lithified (cemented ?) mud ripped up from the depositional surface. The most plausible conclusion of the preceding line of reasoning is that high-energy waves eroded a calcareous mud crust, creating intraclasts and reworking them to form a compact, irregular layer. Despite the evidence for relatively indurated intraclasts, the degree of induration can only be established with respect to intensity of reworking (apparently great as evidenced by bed fabric) and duration of reworking. That is, well lithified clasts could withstand prolonged reworking, while poorly lithified clasts would not exist very long in an intensely
agitated environment (Germann, 1969). There is no evidence in the beds themselves to distinguish between the two possibilities.
APPENDIX II: THE MEASURED SECTIONS

Illustrated in this section are the eleven Shepard sections that I measured. All were measured during the summer of 1984 with the exceptions of the Turquoise Lake and Clearwater Junction sections, which were measured during the summer of 1983. An index map, showing the traverse and surrounding geology, is provided for each measured section. All mapping shown is after Mudge et al. (1982) with, in some cases, unpublished modifications of that mapping by Don Winston. The upper majority of the Blowout Mountain section was measured by Don Winston and Charlie Rubin in 1978, and I thank Don Winston for the use of these unpublished data. The sections, as presented, were taken directly from the field copies, with only the comments edited. All sections are marked off in feet.

KEY TO LITHOLOGIC SYMBOLS AND ABBREVIATIONS

ML -- microlamina sediment type

EC -- even couplet sediment type

LC -- lenticular couplet sediment type
CM -- carbonate mud sediment type

(\sim)calc. -- (slightly) calcareous

sandstone

siltstone

mudchips

mudcracks

accreted mudballs and mudchips

MT -- "molar-tooth" structure

carbonate pods

stromatolites

edgewise conglomerate

"passing up to"

covered interval
FLS — flat-laminated sand
RXLS — ripple crosslaminated sand
ORXL — oscillation ripple crosslaminated
CRXLS — climbing ripple crosslaminated sand
OR, 0 rips — oscillation ripple marks
low — low-angle
cgl — conglomerate
vfg, fg, mg, cg — very fine-grained, fine-grained, medium-grained, coarse-grained
dk, lt — dark, light
qtz — quartz
dol. — dolomitic
sm. — small
E-W, N-S, NW, etc. — east-west, north-south, northwest, etc.
Crazy Fish Lake Section; Stuart Peak quadrangle, T 16 N, R 18 W, section 31, along the boundary between the Rattlesnake Wilderness to the southeast and the Flathead Indian Reservation to the north. Most direct access is via good but unmapped trail from the Jocko Valley up the spur flanking the north side of Agency Creek.
LC w/ silt lenses; soft sed. folds at 83'

slightly calcareous

LC thin

ORXL
cg, ORXL

cg

accrued mudballs, mudchips
red up thru 10.5'
silt lenses
mudballs + mudchips in mg sand, \textcolor{red}{\textit{Red}}
locally \textcolor{red}{\textit{red}}

\textcolor{red}{\textit{Red}}

slightly calcareous

scoured surface

syneresis cracks (?)

\textcolor{red}{?} pyrite staining

\textcolor{red}{vfg} sand lenses

EC very thin, silt beds ORYL

mg
vfg sand lens, squat

thin-bedded fgs sand w/ abund. very angular mudchips

pyrite cubes in cg sand

red

mixed EC + LC

purple

EC grading up to LC

snow cover
Pyrite staining
Silty E
Mixed LC + ML
\( v \) Calcareous

Squat lenses of \( v \) sand, structureless

And 335, foliating at 321°, 329°,
Soft sed. foliating at 321°, 329°.
NOTE: Outcrop between 430' and the top of the Shepard section at 1100' is sporadic, described only generally. (See Plate 1).

- Few isolated Fg sandy ripple lenses; minor soft sed. Folding
- ORKL
- Thick, mudcracked EC
- Thin EC beds sometimes cut out for a short distance, w/ overlying ML squeezed down to ML below; some minor soft sed. Folding
- Structureless
- Pyrite staining
- Crumpled, slumped
Jocko Lake Section; Belmore Sloughs quadrangle, T 17 N, R 17 W, section 21, Flathead Indian Reservation. Outcrop is a ledgey cliff above a large talus pile and is somewhat treacherous because of abundant talus debris lying on ledges.
grey-green siltite, capped by wcalc 119

calc. EC  
clay bed

FLS w/ few sm. RXL

CM

v. thin EC & ML, all ~ calc., slightly wavy

RXL & low XL sand

CM

EC

same as 46'-48'

CM

RXL & low XL sand

22'-46':

interbedded EC & LC, calc. below 40', green above 40'. Rare mudcracks & mudchips.

RXL5, greyish green, some sm. w/ calc.

← fine sandy CM → calc. RXL5

CM, tan-buff

bottom of Shepard not exposed.
RXLS, f-ung, tan-grey; FLs at top? green EC
CM w/ few calc. EC; RXL calcarenite at 171', possibly oolitic w/ few mudchips green, ~calc. ML

CM w/ few thin RXLS beds & some thin calc. EC

← carb. pods siltite w/ few carb. mudchips, OR cap.
CM → EC, some 3-4cm, ~wavy RXLS calc. EC
CM w/ MT ribbons
CM → calc. EC
← red, Cg sand; grains are well rounded, hematite mudstone clasts.
green RXLS thin EC, silty

calc. EC
cm & calc. lc

~ calc.

calc. lc

mg. or xcs

sm. cut surface: "rivulets"

silty lc, ~ calc.

~ calc. mc

thin, ~ calc. lc w/ few sm. compacted mudcracks

cm & calc. lc

thin, wavy sand beds w/ mud partings

grey, mg. sand, few vague lambs.

cm & calc. EC

RXL5

calc. Ec
sum calc. clasts, weather back

calc. lc

mg ORXCS

cm w/ a few calc. lc
calcite, L.C.

with some sand ripple lenses

Green, fine sandy even - wavy couplets

orark, steeply inclined

red sand (similar to beds at 112?)

but not accessible.
calcareous argillite above 390',

~200' of upper shelled green mud
Turquoise Lake Section; Gray Wolf Lake quadrangle, T 18 N, R 18 W, section 1, and T 19 N, R 18 W, section 36, Mission Mountains Wilderness. Most direct access is by good trail up to Lace Lake, then a steep climb up to the outcrop. Exposure is good, but some section is faulted out. Measured section is incomplete only because of personal circumstances.
LC

LC, green, w/ few siltite layers

Fg, w/ few sm. cg lenses

green, ~ wavy ML

~ calc. LC, green

green
red, cg RxLS

green UC

FLS + RxLS

soft sed folds verge 18° NW
bedding: N10E, 25E

green Ec

green

dk. grey, knobby

red EC

base of Shepard
Ec
calc. LC
calc. EC + LC
LC, green
calc LC, very tan weathering
green LC
soft sed folds, small
wavy ML, ncalc., w/ abundant fluid escape structures
LC
MT ribbons
ncalc. LC
ML, green, wavy
MT bed; ribbons disrupt LC
calc. LC
LC
Top of Section

Faulted against Shepard red bed interval

CM w/ carb. pods

Strongly tan weathering at base

LC

Light grey fg sand

tan-gray LC

fg RXLS

LC

RXLS beds & LC

Bifurcating orips trend N35W

Bedding: NSW, 27 E

Patchy stromatolites

LC & ML, mixed

MT ribbons, mostly weathered back

LC, some isolated ripple lenses

calc. EC & LC

LC = MT

Interbedded wavy fg sand & wavy couplets
Red Butte Section; Hemlock Lake quadrangle, T 19 N, R 17 W, section 19, Mission Mountains Wilderness, near its eastern boundary. Best access is via logging road in section 17 (to wilderness boundary), then by hiking up spur leading to peak # 7082. Above covered lower Shepard, exposure is good.
Green silt bed → green EC

Fig. 8

OR cap
some ball + pillow structure
Fig. green-grey, w/mud partings, some LC

Fig. loaded loose

Fig. w/mud partings, OR cap
scoured, loaded loose

Fig. some cracks + fluid escape structures

CM w/kale lenses

Case of exposure not exposed
f-mq, some ORXLS, loading
Sm. scour
Fg. sandy cm

f-mq, some ORXLS → sm. from
bedd + plane-wavy lens

Cm w/ ORXCS lenses, sm. mudcrk
lens, carb. pods
f-mq
Mt. hash cap

f-g

contorted laminae
f-g sand, carob.
e.g., angular granite mudchips in small lenses
Fq sand stringers
540
530
520
510
500
490
480
470
460
450

fig. calc., loose base

fig. ~ calc

fig. some RXL

few angular qtz pebbles at top, fig. ORXLS

RXLS, F. mg, it green
thin calc IC
even - wavy, 2 - 3 cm thick, calc.

green < - 10 cm

ORXLS stringers

fj. thin, EXLS

f-mg FLS, some ORXLS

minor scored surface at 550
For green, w/ irrec. mott., wen layers below: very clean, vsy - fg above

- sm. purple mud parting

---

--- green

--- iron cm

--- m. eq. reddish

--- fg
- Some Silt - Clay
- Thin Sandy Sed. to 60 cm LC
- Sandy, reck LC
- Green
- Grey, loamy sed.
Leota Peak Section; Morrell Lake and Crimson Peak quadrangles, T 18 N, R 14 W, sections 21, 22, & 28, Bob Marshall Wilderness. Simple access is by pack trail over Pyramid Pass to Leota Park, then ascent to ridge west of Leota Peak. Section is cut by a few minor faults, but exposure is excellent.
Fig. 11. Map showing the mapped sections.

Legend:
- Green: Mapped sections
- Red: Corroded, red areas
- Black: edge-wire cag
- Yellow: thin layers + silt layers

Note: Sections 10-15 were not mapped.
red, few mudchips, mudcracks

\~ calc.

green

red

1 to 2 thin

or xls stringers, etc.
red, mag, xls

green

blue carb. pods

mt in calc. argillite
- cg sand in starved ripples

green

- red, few accreted mudballs

- silty, w/ mudchips

- interbedded green LC + ORXLS

red
337'-385': Vague mix of EC, LC, & ML, green, w/ abund. silt & fg sand lenses.

Fig. ORXLS
some mudcracks, mudchips

slightly green

520-590: much like
385-524
c = capped w/ f, sand
cg esr's sand stringer
m-cg FLS, ORXLS cap
1st carbonate bed

f-mg FLS, ORXLS

red

f-mg FLS, ORXLS

mg sandy LC

red, mudcracked

greenish white, cg

red LC, f, ORXLS w/ sm. loads
abund. mudcracks, slump

poorly developed strom.

red ML
900
890
880
870
860
850
840
830
820
810

mudcracks

F
g

cm, uneven couplets

F

thin, silty, green

vaguely lam.

vaguely concreted

now concreted, massive green-grey clay

mg
very silt

very recessive, shady,
mostly green LC
506
vaque LC
fg, ncalc.

fg, w/ HT hash lens at base

cm, some silty, w/ fg EXCS cutting down

+ to LC + ML
calc.

ulaminated
green

green

very tan, w/ a few LC

some mud cracks

cm mudchip layer

pyrite cubes
1570
1520
1510
1500
1490
1480
1470
1460
1450
1440

- green, clay-rich LC
- MT hash lens
- green, gritty silt
cq. reddish sand

- top of peak, dipslope, minor fault in saddle

purple, thick

f9
MT near beach, FLS above

MT beach, FLS above
1890

1880

1870

1860

1850

1840

1830

1820

1810

1800

3 RXLS, FG, some reds

FG, thinly banded

↓ gets sandier, more FG sand stringers

thin, waxy FG sand

red sand

peak ± 8170

red sand, RXLS

FG sandy CM

FG FLS, green
fault, minor, but may repeat section

thin, green, some ladderbacks, interference ripples

5x 5x 5x, straight-crested, et al.

3x 3x, S to N, with mud drapes

m-cq, red

load's

ladderback ripples, primary set truncated

green

red
tan

red

lt pink

red

fg, red

red

RXLS, fg, red

red, silty
Vaguely law CM and based Mount St. Helens.

Red top of section.
Blind Canyon section; Morrell Mountain quadrangle, T 17 N, R 13 W, sections 13 & 14, along boundary between the Bob Marshall Wilderness (Flathead Nat'l. Forest) on the north and Lolo Nat'l. Forest on the south. Most direct access is via logging road up Blind Canyon, then along anastomosing artiodactyl trails to very good outcrop.
Fig. thin, wavy beds; some carbonate grains.

Fig. wavy - lenticular, thin bedding.

Fm. round, 5 cm mud chips, green.

Fig. green, FLS + ORXLS. OR. is trend N-S.

Fig. red.

Fm. red, round, red mud chips.

Cg sand lens, green.

Cg sand lenses, green.
calc.

thinly lam argillite disrupted by carb. pods

It grey

some mudcracks, mudchips, sand stringers

silty, green f-mg

dc red
So, ten mudcracks, etc.
Green, thin EC
Red EC
5 mg ECs, some mud cracks show
very small drifts, 1 cm spacing

- Thin, calc EC, forms prominent tan band

Scour, ECs above

Green, mudcracks
Red
Reddish
And very shallow, 1.5 cm
mostly green LC, silty below, lose silt upwards

partially covered calcite CXL5
f-rung, λ-x κ s - o v e r l a p p i n g  l o a d e s

some sort of mass of ore s in c s - o r c e s c r e d s
314 - 430: 11t with -

peak - to - saddle osteot
fg, green, w/red mudballs, mud chips, + stringers

Red ML \rightarrow rel. hum EC

fg RXLS, purple: 3 beds green

ORXLS, fg

g

green ML, sm mud chips @ 478'
sandy LC

ORXLS, thin, var. beds + thin lenses
650  calcite
620  RT hash at base
610  m-sand
600  ORXLS, ca. 95 → F-mg
590  scour, ca. green sand
580  green
570  red, w/ mud cracks
560  ORXLS, ca. w/mudballs → F-mg
550  red
540  Fg. white calcite
MT hash at base

Fg8 sand

Fg8 sand n squat lenses

= scour surfaces

Clay rich LC & ML = calcs

Green, massive mudstone, clay-rich
lack, recessive

carbonate stromatolite

dk brown

dk brown, chippy, poor outcrop

- rock & sand

isolated stromatolites in quartz silt & sand
black ML: toppy 5.05

sande core Pass
most lightblack ill, occ of wi

sour base

reddish can这样做 w/ py 1t + 178

MT 11 freeze april 11 94
Green LC w/ in situ waterbed
- fg. sand
- w. calc
- lg. scoured base

Fg. white, w/ small whitish clasts
Green, sandy LC
Fg. 4 beds, w/ sm. scours & loads

Wm. ripple lenses in cm

Wd. ML w/ sm. silt/fg sand lenses

Fg. w. calc

Green. w. calc. ML
1260

1250

1240

1220

1200

1190

1180

1170

1240 sand lens probably not "grey"
may be cut loaded ripples

1220

1200

1190

1170

1240 sand lens of cm mud chips sandy cm

1220 thin beds capped by cm

1200 green, veal, thin LC + ML

1190 green ML

1180 green LC + Ec

mostly very sand + silt, some muddy layers, thin fine sand layers — loads

1170 cm — green-tan, veal 3-

1160 — rare mud intercalation
F. mg, green-tan, some cm interlayers
f-mg some ORKLS

g = calc
eg calc in
sandy

g

eg dark-brownish tan, m" 2000
egg cut & soft cutting
egg calc in cases in cl

dip slope, top of measured section, upper Sheford exposed on lower ridge on other side of valley.

Two sand lenses in Calc LC.

Sand LC.
Evans Peak Section; Scapegoat Mountain quadrangle, T 18 N, R 10 W, section 27, Scapegoat Wilderness. Most direct access is via pack trail to Carmichael Cabin, then up secondary trail along ridge between Eagle and Dobrata creeks. Exposure is nearly complete, but intense frost wedging has shattered most of the microlamina sediment type outcrops.
green, w/ few v. thin LC

~ calc., w/ carb. pods

grey, light tan sand lenses

dk green, ~ wavy ML, w/ sand stringers & loaded "pods"

poorly developed

~ calc. LC w/ carb. pods

green, thin beds w/ mud interlayers

green

red

grey, reddish green

red ML

FLS, green
tan-buff, 10-20 mg, w/ few ca. stringers; red ML w/ mud chips
red ML
reddish tan sand
red ML
dk green
poorly formed, calc., dull pinkish
green ML w/ sand stringers
red ML

← greenish tan
w/ calc., thin EC + ML
red ML

green ML
green ML
near. fg RXLS, cm cap
- reddish RXLS lense

green ML

dk grey zone ~ 250'
[sm. slickensides in float]

green

dk green ML

dk green, chippy float, probably ML
< fg. w/ thin m-eg stringers w/ madreps

< tan, calc. ml

< dk grey ml

green

< dk grey, very fine-grained

dk green ml, w/ some v. thin lc

carb. pods, some fg sandy w/ dol. sandy starved ripples

bedding N65W, 84 NE (upright)

green ml
Thin to thin, 4 ft green
Green

Ser. pink calc.stromatolite

White, 10 ft sand
Green wk
Red wk wi fi, green sand (perse)
White, 10 ft sand, red
Green
Red

 abnormal, 10 ft red
Green
Red wk w/ green sltly interlayers
Green
Green
Brownish pink, large lenses
Green wk
Red wk
w calc. mL w/ sand stringers &
some w calc. LC

Fq, white q+2 sand
green mL + LC
red-pink calc. strm.

green

red

← green zone
red
← green zone
red thinly banded
green
red mL
edgewise cal, carb. mud intraclasts
cm
calc. ml
calc. green ml
cm, thinly laminated
grey ml
green ml
OR X LS
green ml
small
green ml, totally disrupted by molar tooth ribbons + pods
cm, vaguely laminated
calc. ml
interbedded cm & calc. ml
mixed ~ calc. ml + lc
dk. green ml
ml + carb. pod float
calc. Mc w/ carb. pods

thiny lam. cm/ Mc

green Mc cut by MT

Few sand stringers

carbonate pods
758' - 814':

thin calc. LC + calc. ML, w/ some sand stringers, cm layers, carb. pods.

dk. grey ML -> whitish-tan ML

calc. LC + calc. ML w/ calc. sand stringers

sandy cm, loaded
calc. MC w/ fig. oryLs stringers 196

starved ripples in cm

oryL

corL

some loading in sand stringers
calc. MC

loading

cm beds throughout this part of section commonly capped by large wave ripples

calc. MC + thin calc. LC
NOTE: section above 1200' described only generally; it is similar in aspect to the 100'-200' below 1200', and continues through 1450' (442 m) to the base of continuous red argillite interval of the lower Mount Shields Fm. The following features were outstanding:

1286' 2  c.g. red sand beds
1290' 3

1375'-80': red ML, above and below green ML
Dearborn River Section; Steamboat Mountain quadrangle, T 18 N, R 7 W, section 32, on private land owned by Montana Wilderness Bible College (formerly C Bar N Camp). Section is well exposed along the river, but waders and low water are required to see most of the exposure. The uppermost Shepard is faulted against the lower Mount Shields.
accreted mudballs
It green, clay-rich ML
thin, wavy-irregular intbld muddy sand, mud
and mg sand w/ sm. mud chips, mudballs

FLS, capped by sm. sinuous OR, E-W trend
thinly intbld fg sand & mud

thin EC

FLS, well sorted; sm., flat-topped ripples, straight cusps; E-W, N-directed

f-vfg FLS + RXLS w/ mud partings

loading

OR, trend NW

FLS ± some RXLS, tan weathering

climbing RXLS, N-directed
carbonate mud chips + pebbles

carbonate mud chips topped by climbing RXLS, N-directed
FLS w/ some ORXLS, slightly asym., N side steep.

ORXLS

w/calc. ORXLS, w/calc. mud chips

FLS w/ thin cg layers of mud chips; FLS cut by
sm. trough X-bed.

most EC layers = sandy

FLS, vfg, or top, E-W trend

loads near top
FLS + low XLS
red ML
scoured etc
vfg RxL
fg, red-brown, apparently FLS, w/ vly. large,
50-70 cm diam. pillow-like downwarps.

algae lam. bed, heads very poorly defined to
nonexistent

channel-form, mildly truncates underlying ML
ML dark grey
cg below → scour → fg above
some sands are FLS below, capped by or (E-W)
some ladderbacks (N-S)

ML black to dk. grey, clay + vfg silt
sands are fg, muddy, dk. grey
greener ML, less sand.

black ML w/ abund. fg, grey sand lenses +
stringers, often w/ loaded bases; mnds
occasionally approach thin EC
black ML w/ sand stringers, lenses & pseudochannels

OR cap, ripples straight w/ flat tops
thin EC w/ ORKL sand lenses, ripples trend E-W.
~ calc.
red-maroon ML

green ML
well-developed red streaks, steeper to overturned on NNE sides.
abundant fg sand stringers & squat lenses.
FLS & low hummocky x-1aw, f-mg sand
numerous sm., laminated, isolated load structures, rotated v sunk down into bed.
mg ORKL sand => fg massive sand, scoured top, capped w/ mg ORKL sand.
red, m-cq sm. trough x-bedded sand, capped w/ mg FLS.
ladderback ripples: primary N-S, secondary E-W.
carbonate mudchips + plates.
sandy EC w/ some load casts

thin EC
carbonate mudchips + plates
fg sandy LC
MT bed

disrupted by MT
fg sand w/ carbonate mudchips, glauconite sand stringers
ORKL sandy LC => thin sand beds
topped by sm asymmetric ripples w/ sinusoidal pam.
FLS, w/ internal load casts
fg sandy LC, mud minor, OR E-W
360
350
340
330
320
310
300
290
280
270

calc. EC (?)

patchy stromatolite
pinkish
thinly bedded CM
minor MT in EC

~ calc. fg ORKLs, thinly bedded, w/ thin CM interbeds

~ thinly interbed: ML & fg sand to sandy EC

fg sand lenses, pseudochannels

ML green to dk. gray
edgewise calp, slightly silicified? mudplates green
red

green, pseudochannels near bottom

thin, wavy, ~ calc. below ~ loaded above, w/ sm. calc. strom.

FLS, top reworked into large wave ripples \( h = 1\)

very steeply climbing wave current RKL below, capped by pillow structures; interference & ladderback ripples on bedding plane.
Large, flattened heads
de green, ml. w. cock. by sand, at sand.
dc green, ml. floor

Lenses, cock, by green bands, some very shaly.

Thinly interbedded sand, layers at ml.
Pure, black ml.

Wavy, thin, by sand layers, mud interbeds.

Oral

Green
Red
Tan

Red, siltstone, mudcake, ml. bed

Wavy, cock, by sand
Cross fault of unknown but probably small displacement, w/ tight kink fold.

(calc., or cap)

(sm., tan., calc.)

cm

(calc. thin f.g. sand & Ec)

(tan weathering, calc., f.g. sand interbeds)
630

Green ML w/ CM interbeds & sm. sand lenses, all ~ calc.

620

Red base, straight OR at top, NE-SW

loaded fine sand layers + lenses in grey ML + thin EC

muddy interlayers

610

Green

internal loading, OR interference ripple top, ripples flat-topped.

large (~1 m wide) pillow structure

600

Loaded interior & bottom
green ML

Thinly interbed silty mud and/or fine sand w/ interference ripples + sm. load casts

590

Green red

Overlapping lenses of loaded, fine sand

LC ~ thin EC

580

Green red

570

560

Green red

550

540

530
top faulted out against red, sandy argillite of the lower Mount Shields.

similar to 670'- 675'

DK green - grey ML
thin, crumbly, mud-dominated LC w/ thin fa ss interbeds. Some of these have "pseudo-channels" attached to their bases.

thin bedded ORXL sand w/ thin mud interlayers. Some sand beds up to 10 cm, most less. Loading near base.

green ML w/ cm interbeds and some sm. sand lenses. All w. calc.
Blowout Mountain Section; Blowout Mountain quadrangle, T 17 N, R 7 W, section 36, and T 16 N, R 7 W, section 1, along the boundary between Lewis & Clark Nat'1. Forest on the northwest and Helena Nat'1. Forest on the southeast. Access is via a private road across the McDonough Ranch, then a hike up spur to peak # 6583. All but lowest continuous interval was measured by Don Winston and Charlie Rubin, June, 1978.
70'-85': muddy sand/sandy mud in thin beds

cg. sand + intrabed lens
fg. dol. sand

tan-brown, dol. fg sand: FLS -> low & x-lam -> climbing ripple XL at top.
grey silt - fg sand, RXL

~calc. RXLS, mostly NW-directed muddy sand, RXL

fg. m-g sand w/ crumbly mud interlayers
cg. sand w/ white dol. mudchips & mudballs
thin, ~calc fg sand w/ cg. stringers & carb. mudchips

sand & mud

interbedded fg ORXLS & ML/mud

calc. ML w/ some MT ribbons & sm. x's

N20 W, 12 SW
FLS = climbing RXL
CM intraclast bed
blue carbonate "ripple" lenses in tan cm

FLS, sm. calc mud chips in middle, RXL at top
muddy RXLS
light green ML
FLS & low RXL
sandy layers in silty mud
thin, green LC at base
silty mud, vague ripple lenses
FLS
silty mud, thin FLS layers

FLS, few sm. mud chips
light green, silty mud

RXL
green ML w/ few sm. silt lenses
cg sand, climbing ripple
dk grey ML

cg RXLS, green, glauconitic red & green ML

red ML w/ some LC

oolite bed
red ML

186' - 435' covered

435' top measured by Dou
Winston & Charlie Rubin, June
1978.

climbing RXLS
dark ML w/ calc. zones

cM interbedded w/ calc. EC

black ML

calc. LC

MT bed
calc. LC

dk grey ML; mostly covered
MT bed capped w/ stromatolites
silty mudstone

MT
silty CM, some FLS + RXLS,
1-10 cm thick, w/ v. thin
mud partings

interbedded dark, fissile ML and
silty CM beds 3-10 cm thick

562'-629' covered
RXLS
red ML

interbedded fg RXLS (3-5 cm) & thinly lam. calc. shale (3-10 cm)

730'-775':
interbedded cm (1-3 cm) and recessive shale (1-10 cm)

dijewise cal., clasts up to 10cm long

calc. muddy siltstone