Fining upward sequences in the lower Mt. Shields Formation middle Proterozoic Belt Supergroup west-central Montana

Susan M. Slover
The University of Montana

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FINING UPWARD SEQUENCES
IN THE LOWER MT. SHIELDS FORMATION,
MIDDLE PROTEROZOIC BELT SUPERGROUP,
WEST-CENTRAL MONTANA

by

Susan M. Slover

B.A., Rice University, 1979

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Geology

Fining Upward Sequences in the Lower Mt. Shields Formation, Middle Proterozoic Belt Supergroup, West-central Montana

Director: Dr. Don Winston

Vertical sequences and lateral stratigraphic relationships of the five rock-types delineated in the lower part of the Mt. Shields Formation record deposition from periodic floods on proximal and more distal parts of what can be called the fan skirt and alluvial flat of the block-faulted Belt basin. These depositional landforms could only have formed in an internally drained basin, indicating that the "Belt sea" was actually a large, non-marine, land-locked body of water.

These rock-types form vertically stacked, sharply bounded fining upward sequences which average between 3 and 10 m thick; within these sequences both bedding thickness and overall grain-size decrease upward. The asymmetric profile these stacked sequences form, with its conspicuous lack of coarsening upward sequences, is attributed to climatic variation in which the "Belt sea" repeatedly rapidly expanded and then slowly evaporated and contracted. Moisture derived from outside the basin resulted in periodic catastrophic primary sheetfloods which rapidly filled the lake, and deposited the coarser sediment at the base of each sequence. During more arid times that followed, an intrabasinal climatic cycle then formed: water evaporated and formed clouds over the lake, migrated across the basin and was reprecipitated. This climatic recycling of the water resulted in progressively smaller-scale, secondary flooding events which deposited the finer-grained, more thinly bedded sediments of the upper part of the sequence as the lake contracted. With the next influx of moisture from outside the basin, primary flooding reoccurred, and the next fining upward sequence abruptly began.

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INTRODUCTION

Most geologists today believe the Proterozoic Belt basin, which covered much of western Montana, Idaho and eastern Washington, and reached north into British Columbia (Fig. 1), was an epicontinental embayment of the Precambrian ocean. However, others have contended that the basin was an intracontinental, land-locked sea or lake. Those who support the oceanic interpretation cite the general shape and sedimentation (Harrison, 1972), presence of salt casts (Fenton and Fenton, 1936), and thickness of Belt deposits, estimated to be 20 km in areas (Harrison, Kleinkopf, and Wells, 1980) as evidence. C.D. Walcott (1914) was the first to believe the Belt was a large lake. Others, having studied cyclic sedimentation in various carbonate units (J.A. Peterson, 1971; Grotzinger, 1981), also conclude a shallow water, lacustrine environment for the Belt "sea".

Detailed sedimentologic study of the lower part of the Mt. Shields Formation, Belt Supergroup, leads me to interpret depositional processes in the Belt basin for this unit as similar to those found today on valley landforms of the Basin and Range Province, southwestern United States. However, the scale of these landforms in the Belt basin was much greater than that of their modern analogues. The "Belt sea" at this time was a non-marine, land-locked body of water comparable to an enormous playa lake, and subjected to repetitive periods of rapid filling and expansion followed by slow evaporitic contraction in response to climatic variation. The rock-types of the lower Mt. Shields
Fig. 1. Map outlining regional extent of the Belt basin. Modified from Harrison (1972) and Winston (1978).
Formation accumulated along the margins of this large lake by sheetflood processes that can be compared to those on the fan skirts and alluvial flats of modern internally drained basins. The lower Mt. Shields Formation is tabularly bedded, and the beds fine and thin upward through repeated intervals of 3 to 10 m forming distinctive sequences. The origin of these fining upward sequences is attributed to periodic large influxes of rain followed by increasingly dryer weather. A description of this climatic variation is also offered.
STRUCTURAL SETTING

Sediments of the Proterozoic Belt Supergroup accumulated in a large, slowly sinking block-faulted basin between 1450 and 850 m.y. ago. Winston et al. (1982) propose three major zones of nearly east-west trending, high angle faulting which controlled the structure of and deposition in the Belt basin. These zones of faulting (referred to as lines) formed the northern and southern boundaries of four more tectonically stable blocks. The Townsend Line, trending approximately northwest-southeast through the Townsend Valley, is believed to mark the eastern boundary of the Deer Lodge, Ovando and Charlo blocks. The western limit of these blocks as delineated by Winston et al. (1982) is the western thrust belt (Fig. 2).

Until recently, the amount of Cretaceous tectonic transport of Belt rocks was not well enough known to make possible a detailed sedimentologic study. Winston et al. (1982) now conclude that Belt rocks on the Ovando block, west-central Montana, were transported rather uniformly during Cretaceous thrusting. Thus, original stratigraphic relationships are sufficiently preserved to permit an interpretation of lateral facies variation. For this reason sections of the Mt. Shields Formation on this block were selected for study (Fig. 3).
Fig. 2. Simplified structure of the Precambrian Belt basin. Modified from Winston (1982).
Fig. 3. Enlargement showing study area. Location of measured sections designated by +.
STRATIGRAPHY

The Precambrian Belt Supergroup consists predominately of fine-grained clastic and carbonate rocks, deposited in enormous thicknesses of repetitive, tabular, continuous bedding which show few erosional surfaces and channels. Harrison (1972) subdivided Belt rocks into four major stratigraphic units: the lower Belt, Ravalli Group, middle Belt carbonate and the Missoula Group (Fig. 4).

Part of the Missoula Group, the Mt. Shields Formation overlies the dolomitic Shepard Formation, and beneath the coarser-grained, clastic Bonner Formation. The Mt. Shields itself, about 1000 m thick on the Ovando block (Winston, oral communication, 1982), consists primarily of mostly medium- to very fine-grained sandstone and argillite. Three regionally mappable units have been informally recognized: 1) Mt. Shields I, consisting of interbedded red argillite and sandstone, 2) Mt. Shields II, comprised of predominately coarser-grained sandstone, and 3) Mt. Shields III, an argillaceous unit with abundant salt casts. Mt. Shields IV, a green argillaceous unit, has been recognized locally in the Jocko Mountains, Montana (Winston, 1977). This study encompasses the rocks of Mt. Shields I and II.

Three sections on the Ovando block (see Fig. 3), which received the thickest sequence of Belt sediments during Precambrian time, were measured and described. Detailed attention was given to composition, texture and sedimentary structures. Although no lateral facies changes were observed within a section, distances between sections are great.
Fig. 4. Stratigraphic subdivision of the Belt Supergroup on the Ovando block, west-central Montana.
enough to demonstrate that the rocks become finer-grained and more thinly bedded to the north.
ROCK-TYPES

General Statement

Although exceedingly thick, the Belt Supergroup can be subdivided into relatively few different rock-types which repeat themselves in quite regular patterns throughout the Belt section. Winston (1978), defines five major rock-types which occur throughout the Missoula Group and elsewhere in the Belt: 1) the conglomeratic rock-type, 2) the coarse, cross-bedded rock-type, 3) the fine, horizontally laminated rock-type, 4) the red argillite rock-type, and 5) the green argillite rock-type. In the argillite he recognizes centimeter scale units, called "couplets", composed of lower fine-grained sandstone and siltstone laminae which grade up into claystone laminae. Grotzinger (1981), who studied the stratigraphy and sedimentation of the Wallace Formation, middle Belt carbonate, defines two more: 1) the black argillite rock-type, and 2) the dolomitic rock-type. By recognizing the stratigraphic distribution and by analyzing the depositional processes of these rock-types within their stratigraphic framework, one can begin to discern a depositional model for the Belt basin.

Rock Types of Mt. Shields I and II

Analysis of mineralogy, texture and sedimentary structures in this study led to the recognition of five major rock-types within the lower Mt. Shields Formation. Two of these, the cross-bedded sandstone and
the horizontally laminated sandstone, are similar to those described by Winston (1978). However, my detailed sedimentologic study of these rocks leads me to redefine his red argillite rock-type as two types: 1) the coupled red sandstone rock-type, and 2) the coupled red argillite rock-type. In addition, I introduce a fifth rock-type, the vaguely coupled sandstone, which contains all of the constituents of the coupled red sandstone, but in poorly defined, discontinuous layers.

Cross-bedded Sandstone

Description. The cross-bedded rock-type is mostly medium- to coarse-grained, well sorted, tan to pink feldspathic quartz sandstone (now quartzite) (Fig. 5). Unimodal planar and trough cross-bed sets 10 to 50 cm thick occur in tabular, continuous beds. The planar sets are by far more abundant than trough cross-beds. An upward decrease in grain-size and scale of sedimentary structures within single beds is not well developed except in the upper part of the Prickly Pear section. There, marked by scoured bases, beds 2½ to 3 m thick consist of medium- to very coarse-grained, moderately to poorly sorted, planar cross-bedded sandstone with large mud clasts and pebbles. This passes upward into moderately sorted, medium- to fine-grained, horizontally laminated sandstone, which in turn grades upward into rippled sandstone. The cross-bedded rock-type occurs more commonly in Mt. Shields II, and is most abundant in the southern part of the study area.
Interpretation. The unimodal planar and trough cross-bed sets of this rock-type result from lower flow regime bedload transport of coarse sand. The continuity and dominant cross-bed direction are characteristic of braided streams of the Platte River type (Miall, 1978), and for this reason the cross-bedded sandstone is believed to represent avalanche-face bar migration in very broad, shallow, braided stream channels.

Horizontally Laminated Sandstone

Description. This rock-type consists of tan to pink, well sorted, fine- to mostly medium-grained sandstone in tabular beds 3 to 50 cm or more thick (Fig. 6). The lower one to 2 cm thick layer of most beds contains paper-thin mudchips. Grainsize tends to grade from medium-grained sand upward to fine-grained sand within beds. This rock-type is dominately horizontally laminated, although very low-angle planar cross-beds are also present. Occasional thicker beds contain planar or trough cross-bed sets in coarse-grained, mudchip-rich sandstone which grades upward into the horizontally laminated, fine- to medium-grained sandstone. This in turn occasionally grades into muddier, finer-grained, climbing ripple cross-laminated sandstone, particularly in Mt. Shields II. Thin, commonly mudcracked mud-drapes mark the top of most beds.

Interpretation. The medium-grained, horizontally laminated sandstone was deposited by upper flow regime traction load sedimentation.
Medium- to coarse-grained, well-sorted sandstone.

Unimodal and trough cross-bed sets in beds 10 to 50 cm thick.

Occasionally coarser-grained sandstone with mudclasts at the base of a bed grades upward into finer-grained, climbing ripple cross-laminated sandstone.

Fig. 5. Diagram of the cross-bedded sandstone. Key for grain size is the same for Figures 6 to 9: c - clay, s - silt, v - very fine sand, f - fine sand, m - medium-grained sand, cr - coarse sand.

Fine- to mostly medium-grained, well sorted sandstone.

Dominately horizontally laminated in beds 3 to 50 cm or more thick. Climbing ripples, planar, trough, and very low angle cross-beds are occasionally present.

Grainsize fines upward within a bed. The lower one to 2 cm commonly contain paper-thin mudchips, and the top of most beds is marked by a thin mud-drape.

Fig. 6. Diagram of the horizontally laminated sandstone.
The very low angle planar cross-beds also formed from antidunes generated in upper regime flow (Reineck and Singh, 1980). The mud-drapes which cap most of the beds were deposited from suspension and are commonly mudcracked. These mud-drapes show that upper regime flow decreased in velocity to standing water. Mudcracked surfaces indicate that the surface eventually dried between depositional events, and therefore water flow was not continuous.

As flow velocity decreased, development of lower flow regime bedforms such as bars and dunes would be expected. Lack of cross-beds in the medium-grained, horizontally laminated sandstone suggests that water depth was too shallow to generate these bedforms. However, beds are tabular with unscoured bases, reflecting extensive, unconfined flow which I interpret to result from sheetflooding (Davis, 1938). Each bed was deposited by individual floods in which shallow water in upper regime flow deposited horizontally laminated sand. As water slowed and ponded, mud was deposited from suspension. Between successive floods this mud-drape dried and became mudcracked.

Coupled Red Sandstone

Description. This rock-type is part of the red argillite rock-type described by Winston (1978), in which he recognizes sedimentary couplets one to 5 cm thick of fine-grained sand- and siltstone that grade up into claystone; sand-sized grains dominate the thicker couplets while most of the thinner couplets are dominated by clay-sized grains.
In the rocks of this study, well sorted, medium- to fine-grained sandstone passes gradationally up to very fine-grained sandstone in even beds from less than 3 cm up to 20 cm thick. An argillite is "... a rock derived either from siltstone, claystone or shale ... (Dictionary of Geologic Terms, 1962, p. 23)" and the term "argillaceous" refers to rocks "... composed of clay, or having a notable proportion of clay in their composition ... (Dictionary of Geologic Terms, 1962, p. 23).

Since the thicker couplets consist of predominately coarser than silt- and clay-sized grains, the term "red argillite" is not totally appropriate. As sand-dominated couplets tend to be greater than 3 cm thick, I introduce the term "couple" to refer to beds 3 to 20 cm thick that fine upward from fine-grained sandstone to siltstone. It is for these reasons that I delineate the coupled red sandstone rock-type (Fig. 7).

The lower, coarser layers within the couples, commonly containing mudchip lag deposits, are horizontally laminated or current ripple cross-laminated. These are capped by darker red, very fine-grained sandstone and siltstone. Upper surfaces of these couples are often covered with symmetric, straight-crested oscillation ripples and mud-cracks.

Interpretation. The upward fining transition from traction load bedforms to those of standing water, plus evidence of subaerial exposure, offers a clear depositional picture for this rock-type. Upper regime shallow flow deposited horizontally laminated sands. Mudchips were ripped up from mudcracked surfaces of previous depositional events, and mark the base of each couple. As velocity decreased, lower flow regime current ripples formed, and finally silt was deposited from
suspension. Extensive surfaces of oscillation ripples and mudcracks are good evidence of ephemeral standing water which eventually evaporated.

**Coupled Red Argillite**

**Description.** This rock-type differs from the coupled red sandstone in that sedimentary couplets are generally less than 3 cm thick and are dominated by well sorted, very fine-grained sandstone and siltstone which passes in some couplets gradationally and in other couplets abruptly upward into claystone (Fig. 8). Mudchip lag deposits, though not so common as in the coupled red sandstone, occur in the horizontally laminated and current ripple cross-laminated lower layer of the couplets. In places starved ripples mark the contact between this lower very fine-grained sand- and siltstone layer and the finer-grained upper claystone layer. Upper surfaces of the couplets are commonly covered with symmetric, straight-crested oscillation ripples and mudcracks.

**Interpretation.** The horizontally laminated and current ripple cross-laminated, very fine-grained sand- and siltstone layer was deposited by upper regime and lower regime flow, respectively. The finer material which comprises the upper claystone layer settled out of suspension, and extensive straight-crested oscillation rippled surfaces are evidence of standing water. These clay surfaces are commonly mud-cracked, indicating that the surface dried between successive depositional events. Depositional processes responsible for the coupled red argillite rock-type are virtually identical to those which formed
Ocillation rippled and mudcracked surface.

Very fine-grained sand and silt deposited out of suspension.

Very fine- to fine-grained, current ripple cross-laminated sand.

Fine- to medium-grained, mudchip-rich horizontally laminated sand.

Fig. 7. Diagram of the coupled red sandstone.

One couplet:

Ocillation ripples and mudcracks in mud deposited out of suspension.

gradational or sharp upward transition

Horizontally laminated, current ripple cross-laminated sand with or without mudchips.

Fig. 8. Diagram of the coupled red argillite.

Poorly defined, discontinuous layers of very fine- to fine-grained, occasionally mudchip-rich sand which grades up into wavy mud laminae.

Small scale scours, cut-and-fill structures and ripple cross-laminations are present.

Fig. 9. Diagram of the vaguely coupled sandstone.
the coupled red sandstone. This rock-type merely reflects a decrease in competency of the depositional event.

**Vaguely Coupled Sandstone**

**Description.** This rock-type contains the same constituents as the coupled red sandstone rock-type, but in poorly defined, discontinuous layers (Fig. 9). Very fine- to fine-grained, moderately to well sorted, occasionally mudchip-rich sandstone grades up into discontinuous and wavy mudstone laminae. These poorly defined layers form indistinct couples which appear to range from less than 3 cm up to 10 cm thick, and have indistinct boundaries. Few well developed mud-draped and mud-cracked bedding surfaces exist. Small scale scours, cut-and-fill structures and climbing ripple cross-laminations are more characteristic of this rock-type.

Stratigraphically, the vaguely coupled sandstone rock-type occurs primarily in Mt. Shields II in the Clearwater Junction and Mt. Morrell sections, where it is commonly interbedded with the horizontally laminated and coupled red sandstones. Boundaries between the rock-types tend to be gradational.

**Interpretation.** The sand in this rock-type was deposited by traction load sedimentation, and the mud settled out of suspension. Cut-and-fill structures, small scale scours, discontinuous wavy laminae and indistinct boundaries suggest that the sediment was still soft and easily reworked during subsequent depositional events. Sedimentary structures offer little evidence of a gradational decrease in flow, as in the coupled red sandstone rock-type; rather, climbing ripple cross-laminations
formed by rapid sedimentation represent a sudden drop in velocity (McKee, 1966). Scarcity of mudcracked surfaces shows that the sediment did not dry between successive influxes of water. With each depositional event, the sandier material settled into the soft mud, further obscuring boundaries between the layers.
FINING UPWARD SEQUENCES

Two fining upward scales occur in stacked sequences throughout Mt. Shields I and II. I use the term "sequence" as defined by Heward (1978, p. 671) as being "... m - 10's m thick, consisting of a single bed or a series of related beds." The smallest fining upward scale has already been described, in which grainsize and sedimentary structures decrease in scale upward within single beds. This is especially well developed in the coupled red sandstone and coupled red argillite, in which very fine-grained sand commonly containing mudchips and transported in upper regime flow grades up into mud deposited from suspension. This is also common in beds of the horizontally laminated sandstone, which are marked at the base by a layer of very thin mudchips occasionally accompanied by coarser sand, and are capped by a thin mud-drape. In Mt. Shields II, the horizontally laminated sandstone grades up into finer-grained, climbing ripple cross-laminated sandstone.

In the larger fining upward scale, beds thin upward to couple and couplet scale within a sequence. Part A (Fig. 10) tends to consist of medium- (10 to 30 cm) to thick-bedded (greater than 30 cm), horizontally laminated or cross-bedded sandstone. Bedding thickness decreases in these rock-types as they pass upward into the thin- (3 to 10 cm) to medium-bedded coupled sandstone which comprises part B of the sequence. Very thin-bedded (less than or equal to 3 cm), coupled red argillite (part C) may in turn occur above this. While part A of the sequence is always present, parts B or C are locally absent (Fig. 11).
Part A - Medium- to thickly bedded horizontally laminated or cross-bedded sandstone

Part B - Thinly to medium-bedded coupled red sandstone

Part C - Very thinly bedded coupled red argillite

Note: 1) Grainsize fines upward within a bed and within a sequence

2) Bedding thickness thins upward within a sequence

3) No coarsening upward sequences are present

Fig. 10. Idealized stacked vertical fining upward sequences of Mt. Shields I and II.
Fig. 11. Examples of stacked vertical fining upward sequences present in each of the studied sections.
A corresponding overall decrease in grainsize accompanies this upward thinning of beds to couplet scale. The horizontally laminated or cross-bedded sandstones which occur at the base of the sequence consists of mostly fine- to medium-grained, well sorted sand. The coupled sandstone which occurs above these rock-types is comprised of mostly fine-grained sand which grades into very fine-grained sand within individual beds. Coupled argillite, which occurs uppermost in the sequence, consists of beds of very fine-grained sand- to siltstone which grades into claystone.

These vertically stacked, fining upward sequences average between 3 and 10 meters thick and tend to have sharp boundaries. A tally was made of Mt. Shields I and II in the Prickly Pear section of rock-type and bedding thickness vertical transitions, noting whether the change was abrupt or gradational. The observed frequency with which each transition occurs was calculated and compared to the probability frequency of that transition occurring if the changes were randomly generated (Walker, 1979).

Vertical facies relationship diagrams of those transitions which do occur significantly more often than randomly are presented in Fig. 12 and 13. These clearly show that coarser-grained, sharply based, more thickly bedded rock-types commonly pass gradationally to finer-grained, more thinly bedded ones, but this transition in some places is sharp. It is important to note that no gradational coarsening upward sequences are evident, i.e., the change from finer-grained, more thinly bedded rock-types back to coarser ones is always abrupt. The gradational changes
Fig. 12. Vertical facies relationship diagram for Mt. Shields I, Prickly Pear section. The section was subdivided on the basis of rock-type and bedding thickness, and abrupt and gradational vertical transitions were tallied. Those transitions which occur more often than random show that coarser-grained, more thickly bedded horizontally laminated sandstone passes gradationally to progressively finer-grained, more thinly bedded coupled red sandstone and coupled red argillite. The change back to the horizontally laminated sandstone is always abrupt, and marks the beginning of the next fining upward sequence.
Fig. 13. Vertical facies relationship diagram for Mt. Shields II, Prickly Pear section. The section was subdivided on the basis of rock-type and bedding thickness, and abrupt and gradational vertical transitions were tallied. Those transitions which occur more often than random show that coarser-grained, more thickly bedded horizontally laminated sandstone passes gradually to finer-grained, more thinly bedded coupled red sandstone. The change back to the coarser-grained rock-types is abrupt. Changes between horizontally laminated, cross-bedded and rippled sandstones represent flow regime fluctuations within single depositional events (see Fig. 12 for key).
between the horizontally laminated, cross-beded and rippled sandstones in Figure 13 represent flow regime fluctuations within depositional events, and do not represent coarsening upward trends through time.

Transitions which occur significantly less often than randomly support these observations. Within a rock-type, thinner beds do not pass upward into thicker beds. For example, medium bedded, horizontally laminated sandstone is not commonly overlain by thickly bedded sandstone, and thinly bedded, horizontally laminated sandstone is not commonly capped by either medium or thick beds of this rock-type.
DEPOSITIONAL INTERPRETATION

A depositional model for the lower Mt. Shields Formation must account for the two fining upward scales of sedimentation: 1) the single bed deposited by a single depositional event, and 2) the fining upward, vertically stacked sequences these beds form.

Single Depositional Event

The fining upward of grainsize and corresponding change in bedforms which parallel a decrease in flow velocity within single beds, couples or couplets of the lower Mt. Shields Formation is attributed to the waning of individual flood events. Other things must be considered, however, in proposing a depositional environment. These are:

1. Lack of lateral variation across wide outcrops
2. Tabular, even bedding
3. Lack of erosional surfaces and channels.

The geomorphology and depositional processes found on the fan skirt of the lower piedmont slope and basin floor of an internally drained "bolson" in the Basin and Range Province satisfies each of these points (Fig. 14). These huge, intermontane basins are deep, alluvium-filled structural depressions which may form in response to downdropping of fault blocks similar in shape to that proposed for the Belt basin (Winston et al., 1982). Here, alluvial fans parallelling the mountain front coalesce downslope, forming the fan skirt, which in turn merges with the basin floor along its lower boundary (F.F. Peterson, 1981).
Fig. 14. Major landforms of an internally drained, intermontane basin. Modified from F.F. Peterson (1981).
Coalescing fans would supply a lateral rather than point sediment source, and may explain the lack of lateral facies changes across outcrops of the lower Mt. Shields Formation.

In the Basin and Range the fan skirt, with a 1% grade, is the smoothest and flattest zone on the piedmont slope, and merges with the alluvial flat, the most extensive landform of the basin floor. Because both are primarily depositional landforms, they are undissected. Channels, if present, are only very slightly incised and are cut by broad, ephemeral braided streams. Fan skirts are built up primarily by sheet floods. In order for these landforms to exist, it is essential that the basin be internally drained and land-locked on all sides. Externally drained basins, or semi-bolsons, develop an axial drainage system which dissects lower piedmont and basin floor landforms (F.F. Peterson, 1981). Given the geomorphology and depositional processes found on these landforms, the tabular, even bedding and lack of erosional surfaces and channels of the Mt. Shields best fit this model.

**Lateral Stratigraphic Relationships of Rock-types**

Coarser-grained, sandier rock-types are most dominant in the Prickly Pear section, the southern most section in the study area. The Clearwater Junction section is in turn sandier than the northern most Mt. Morrell section, which contains the greatest percentage of the finer-grained, coupled and coupled rock-types (Plate 1). Distinct
fining upward sequences can be correlated among the three sections, as seen in Figure 15 and 16. These clearly show that cross-bedded sandstone passes downslope to horizontally laminated sandstone, which in turn may pass to a more thinly bedded horizontally laminated sandstone or to the coupled red sandstone rock-type. The coupled red sandstone passes distally to the coupled red argillite rock-type. This is especially well developed between the Prickly Pear and Mt. Morrell sections in Mt. Shields I (Fig. 16). Similar facies changes are evident throughout the sections (Plate 1).

This fining of rock-types seen from the southern part of the study area northward represents deposition on proximal and distal parts of a depositional slope in response to floods by processes similar to those active on the fan skirt and alluvial flat of modern internally drained basins (Fig. 17). First, coarse-grained, cross-bedded sand was deposited on what may be compared to the upper part of the fan skirt, where very broad, shallow, slightly incised braided stream channels and bars are present (F.F. Peterson, 1981); as the water continued downslope, sheetfloods deposited the sediment of the horizontally laminated sandstone rock-type. As the flood reached what may be compared to the alluvial flat of the basin floor and spread out, a layer of fine sand grading up to very fine sand, which comprises a single bed of the coupled red sandstone, was deposited (see Fig. 15). Floods which entered ponds occupying slight depressions, similar to those found on the basin floor as described by F.F. Peterson (1981), deposited sediment on softer
Fig. 15. Correlation of stacked vertical fining upward sequences between sections, and lateral transition of facies. The cross-bedded sandstone passes laterally to the horizontally laminated sandstone, which passes laterally to the coupled red sandstone.
Fig. 16. Correlated portions of the Prickly Pear and Mt. Morrell sections (Mt. Shields I) showing lateral facies transitions. The horizontally laminated sandstone and coupled red sandstone pass laterally to the coupled red argillite (see Fig. 15 for key).
Fig. 17. Distribution of rock-types on the lower piedmont fan skirt and alluvial flat of the basin floor of an internally drained basin.
surfaces, which eventually formed the vaguely coupled sandstone rock-type. As flood water continued to dissipate downslope, silt and clay were deposited primarily from suspension, and formed the most distal rock-type, the coupled red argillite (see Fig. 16).

Origin of Fining Upward Sequences

In reviewing the deposits of Mt. Shields I and II, two trends become apparent which must be explained.

1) Fining and thinning upward sequences averaging 3 to 10 m thick and comprised of a series of related beds, couples and couplets are vertically stacked within a section.

2) In these sequences, bedding thickness and overall grainsize decrease upward.

The lack of coarsening upward sequences in the Mt. Shields is as important a constraint for interpreting a depositional model as are those listed above. As shown in Figure 18, the model must generate an asymmetric fining upward profile compatible with the observed pattern of rock-type occurrences.

F.F. Peterson's study focuses primarily on the geomorphology of landforms in modern block-faulted basins (1981). Heward (1978) comprehensively reviews the origin of coarsening and fining upward sequences in alluvial fans of ancient block-faulted basins (Table 1). He points out that sequences 10's m thick record short term fan behavior, and megasequences 100's m thick result from longer term fan behavior. Most processes, such as a response to initial
Fig. 18. Idealized stacked vertical fining upward sequences of the lower Mt. Shields Formation, and corresponding asymmetric fining upward profile formed by the observed pattern of rock-type occurrences.
Table 1. Classification by Origin of Alluvial Fan Sequences and Megasequences. Modified from Heward, 1978.

1. Initial Topography
   Assymmetric to partially symmetric coarsening upward megasequences near the fan apex, sequences near the fan toe.

2. Short-Moderate Duration Fanhead Entrenchment
   Assymmetric or symmetric coarsening or fining upward sequences reflecting gradual or abrupt initiation or termination of sediment supply.

3. Prolonged Fanhead Entrenchment
   Assymmetric coarsening upward sequences, or symmetric coarsening and fining upward sequences. Results from a decrease in sediment supply or lowering of base level.
   Note: Fining upward sequences may predominate on fans characterized by a decline in amount and grade of source area debris. "Fan accumulations of these types are unlikely to be of great volumetric importance and in the case of those initiated by lowering of base level, the eventual preservation of such deposits is questionable (Heward, 1978, p. 684)."

4. Scarp Retreat and Lowering of Relief
   Assymmetric fining upward sequences-megasequences.

5. Tectonic Uplift
   Assymmetric to partially symmetric coarsening upward megasequences (proximal locations) and sequences (distal locations).

...
relief in the source area consistently produce asymmetric fining upward sequences and megasequences. These fining upward sequences and megasequences, however, form deposits 10's to 100's m thick, much larger than the sequences in the lower Mt. Shields Formation.

In addition to the lack of coarsening upward sequences and the difference in scales of fining upward sequences, Mt. Shields I and II rock-types differ lithologically from alluvial fan deposits. Besides conglomeratic mudflow deposits, Steel (1974) cites stream flood and braided stream deposits as typical alluvial fan facies. Stream flood deposits consist of laterally discontinuous, large scale planar cross-stratified conglomerate and sandstone units which show clear evidence of erosion. Braided stream deposits are characterized by trough cross-stratification, channel cut-and-fill, the frequency of erosional surfaces, and rapid lateral lithologic and textural variation (Steel, 1974). Mt. Shields rock-types in the study area, however, are lithologically and texturally quite consistent, are tabular and evenly bedded, and lack erosional surfaces.

Deposits of the Devonian Hornelen Basin in Norway are the most similar to those of the Mt. Shields Formation in both overall thickness and lithology. Each depositional unit records a flooding event. However, coarsening upward sequences dominate the Devonian section, and Steel and others (1977) consequently interpret this to be the result of shifting and prograding sand lobes. This process does not generate the asymmetric, fining upward profile seen in the Mt. Shields Formation.
Rather, the shifting and progradation of the lobe results in a more symmetric profile of both coarsening and fining upward sequences (Fig. 19). Therefore, the alluvial fan model based on studies of ancient deposits does not explain the fining upward sequences of the lower Mt. Shields Formation.

In addition, if the sequences are the result of transgressive-regressive cycles of the "Belt sea", one would expect to see more coarsening upward sequences marking a drop in shoreline. The profile generated by this model would again tend to be more symmetric (Fig. 20). This model is also discarded because it cannot accommodate the sedimentary features, such as extensive mudcracked surfaces, tabular bedding, and lack of erosional surfaces and channels, which characterize the deposits of a single depositional event.

Climatic Explanation for Sequences

Since alluvial fan deposition, progradation and shifting of sand lobes, and transgressive-regressive cycles of a sea do not generate the sharp, asymmetric stacking of fining upward sequences of Mt. Shields I and II, cyclic alteration of rainy and dry climatic periods appears to be the most likely explanation of their origin for the following reasons. The thicker-bedded, coarser-grained rock-types which comprise part A of the sequence represent deposition during rainy periods when the amount of runoff was greatest, moving this coarsest grainsize downslope and forming the thickest beds. Parts B and C of the sequence, comprised of
Fig. 19. Schematic presentation of the coarsening and fining upward rock profile generated by a prograding and shifting sand lobe.

Fig. 20. Schematic presentation of the symmetric, coarsening and fining upward rock profile generated by changes in shoreline due to transgressive-regressive cycles of a sea.

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the progressively finer-grained, more thinly bedded rock-types, represent deposition during dryer periods when rainfall and flooding were not so great.

If, however, the change between arid and rainy periods was gradational, the resulting rock record should contain coarsening upward sequences. The corresponding profile would be symmetric, and the same problem would exist as for the other models (Fig. 21). An abrupt increase in rainfall through time must be followed by a gradational increase in aridity in order to generate the asymmetric, fining upward profile of Mt. Shields I and II (Fig. 22).

R.L. Ives (1936) described primary and secondary desert flooding in the Sonoyta Valley, Sonora, Mexico. Here, primary flooding is generated by moisture brought in by clouds from outside of the basin. The clouds rise over the mountains, cool, and produce intense rainfall. These rains result in violent sheetfloods on the fan skirt and alluvial flat, and fill the playa lake in the center of the internally drained basin.

Secondary flooding is derived from intrabasinal moisture (Ives, 1936). As the water in the lake evaporates, clouds form over the playa. These clouds move and drop water away from the playa, but still within the basin, producing smaller scale flooding events. Some of the clouds escape from the basin before dropping their moisture, and other water is absorbed into the ground. In this way the lake becomes smaller, the amount of moisture available to form clouds decreases, and the flash cloudbursts decrease in scale as the lake contracts. This filling of
Fig. 21. Schematic diagram of the symmetric coarsening and fining upward rock profile generated by a gradational change in the amount of rainfall through time.

Fig. 22. Schematic diagram showing the need for abrupt climatic cycles to generate the asymmetric fining upward profile of Mt. Shields I and II.
the lake, evaporation and subsequent flooding recycling process continues until all of the water has either escaped from the basin or been absorbed into the ground.

Although the difference in scale between the Belt basin and those in the Basin and Range Province today is great, I propose that the asymmetric profile of fining upward sequences of Mt. Shields I and II resulted from similar, possibly long term climatic cycles in the Belt basin during Precambrian time. Part A of each fining upward sequence, which consists of the coarser-grained, thicker-bedded, cross-bedded or horizontally laminated sandstones, was deposited by primary floods which also filled the Belt lake. As the lake evaporated, secondary floods decreased in magnitude, producing the progressively more thinly bedded, finer-grained, coupled and coupled sandstone and argillite rock-types which comprise parts B and C of the sequence. The next influx of moisture from outside the basin generated new primary floods, and as the cycle was reactivated, a new fining upward sequence abruptly began. This interpretation explains the absence of coarsening upward sequences in Mt. Shields I and II.
BASIN-FILL SEQUENCES

One fining upward interval which occurs approximately 200 m up section records the lithologic change from Mt. Shields I to Mt. Shields II (Plate 1). In Mt. Shields I, the fining upward sequences described earlier are dominated by part B and C (see Fig. 10), which consist of the coupled red sandstone and coupled red argillite rock-types. These fining upward, vertically stacked sequences are present in Mt. Shields II, but in the Prickly Pear and Clearwater Junction sections are dominated more by part A, which is comprised of the cross-bedded or horizontally laminated sandstone rock-types. Very poorly sorted, scoured, coarse-grained, cross-bedded sandstone occurs only in Mt. Shields II in the Prickly Pear section, in the southern part of the study area. Parts B or C of the sequence are occasionally replaced by the vaguely coupled sandstone rock-type in the other two sections. Both the finer-grained Mt. Shields I and the coarser-grained Mt. Shields II are basin-fill sequences (Heward, 1978).

The rather abrupt stratigraphic boundary between Mt. Shields I and II correlates well among the studied sections (see Fig. 15; Plate 1). Comparably scaled basin-fill sequences recognized in lithologically similar rocks of the Devonian Hornelen Basin, Norway, are attributed by Steel and Aasheim (1978) to rapid basin subsidence. On this basis I interpret this change in the lower Mt. Shields Formation to also reflect a major episode of basin subsidence with respect to the source area. In response to the lowering of base levels, facies...
characterized by more proximal deposition prograded downslope, 
producing the coarse-grained rock types which dominate Mt. Shields II.
CONSIDERATION OF OTHER BELT SUPERGROUP ROCK-TYPES

The internally drained basin and primary and secondary flooding models can be expanded to encompass other rock-types of the Middle Proterozoic Belt Supergroup (Fig. 23). Winston (1978) interprets five major Belt rock-types corresponding to a fluvial facies model which fines northward. Winston attributes the conglomeratic rock-type to braided stream deposition on proximal parts of the fan surface close to basin margin faults. This passes down fan into the cross-bedded rock-type which formed from linguoid and transverse bars in broad braided stream channels. Both of these rock-types could form by depositional processes active on the upper and middle piedmont slope.

The fine, horizontally laminated rock-type and the red argillite rock-type, which correspond to my horizontally laminated sandstone, coupled red sandstone and coupled red argillite rock-types are typical of most of the lower Mt. Shields Formation. Winston (1978) proposes shallow sheetwash across distal parts of the fan and nearshore deposition as resulting in these rock-types. As described above, these represent sedimentation by processes similar to those on the lower piedmont fan skirt and alluvial flat of the basin floor.

Finally, Winston's red argillite rock-type passes distally to his green argillite rock-type, deposited almost entirely from suspension, and which he feels formed under continual standing water conditions. In addition, the dolomitic rock-type and black argillite rock-type...
Fig. 23. Distribution of Belt Supergroup major rock-types within a block-faulted, internally drained basin. Base drawing modified from F.F. Peterson (1981).
found in the Belt Supergroup (Grotzinger, 1981) may represent lacustrine sedimentation in what is comparable to the playa lake of this model.
DISCUSSION

Scale Difference Between the Belt Basin and Basins of the Basin and Range

There is a major scale difference between the Belt basin and basins of the Basin and Range Province today. It is questionable as to whether similar landforms and depositional processes in modern, arid, internally drained basins could exist on a much greater scale. Sheetfloods are short-lived events in modern desert basins (McGee, 1897).

Although similar to a desert in its lack of vegetation, the Belt basin may have received a greater amount of precipitation. This combination of high rainfall rate and lack of vegetation does not exist today. Precambrian landforms would not have been stabilized by vegetation, and a large amount of sediment would have been available for transport. Runoff would have become saturated with sediment and would not have eroded deep channels; therefore sheetfloods would have occurred more frequently than it does today. Given a greater supply of water and sediment, I propose that sheetfloods would have been of greater magnitude and duration, and associated landforms and depositional processes would have been correspondingly more extensive during Precambrian time.

Comparison of Sequences with Cycles in the Wallace Formation

The model of climatic variation corresponds amazingly well with the
conclusions drawn by Grotzinger (1981). In his study of the Wallace Formation, middle Belt carbonate, which he interprets as resulting from lacustrine sedimentation, Grotzinger recognizes a cyclic member dominated by the asymmetric repetition of shoaling upward cycles one to 8 m thick. He divides an ideal cycle into four phases. In ascending order each phase consists of: 1) intraclastic packstone and horizontally laminated sandstone, 2) coupled to coupled fine sand-, silt- and claystone, 3) fine sand-, silt- and claystone plus bedded dolomite and 4) bedded dolomite with only minor amounts of terrigenous sediment. The next cycle abruptly begins, and is often marked by a scoured surface.

Grotzinger (1981) concludes that:

It is obvious in many ways that the dolomite has replaced beds that were once extremely fine grained calcium carbonate and that the calcium carbonate was most likely chemically precipitated as a result of evaporation. This dictates that the rate of evaporation exceeded the influx of fresh water; there must have been a change in climate (p. 57).

He goes on to state that:

Alternating humid and arid climatic periods rapidly expanded and contracted the sea many times (p. 64). . . . The onset of each cycle marked the expansion of the sea during humid periods and increased inflow of fresh water. . . . Through the course of each cycle, rainfall began to wane and the sea began to shrink as it entered a new phase of chemical sedimentation (p. 65).

Grotzinger's observations and conclusions further strengthen this model; they show the effects of the climatic cycles present in the sediments of the fan skirt and alluvial flat can be correlated to more distal sedimentation in the lake itself. These similarities are even
more pronounced when an idealized cycle in the Wallace Formation and one of a fining upward sequence in the lower Mt. Shields Formation are compared (Fig. 24). Sediments of the cross-bedded and horizontally laminated sandstones (part A) in Mt. Shields I and II and the packstone, horizontally laminated sandstone and coupled (Grotzinger's coarser coupled) rock-type (Phases 1 and 2) in the Wallace Formation were deposited by primary floods which simultaneously filled the Belt lake. As the lake began to evaporate and contract, calcium carbonate started precipitating (Phases 3), and secondary floods deposited the sediment of the coupled red sandstone on the basin floor (part B). Finally, as this process continued, flooding became progressively smaller scaled and only the finest sediment reached the basin floor, resulting in the coupled red argillite which often caps a sequence in the lower Mt. Shields Formation (part C). Little to no terrigenous material was carried out into the Belt lake, where sedimentation was dominated by continued precipitation of calcium carbonate.
As the lake continues to contract, secondary flooding decreases in intensity, depositing only the finest sediment of the coupled red argillite.

Secondary flooding of interbasinal moisture supplied from lake evaporation deposits sediment of the coupled red sandstone.

Primary flooding from moisture derived outside the basin fills the lake, and deposits cross-bedded and horizontally laminated sand.

Continued contraction and rapid deposition of carbonate (now dolomite). Terrigenous sediments are minor.

Contraction of the lake and deposition of both chemically precipitated CaCO\(_3\) (now dolomite) and terrigenous fine sand, silt and clay.

Continued expansion and deposition of offshore fine sand, silt and clay.

Expansion of the lake and deposition of intraclastic packstone and horizontally laminated sand.

Fining upward sequence
Lower Mt. Shields Formation

Shoaling upward cycle
Wallace Formation

Modified from Grotzinger (1981)

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Fig. 24. Comparison of an idealized sequence and cycle in the lower Mt. Shields Formation and Wallace Formation, respectively, correlating rock-types and subsequent interpretations. Part A of a sequence in the lower Mt. Shields Formation and Phases 1 and 2 of a cycle in the Wallace Formation record rapid expansion of the Belt lake by primary floods. Parts B and C and Phases 3 and 4 record slow contraction of the lake by evaporation as secondary floods decrease in magnitude.
CONCLUSIONS

Deposits of Mt. Shields I and II are characterized by few erosional surfaces and channels, and lack of lateral facies variation in tabular, even beds. Grainsize and sedimentary structures decrease in scale upward within single beds. The sediment was deposited on what can be considered the fan skirt of the lower piedmont slope and basin floor of the Middle Proterozoic Belt basin by processes similar to those found on these landforms in modern internally drained basins. These primarily depositional landforms exist only if a basin is internally drained; in a semi-basin, an axial drainage system develops and dissects them. This provides evidence that the "Belt sea" was at this time in fact a large, land-locked body of water. The five rock-types recognized in the lower Mt. Shields Formation -- the crossbedded and horizontally laminated sandstones, coupled red sandstone, vaguely coupled sandstone and coupled red argillite -- represent deposition on proximal and more distal reaches of the "fan skirt" and "basin floor" in the Belt basin, respectively.

These rock-types combine to form vertically stacked, sharply bounded fining upward sequences (3 to 10 m thick) in which bedding thickness and overall grainsize decrease upward. The base of each sequence is marked by the cross-bedded or horizontally laminated rock-types (part A). These pass upward into the coupled red sandstone or vaguely coupled sandstone rock-types (part B), which may in turn pass upward into the coupled red argillite rock-type (part C), which often caps a sequence.
The assymetric profile these vertically stacked sequences create is attributed to climatic variation in which the Belt lake was subjected to repetitive periods of rapid expansion followed by slow evaporative contraction. Violent primary floods, generated by moisture derived from outside the basin, deposited the coarser-grained sediments which form part A of each sequence, and quickly filled the Belt lake. As the lake then evaporated and contracted, smaller scale secondary floods derived from intrabasinal moisture resulted in deposition of the progressively more thinly bedded, finer-grained sediments of the rock-types which comprise parts B and C of a sequence (see Fig. 10 and 22). With the next influx of moisture from outside the basin, primary flooding reoccurred, and the next fining upward sequence abruptly began.
REFERENCES


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