The stratigraphy and sedimentation of the Wallace Formation northwest Montana and northern Idaho

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THE STRATIGRAPHY AND SEDIMENTATION
OF THE WALLACE FORMATION
NORTHWEST MONTANA AND NORTHERN IDAHO

by

John P. Grotzinger

B.S., Hobart College, 1979

Presented in partial fulfillment of the
requirements for the degree of

Master of Science

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Approved by:

Chairman, Board of Examiners

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ABSTRACT

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The Stratigraphy and Sedimentation of the Wallace Formation, Northwest Montana and Northern Idaho

Director: Don Winston

Three informal members within the Wallace Formation can be correlated in northwestern Montana and northern Idaho from sections at Big Hole Peak and Graves Creek, Montana, and Clark Fork, Idaho. The Wallace sediments are interpreted to be lacustrine rather than marine both on the basis of their significant dissimilarity with marine sediments, and, conversely, their close similarity with lacustrine sediments of several different ages.

Transgression of the Belt Sea is recorded by the lower, green member which is characterized by alternating sequences of green argillite and dolomitic green argillite. These sediments were derived from enormous alluvial fans and accumulated on fringing, lacustrine mud flats.

The middle, cyclic member represents stabilization of the sea and the onset of alternating humid and arid climatic phases that expanded and contracted the sea. More than 200 shoaling upward sedimentary cycles correspond to more than 200 expansions of the sea, ultimately dependent upon humid to arid climatic oscillations.

The lower part of the uppermost, sandy member records continued transgression by the Belt Sea. Sedimentation was dominated by the deposition of sand to clay turbidities, that accumulated on the slope of the sea floor. The upper part of the member records the regression of the Belt Sea, probably in response to both progradation of the alluvial systems and simple eutrophication of the sea.
ACKNOWLEDGMENTS

I extend my gratitude to Don Winston who supervised this thesis. Don is responsible for suggesting the thesis topic, helping me develop the ideas presented in the body of the thesis, and suffering through several drafts of the thesis. Certainly, his many helpful suggestions helped me transform diffuse ideas into words on paper.

I thank my other committee members, Robert Fields, Mark Behan, and Paul Hoffman, for reviewing and editing an earlier draft of this thesis. Mac, Buttocks and Hag helped in the field. John Herrlin printed some of the photographs used in this thesis and provided a place to stay during the transient times. I am grateful to Shirley Pettersen for typing this manuscript.

I am most grateful to my father, Paul Grotzinger, for instilling in me a philosophy that will continue to serve. Inspiring discussions with him always sent me back to work with renewed enthusiasm. I dedicate this thesis to him.
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CHAPTER I
INTRODUCTION

General Statement

The sediments of the late Proterozoic Belt Supergroup were deposited between approximately 1,450 and 850 million years ago in a broad, northwesterly-trending, intracratonic basin. Today the Belt basin occupies most of western Montana, northern Idaho, eastern Washington and adjacent Canada, where it passes into the Purcell Supergroup (see Fig. 1). Four major stratigraphic subdivisions have been delineated by Harrison (1972): the Lower Belt, the Ravalli Group, the Middle Belt Carbonate Interval, and the Missoula Group (see Fig. 2).

Transitions, formations and members within the Missoula Group have been studied by McGill and Summers (1967), Childers (1963), Smith and Barnes (1966), Bleiwas (1977), Quattlebaum (1980), Lemoine (1979), and Mudge (1972). Winston (1978) measured sections within the Missoula Group and developed an integrated fluvial facies model which explains the origin of the several rock types that compose the Missoula Group as well as parts of the Ravalli Group. Additional work by White, et al. (1977) and White and Winston (1977) helped corroborate that model.

The Middle Belt Carbonate Interval (M.B.C.I.) may contain some of the most definitive information for interpreting the "Belt Sea" but has been studied by few geologists. The M.B.C.I. includes the Helena, Siyeh and Wallace Formations. Parts of the Helena and Siyeh Formations
Figure 1. Regional correlation of the Middle Belt Carbonate Interval within the Belt Supergroup and Purcell Supergroup. Smith and Barnes (1966) correlated the Siyeh Fm. with the Kitchner Fm., Helena Fm. and Wallace Fm. Sources of data: Sections 1, 2, 4 (Smith and Barnes, 1966) and section 3 (Harrison, 1972 and Grotzinger, this study).
Figure 2. Stratigraphic subdivisions of the Belt Supergroup near Libby, Montana. At that location, the Wallace Formation is equivalent to the Middle Belt Carbonate Interval and the Prichard Formation is equivalent to the Lower Belt.
have been studied in detail by Horodyski (1976) and Peterson (1971). O'Connor (1967) and Eby (1977) have contributed regional stratigraphic and sedimentologic syntheses of the Helena Formation. However, the Wallace Formation has remained unscathed by the geologist's pick and is the focus of this study.

Previous Studies Concerning the Middle Belt Carbonate Interval

In 1914, Walcott pointed out that stromatolites were common in the M.B.C.I., realized their organic origin, and interpreted them as having grown in a fresh water, shallow lacustrine environment. Later Fenton and Fenton (1936) discovered salt crystal casts in the Siyeh Formation near Glacier National Park. Because of this discovery, plus the additional implications of the astoundingly thick Belt section, they propounded a marine interpretation for the rocks of the M.B.C.I.

Since that time, most researchers have based their interpretations on a marine model. One particular exception to the marine model was published by Peterson (1971) who, after measuring, describing, and interpreting sections in the Helena Formation, concluded that it may have a lacustrine origin.

The only studies that interpret the regional environmental stratigraphy within the M.B.C.I. have been published by O'Connor (1967; 1972) and Eby (1976; 1977). Both authors interpreted the Helena Formation to be a marine carbonate platform. Additionally, Eby was able to show along several lines of evidence that periods of hypersalinity existed in the "Belt Sea".
Present Study

The results of this study are multifold: 1) the study fills the stratigraphic gap between the Ravalli and Missoula Groups, 2) it subdivides the Wallace Formation into informal members which may be used to correlate more precisely the Wallace sequence with the Helena sequence, and 3) it presents a lacustrine paleoenvironmental interpretation of Wallace deposition.

Because they lack animal fossils, Precambrian rocks can only be correlated lithostratigraphically. Belt rocks have commonly been correlated on the basis of homotaxial lithosomes. Winston (1977) has identified a series of lithosomes he calls "rock types". These are characterized by sedimentary structures, grain size, texture, color and mineralogy and correlations on the basis of these have met with large success in the past as well as the present study.

The boundaries of the Wallace Formation are transitional but can be narrowed to a few feet by arbitrarily choosing a small number of criteria defining the boundaries. I have placed the lower boundary above the highest red argillite of the St. Regis Formation. At this point, red argillite passes upward into green argillite and dolomititic green argillite which dominate the lower Wallace lithology. The upper boundary is placed where the black argillite characteristic of upper Wallace lithologies passes into the lowest thick (>50 feet) sequence of green argillite marking the base of the Snowslip Formation. This boundary is more gradational than the lower one and hints of green occur shortly below the major lithologic change from black to green.
It can be argued that because the color changes which define the boundaries result from secondary diagenesis, they do not represent a primary rock feature. Nevertheless, detailed stratigraphic and sedimentologic investigations have demonstrated that these diagenetic color changes do, in fact, reflect primary depositional environments (Lemoine, 1979; Winston, 1978; O'Conner, 1967). Generally, there is also a change in bedding thickness which accompanies the inflection in color. These boundaries carry well and should prove to be satisfactory for use in future studies.

Three unfaulted sections were measured along a line defined by the trend of the Clark Fork River Valley between the towns of Plains, Montana, and East Hope, Idaho (see Fig. 3). This transect was chosen so that correlations in the Wallace Formation could tie in directly with those made by Lemoine (1979) who correlated the top of the Wallace with the base of the Missoula Group along this same line. Sections were also measured in the St. Regis Formation by Malcolm Donofrio and in the Revett Formation by Don Winston and Jim Reid. The St. Regis underlies the Wallace, and measured sections of the St. Regis provided control for the correlations at the base of the Wallace. This NW-SE panel of sections in the Ravalli Group, Wallace Formation and Missoula Group should provide the ground work for future correlations into the structurally complex area south of the Hope Fault. The Big Hole Peak section is well exposed except for the top 210 feet which are covered. The Graves Creek section is locally covered with one very thick covered
Figure 3. Index map showing location and extent of Precambrian Belt basin (modified after Harrison, 1972) and location of measured sections (3).
part of the middle of the section. The Clark Fork section is mostly exposed. A total of 16,050 feet of section was measured with a Brunton compass and Jacobs Staff. Where the rocks were exposed, marks were painted every five feet and numbered every ten feet. In describing the sections I compiled a graphic and written log on square ruled paper using a scale of 1 inch = 10 feet.

Harrison and Campbell (1963) estimate that about 90 percent of the Belt rocks are finer than coarse silt. Wallace rocks are no exception to this generalization and consequently, the examination of 26 thin sections revealed little more than textural information. Fortunately, this fine grain size also helped preserve a wealth of primary and penecontemporaneous sedimentary structures in the Belt rocks. Thus, examination of polished slabs illuminated the finer details of the structures.

Calcite/dolomite ratios were determined by x-ray analysis of the carbonate rocks. Beyond this, x-ray analysis is generally not useful because lower greenschist load metamorphism has altered the primary assemblage of clay minerals (Maxwell and Hower, 1967). Metamorphic grade is directly proportional to section thickness which increases from east to west.

**Structural Setting of Study Area**

It is important to point out that the Big Hole Peak section is located on a more eastern thrust sheet than the Graves Creek section. Also, the Clark Fork section lies to the south of a combination normal and right-lateral strike-slip fault (Hope Fault) that strikes NW and
dips steeply to the southwest. According to Harrison and Jobin (1963), the true strike slip approximates 12 km and the apparent dip slip about 6 km. Harrison, et al (1980) believe that the total crustal shortening from thrusting and associated folding may be on the order of 180 km. The major thrusts all place older over younger strata and a few smaller splays thrust younger over older. Block faulting has further deformed the area and is well documented by Reid and Greenwood (1968) and Harrison, et al. (1972).

**Lacustrine Processes in the "Belt Sea"**

I believe that the "Belt Sea" was an intracratonic, chemically isolated body of water. Thus, it was more like a lake than part of the marine system and, as such, sedimentation was controlled by lacustrine types of processes. In this thesis I retain the term "sea", which is used in the same sense as the Caspian Sea is an inland sea. My definition of the "Belt Sea" is: a body of open, relatively deep water whose surface dimensions were sufficiently large to sustain waves capable of producing a wave-swept shore, and that was sufficiently closed so as to have been isolated from the homogenizing effects of marine water and marine tides, and easily influenced by the climate of its hydrographic province.
CHAPTER II

ROCK TYPES: DESCRIPTIONS AND INTERPRETATIONS

General Statement

Several different rock types can be recognized in the Wallace, which is the most heterogeneous unit in the Belt Supergroup. Some of these have never been described and interpreted before. Criteria such as sedimentary structures, grain size, textures, color and mineralogy define the rock types and can be analyzed to interpret depositional processes and paleoenvironments. In this chapter, the rock types are examined individually, depositional processes deduced, and possible paleoenvironments outlined. In the next chapter, the rock types are surveyed in vertical stratigraphic sequence. This analysis within a stratigraphic framework further constrains the interpretations to a single most likely paleoenvironment for each of the rock types.

The rock types, in order of decreasing abundance, are: 1) black argillite rock type; 2) white sand rock type; 3) dolomite rock type; 4) green argillite rock type, 5) dolomitic green argillite rock type; 6) intraclastic conglomerate rock type, and 7) gray, thickly crossbedded rock type. Further, the black argillite rock type can be subdivided into the following rock subtypes: 1) coarsely coupled rock subtype; 2) microlaminated rock subtype; and 3) tripled rock subtype. The white sand rock type consists of the following rock subtypes: 1) horizontally laminated rock subtype; and 2) lenticular, crosslaminated...
rock subtype. The intraclastic conglomerate rock type includes these rock subtypes: 1) molar tooth hash rock subtype, and 2) flat pebble conglomerate rock subtype.

In describing the rock types, I have parted from the incorrect idea that "argillite" and "siltite" correspond to the lower grade metamorphic equivalents of claystone and siltstone and have returned to the original definitions. Argillite is defined as "a compact rock, derived from mudstone (claystone or siltstone) or shale, that has undergone a somewhat higher degree of induration than is present in mudstone..." (AGI Glossary of Geology, Second ed.). Low grade metamorphism is correctly inferred. However, siltite is a term used for an unmetamorphosed siltstone. Siltstone is defined as "...a massive mudstone in which silt predominates over clay..." that is "...indurated or somewhat indurated..." (AGI Glossary of Geology, Second ed.). No metamorphism is inferred. A claystone is regarded as "...a massive mudstone in which clay predominates over silt..." (AGI Glossary of Geology, Second ed.). An argillite then, is a mixture of both silt and clay that has undergone low grade metamorphism. A siltite is mostly silt but has not undergone metamorphism. I therefore propose the more accurate terms of claystone and siltstone to correspond to the terrigenous rocks of the Wallace Formation which are dominated by clay and silt size grains respectively. Finally, it should be understood that all Wallace rocks (as well as all the other Belt rocks) have at least a low grade metamorphic overprint. In naming the rock types I have used the term argillite if the rocks are composed of both siltstone and claystone.
The phrase "sedimentary couplet" has been used by Winston (1978) to describe the extremely common laminated sequences in Belt rocks of siltstone up to claystone in which siltstone layers have sharp bases and grade up into, or are sharply overlain by claystone layers. The classification of Lemoine (1979) has been applied to couplet thickness. The categories are: 1) very finely coupleted or "paper thin" (microlaminated) = laminations less than 1 mm; 2) finely coupleted = laminations 1 mm to 0.5 cm; 3) medium coupleted = laminations 0.5 to 1.0 cm; 4) coarsely coupleted = layers 1 cm to 3 cm; and 5) very coarsely coupleted or interbedded = layers greater than 3 cm.

**Black Argillite Rock Type**

This rock type is composed of light gray to black, fine sandstone and siltstone layers to claystone layers that form couplets of micro-laminated to very coarse scale. Organic carbon is an important constituent of these rocks, and its relative content is directly proportional to their color. Concentrations of both finely disseminated and euhedral cubes of pyrite up to 2 cm commonly parallel bedding.

Soft sediment deformation in these deposits has been extensive and includes: intricately crumpled shrinkage cracks, pull-aparts, horizontal compaction shears, vertical zones of brecciation, and other ubiquitous forms of hydroplastic disruption. All of these structures are thought to have resulted from synaeresis (see Appendix A) and are strikingly similar to those found in the lacustrine Triassic Lockatong Formation of New Jersey and Pennsylvania (compare Van Houten, 1964).
This is the most common rock type in the Wallace and can be subdivided into three distinct rock subtypes based on what first appear to be subtle differences.

A. **Coarsely Coupled Rock Subtype**

**Description.** This is the most common of the three subtypes but others may dominate sections of the Wallace elsewhere (see Godlewski, 1980). The rock subtype consists of very dark gray to light gray, coarsely coupled to very coarsely coupled, abruptly graded, fine sandstone, siltstone and claystone (see Fig. 4). The couplets are grouped into beds up to 2 meters thick. The boundaries between succeeding couplets are sharp but undulatory, and couplets pinch and swell along the outcrop. Nevertheless, they are very continuous and can be traced across the outcrop for distances exceeding one kilometer.

The fine sand and silt portion of these size graded couplets is either massive or crosslaminated or, less commonly, horizontally laminated. The claystone is massive and nonfissile.

Here, penecontemporaneous deformation includes: loading, convoluted bedding, and all of the synaeresis features described in Appendix A. Enormous halite crystal casts were also found in this rock subtype and are described in Appendix B.

This rock subtype differs from the microlaminated rock subtype by 1) having sedimentary couplets of a much larger scale, 2) containing no interstratified organic films, and 3) containing no stromatolites. This rock subtype differs from the tripled rock subtype by: 1) not
Figure 4. Coarsely coupled rock subtype.
having as much fine sand at the base of the couplets, and 2) not having dolomite concentrated only in the silt laminae.

**Interpretation.** The fining upward gradation of sediment size in the couplets indicates that each was deposited from a single depositional event. Some of the silty portions are cross laminated and horizontally laminated which indicates that these sediments were deposited as traction load. As grain size decreases upward in the couplets, internal stratification disappears and the upper parts of the couplets represent settling from suspension. Because traction load deposition precedes suspended load deposition in most cases, the following sequence of events probably occurred. First, a sediment laden current that was in contact with the substrate passed over the surface. As it did so, rolling, sliding and saltating fine sand and silt grains were built into ripples in the lower flow regime or deposited in plane beds in the upper flow regime. This produced cross laminations and horizontal laminations. However, the velocity of this current eventually waned in all cases and, as it came to a halt, the very finest grains which it had previously suspended settled onto the depositional surface. Thus, each of the couplets of this rock subtype represents a single sedimentation event.

The occurrence of syngenetic pyrite indicates that the substrate was reducing. The preservation of organic carbon indicates that the water directly above the substrate was also reducing (Zangerel and Richardson, 1963). The growth of salt in the sediment proves that the bottom was also hypersaline at times. Finally, the absence of oscillation ripple marks shows that this environment was below active
wave base. The abundant synaeresis structures and other soft sediment features indicate that the rate of sedimentation was probably high (McKee, 1957; Shelton, 1962).

B. Microlaminated Rock Subtype

Description. Sedimentary units of this rock subtype are mostly microlaminated, very dark gray to black, nongraded siltstone or claystone couplets but locally become dark gray to light gray, abruptly graded siltstone to claystone couplets of fine to medium scale (see Fig. 5). In the microlaminated couplets, the claystone portion is so thin that it is better described as a film. These films also tend to be interstratified with very thin (<1 mm) laminae of extremely fine graded dolomite. Significantly, the only stromatolites found in the study area are built with this rock subtype. The mound shaped, domal and undulatory stromatolite morphologies can be classified as LLH and SH forms of Logan, et al. (1964).

Soft sediment deformation of this rock subtype is extensive. All the synaeresis features discussed in Appendix A can be found as well as small scale convoluted bedding and loading. Additionally, thin section study shows patches where the films have been locally stretched apart and are thinned to isolated threads which bridge the zone of detachment. These patches are now filled with microspar.

Interpretation. The organic films have two possible origins. First, they may be cryptagalaminate. This is suggested by their "thread-like" appearance at times. Alternatively, they may represent the accumulation
Figure 5. (top) Microlaminated rock subtype.

Figure 6. (bottom) Tripled rock subtype.
of very pure organic remains of photosynthetic unicellular algae or bacteria which either grew in the water column, died and fell down onto the substrate or grew as an organic film on the substrate. The inter-stratified, abruptly graded couplets indicate that sediments were periodically brought into the depositional locus by suspension and then deposited as the suspending current waned. The stromatolites are evidence that algae grew on the substrate and that the bottom was within the photic zone. Oscillation ripples are absent from this rock type. Therefore, the environment of deposition must be below wave base but within the photic zone. Possibly, the substrate was above wave base but effectively protected from reworking by the algalaminate which grew on the substrata as a film. Bathurst (1967) noted that this is an effective process in the Bimini Lagoon. Preserved organic carbon and pyrite testify that the bottom conditions were reducing. Soft sediment deformation and synaeresis features denote rapid deposition.

Based on the intimate interlamination of the organic films and dolomite, I suggest that this indicates magnesium-enrichment of calcite by the algae as proposed by Geblein and Hoffman (1973). Alternatively, dolomite replaced chemically precipitated calcite by the mechanism proposed by Baker and Kastner (1980).

C. Tripleted Rock Subtype

Description. This rock subtype was first described and interpreted by Godlewski (1980) from the Wallace Formation near Superior, Montana. In that location, it dominates Wallace lithology. The laterally
continuous, centimeter to decimeter scale units ideally have three components: 1) basal sand, 2) middle dolomitic silt, and 3) black claystone cap (see Fig. 6). In many units one or more of the components is absent.

The basal sand is mostly clean or light gray and occasionally is broken into distinctive sedimentary boudinage (see Fig. 7). The sand commonly covers a scoured surface, and internal stratification progresses from horizontal laminations at the base to ripple cross-laminations at the top.

The middle dolomitic component is thinner and consists of varying proportions of dolomite mud mixed with quartz silt and very fine sand. The boundary between the sandy and dolomitic components is gradational. Grain size decreases upward in these laminae.

The uppermost black claystone sharply caps the dolomitic component. It tends to be very thin, carbon rich and exhibit indistinct bedding that is nonfissile.

Interpretation. The progression of grain size and sedimentary structures in the sandy and dolomitic components suggests that they were deposited during a single event. First, traction currents in the upper flow regime deposited the horizontally laminated sand. Then, as velocity decreased, the bedforms proceeded to ripples, climbing ripples and eventually, as the current came to a halt, the dolomite silt and clay were deposited from suspension. Pelagic sedimentation followed, forming the black claystone cap. This component is often absent, suggesting that either the black claystone was eroded during the deposition of
Figure 7. Sedimentary boudinage. Boudins are located near hammer in center of picture.
the succeeding triplet, or it never had time to accumulate because the rate of pelagic sedimentation was much slower relative to the rate of nonpelagic sedimentation. The evidence favors both possibilities. Scoured surfaces beneath the basal sand of some triplets point to erosion by traction currents that deposited the sand. But, soft sediment deformation is also common in these deposits and indicates that the nonpelagic sediments accumulated rapidly; probably much faster than the pelagic sediments. I believe that both of these situations occurred as a normal part of sedimentation and each can adequately explain the absence of the black claystone cap.

The preservation of organic carbon and syngenetic pyrite indicates that the bottom conditions were reducing. Further, the presence of organic carbon as pelagic sediment suggests that the water column contained and supported the production of a photosynthetic microbiota. Finally, the occurrence of both life supporting and poisonous chemical conditions within the water column connotes that the body of water was stratified, like the Black Sea where the bottom waters are oxygen-depleted and organic material is unoxidized. Berner (1971) has shown that the organic matter is almost completely destroyed in constantly aerated waters. Conversely, in anaerobic sediments some organic carbon escapes bacterial destruction and is eventually transformed into coal, oil, or kerogen.

I believe that the sand and dolomitic sediments were transported and deposited by turbidity currents. This dolomite was probably carried from shallower, more nearshore areas. This interpretation follows that of Godlewski (1980).
**White Sand Rock Type**

This rock type is composed of two subtypes, neither of which has been described before. Both of these are common in the cyclic member.

a) **Horizontally laminated rock subtype**

**Description.** This rock subtype is restricted to the cyclic member. White or buff colored, well sorted, well rounded, very fine to medium sandstone forms tabular beds up to one meter thick. These are laterally continuous for more than one kilometer. The beds are horizontally to sub-horizontally laminated at the bases but are ripple crosslaminated at the tops (see Fig. 8). Bedding surfaces at the top of these beds exhibit bifurcating symmetrical, asymmetrical and interference ripples. Soft sediment deformation of these beds is rare.

This rock type commonly overlies the intraclastic conglomerate rock type. The sand of the lower part of the beds grades down into the conglomerate.

**Interpretation.** Horizontal laminations were produced by traction currents in the upper flow regime followed by bifurcating symmetrical and asymmetrical ripples produced by oscillatory wave generated currents in standing water.

Because this rock subtype closely overlies the intraclastic conglomerate rock type, I believe the horizontal and subhorizontal laminations were generated in the upper foreshore swash zone of a strandline (McKee, 1957). The occurrence of wave ripples at the top of the sand beds suggest that the strandline was replaced upward in the sequence by nearshore deposits. The depositional locus at this time was above wave base.
Figure 8. Horizontally laminated rock subtype.
B) **Lenticular, cross-laminated rock subtype**

**Description.** Thin beds (1-10 cm) of poorly sorted, moderately rounded, very fine to medium size sandstone occur throughout the entire green member and cyclic member of the Wallace Formation, but are particularly abundant in the sandy member. Stratification is dominated by current ripple crossbedding (see Fig. 9). This rock subtype characteristically occurs as intercalations in thicker sequences of several of the other rock types. Beds are laterally persistent.

**Interpretation.** These sands were transported by traction currents with velocities in the lower flow regime. Because of their lenticular, but laterally continuous geometry and general association with many other rock types, I suggest that this rock subtype represents sheets of sand that shifted around on the "Belt Sea" floor through the action of low velocity, intrabasinal circulatory currents.

**Bedded Dolomite Rock Type**

**Description.** This rock type is composed of laminated (1 to 3 cm) dark gray to blue gray, dolomite with occasional lensoidal intercalations of cross laminated silt and very fine grained sand (see Fig. 10). It weathers orange to brown and is characterized by even to slightly undulose, graded and non-graded stratification that contains several types of molar tooth structures.

In the cyclic member of the Wallace the bases of dolomite intervals grade down into the coarsely coupled subtype of the black argillite rock type below. The tops of dolomite intervals are scoured to various
Figure 9. Lenticular, crosslaminated rock subtype.
Figure 10. Bedded dolomite rock type.
extents and, where the scouring has been negligible, sand filled desiccation cracks occur (see Fig. 11). Less commonly, cryptalgalaminate and collapse breccia caps the beds (see Fig. 12). O'Conner (1967) and Eby (1977) noted all three of these features at the tops of similar dolomite intervals in the Helena Formation. Pyrite is common in the dolomite.

Interpretation. The interpretation of this rock type delves into one of the most interesting problems of Wallace sedimentology. In light of the experimental work of Baker and Kastner (1980), I prefer the replacement of chemically precipitated calcite and aragonite by dolomite as a process of dolomite formation. I propose that the "Belt Sea" was a large intracratonic sea and evaporated periodically beyond the point of calcium carbonate supersaturation. This led to the direct precipitation of calcium carbonate either as pore cement or directly in the water column. As the precipitate accumulated as sediment, it entered a favorable environment for dolomite replacement. The dolomitization mechanism of Baker and Kastner (1980) requires that the concentrations of dissolved sulphate and silica be low. The evidence of meeting these criteria is supportive. First, no chert beds or quartz nodules occur in the rocks I studied, and the only authigenic quartz is chert that is restricted to the replacement of molar tooth fragments. Second, pseudomorphs after sulphate minerals such as anhydrite or gypsum were not found, indicating that they were not preserved, or, more likely, they were deposited or were later reduced
Figure 11. Sand filled desiccation crack. Arrow points to crack which is uncrumpled, sand filled, and approximately 2 cm long.
Figure 12. Solution collapse breccia. Breccia is located between 6 and 8 cm marks and overlies dolomite. Desiccation cracked cryptagalaminate overlies the breccia, and the whole sequence is overlain by flat pebble conglomerate.
to form sulphides. Since halite crystal casts occur and syngenetic pyrite is extremely common, sulphate was probably reduced as quickly as it amassed. Therefore, one may conclude that both the concentrations of dissolved silica and sulphate were low, and that dolomite replacement in the manner proposed by Baker and Kastner (1980) was favorable.

The cryptalgalaminate and desiccation cracks at the tops of the dolomite intervals suggest that subaerial exposure occurred after the dolomite accumulated. During these periods of exposure the more soluble salts such as calcium sulphate and sodium chloride dissolved and formed solution collapse breccias (see Fig. 12).

Green Argillite Rock Type

Description. This rock type has been previously described and interpreted by Winston (1978) and Lemoine (1979). Generally, it consists of green, size graded, siltstone to claystone couplets of fine to coarse thickness (see Fig. 13). Occasional intercalations of the lenticular, crosslaminated rock subtype are present. Bedding surfaces and couplet boundaries carry laterally for long distances but are somewhat undulatory. Bifurcating symmetrical, asymmetrical and interference ripples are very common as well as penecontemporaneous deformation features such as: load casts, convoluted bedding and subaqueous shrinkage cracks. Other synaeresis features are not common and desiccation cracks are rare. Occasional claystone mudballs occur in the siltstone. Pyrite is common and concentrations parallel bedding.
Figure 13. Green argillite rock type.
Interpretation. The graded stratification of the couplets indicates deposition of most of the sediment from suspension. Occasional cross-laminated very fine sand beds indicate that transportation and deposition occurred also by traction currents. The green color is due to chlorite which fills interstitial spaces. The presence of chlorite and pyrite in these rocks indicates that the substrate was reducing.

Dolomitic Green Argillite Rock Type

Description. This rock type was first described by Lemoine (1979). It consists of dolomitic, mostly fine to medium scale couplets of graded siltstone and claystone (see Fig. 14). In outcrop, the dolomite stains the weathered surfaces light tan, which obscures the otherwise pale green color. Primary sedimentary structures include: bifurcating symmetrical ripples and asymmetrical ripples (see Fig. 15). Soft sediment deformation includes: loading, convoluted bedding and subaqueous shrinkage cracks. Desiccation cracks are rare, but molar tooth structures are fairly common. Intercalations of the lenticular, crosslaminated rock subtype are more common than in the green argillite rock type. These occur as very wide and thin sheets.

Interpretation. The non-chemical processes recorded in this rock type are similar to those in the green argillite rock type. Terrigenous silt and clay settled out of suspension and accumulated as size graded couplets during periodic episodes of rapid, turbid sediment influx. Sand was also intermittently transported as very wide and thin sheets across the depositional surfaces. These sheets were more numerous over
Figure 14. Dolomitic green argillite rock type.
Figure 15. Bifurcating symmetrical ripples.
the depositional tracts where this rock type developed than over those where the green argillite rock type developed. The next chapter reveals that the dolomitic green argillite rock type occupies a more "seaward" stratigraphic position than the green argillite rock type does.

I believe that the dolomite in this rock type is also a product of the replacement of calcite and aragonite by dolomite according to the process described by Baker and Kastner (1980). Calcite and aragonite were formed by primary evaporitic precipitation either as pore cement or directly in the water column during periods when the sea was drying up and the shoreline was retreating. Thus, the more seaward portions of the green argillite rock type depositional tracts became dolomitic; producing the dolomitic green argillite rock type.

Intraclastic Conglomerate Rock Type

A) Flat Pebble Conglomerate Rock Subtype

Description. Laterally extensive scoured surfaces are very commonly covered by pavements of well rounded and moderately sorted intraclasts composed of the bedded dolomite rock type. These intraclasts are extremely flat and average 1 to 20 cm broad but are generally less than 7 mm thick. The intraclasts are grain supported and weather recessively into the matrix which is mostly fine to medium quartz sand. This sand is identical in composition to the sandstone beds of the horizontally laminated rock subtype that directly overlie the conglomerate. The intraclasts range from flat-lying to vertically packed. The latter, vertically stacked intraclasts cluster together to form polygonal arrays
in plan view and closely resemble the "beach rosettes" described by Ricketts and Donaldson (1979). When the clusters are viewed parallel to bedding, they are packed on edge and exhibit a range of imbrication from vertical to subhorizontal (see Fig. 16). This rock type rests everywhere on a scoured surface.

Interpretation. This rock subtype is of great importance in deciphering Wallace deposition. It provides a datum from which all other rock types can be interpreted as they occur in vertical sequence.

Sheets of vertically packed, polygon forming, self supported intraclasts can be "stacked up" by only one process: the to-and-fro swash action of breaking waves along strandlines. This phenomena has been well documented in the recent by Dionne (1970); Ball (1976) and Gregory (1930). Proterozoic beach rosettes occur in the McCleary Formation (Donaldson and Ricketts, 1977) and in the Rocknest Formation (Hoffman, 1975).

The lateral continuity of these beach deposits suggests that the shoreline migrated. When migration was slow the intraclasts had time to organize into distinct polygons. When migration was faster a more recumbant orientation was preferred.

B) Molar Tooth Hash Rock Subtype

Description. This rock subtype is composed of beds up to 15 cm thick of poorly sorted, well rounded fragments of molar tooth ribbons and blobs. They are distributed as small lenses filling in local scoured depressions or as more extensive, laterally continuous sheets
Figure 16. Beach rosettes. Top - subvertical; bottom - subhorizontal.
that pave scoured surfaces, similar to the flat pebble conglomerate rock subtype (see Fig. 17).

Generally, the fragments are elongate, but less than 5 mm long. Where they occur in local depressions, they fill the deepest parts and tend to be matrix supported by the sand of the lenticular, crosslaminated rock subtype. But, where they occur as sheets, they are grain supported and are found at the bases of beds composed of the horizontally laminated rock subtype. In either case, they weather deeply into the matrix because of their pure calcite microspar composition and are easily identified.

**Interpretation.** This rock subtype was deposited in two different environments by two different processes. First, the hash which fills in the local depressions usually occurs at the bases of beds of the lenticular, crosslaminated rock subtype. Therefore, the traction currents which moved the sand probably also scoured the sediment surface at time and reworked the early cemented molar tooth structures. Once freed from the host sediment, they accumulated as lag deposits in the freshly scoured microchannels. This relationship is very common throughout all Wallace lithologies where molar tooth structures occur.

The sheet-like beds of molar tooth hash have a much more restricted distribution. These deposits are found only above scoured surfaces of widespread extent and are everywhere covered by the horizontally laminated rock subtype which also acts as matrix between the molar tooth fragments. This association is identical to that of the flat pebble conglomerate rock type and originated similarly. As strandlines migrated,
Figure 17. Molar tooth hash rock subtype. Top-filling in local depressions; bottom covering regionally scoured surfaces.
depositional surfaces were eroded and the molar tooth structures broken, reworked and deposited as lag.

**Gray, Thickly Crossbedded Carbonate Rock Type**

**Description.** This rock type is so rare that it forms only a single bed at the Big Hole Peak section where it occurs as a long, thin lens (50 cm x 100 m) containing large, high angle, planar crossbeds up to 15 cm high (see Fig. 18). This rock type is composed of poorly sorted, moderately rounded, intraclastic conglomerate. Grains are dominantly calcite with minor amounts of quartz sand that weather resistantly and help define crossbed foresets.

**Interpretation.** Crossbeds of the scale seen were left by large ripples and megaripples migrating across the substrate. Ripples of this size are moved by traction currents with velocities in the upper part of the lower flow regime.

This rock type was found as a single interbed in the coarsely coupled rock subtype. I suspect that these ripples were part of an offshore bar system that was affected by a slightly stronger version of the same intrabasinal, circulatory bottom currents that moved the sand sheets of the lenticular, crossbedded rock subtype.
Figure 18. Gray, thickly crossbedded carbonate rock type. Hammer at very top of picture.
CHAPTER III
WALLACE CORRELATIONS, STRATIGRAPHY AND FURTHER INTERPRETATIONS

General Statement

Ultimately, all rock types should be interpreted and assigned a specific environmental interpretation. In the previous chapter all the rock types were interpreted in terms of depositional processes and possible environments. But, except for the intraclastic conglomerate rock type, these possible environments were quite general and some were ambiguous. The next step then toward a more specific set of interpretations, is to analyze all of the rock types together, in a stratigraphic context.

The stratigraphic sequence in which Wallace rocks occur contributes as much information as the physical characteristics of the rocks alone. The vertical succession of rock types is well understood because sections were measured and described in detail (see Appendix C). The exposure at the Big Hole Peak section was superb both vertically and parallel to bedding. The lateral continuity of the rock types could be tested for distances over one kilometer. Amazingly, beds as thin as a single couplet could usually be traced this distance. Unfortunately, the tracing of sedimentary units laterally on a regional scale is hampered by limited exposures and fragmentation of the basin by the thrust faults discussed earlier. Therefore, this study is mostly based on the analyses of vertical profiles.
Lithic Correlation

Sections were correlated on the basis of the sequence of rock types rather than on "key" beds. The units of correlation are on the order of hundreds of feet and form three informal Wallace members which can be correlated over the study area (see Fig. 19). They are: 1) green member, 2) cyclic member, and 3) sandy member (see Fig. 20). The lower boundary of the green member coincides with the lower boundary of the Wallace Formation. The upper boundary of the green member is defined by the lowest occurrence of bedded dolomite marking the base of the overlying cyclic member. The upper boundary of the cyclic member is not so sharp as the others. It is defined as the highest bedded dolomite involved with the multi-component cycles described on page 50. Bedded dolomite does occur higher in the section but is not a part of those cycles. The cyclic member then, is gradational with the uppermost member, hereafter designated the sandy member. The top of the sandy member coincides with the top of the Wallace Formation.

Green Member

Description. This member consists of alternating sequences of the green argillite rock type and dolomitic green argillite rock type. The base of this member is defined by the highest red argillite of the St. Regis Formation. Below this level, the green argillite is interbedded with the red argillite. Farther up in the green member, where the dolomitic green argillite first appears, it too becomes interbedded with the green argillite. So, upward in this vertical sequence, red
Figure 19. Correlation of the three informal Wallace members over the study area.
Figure 20. The members of the Wallace Formation at Big Hole Peak.
argillite is replaced by green argillite which is upward replaced by tan weathering, dolomitic green argillite. The transition in color is also accompanied by an increase in dolomite content, a decrease in the number of desiccation cracks and an increase in the number of intercalated sand beds of the lenticular, crosslaminated rock subtype.

The thickness of dolomitic and non-dolomitic green argillite sequences ranges from 1 to 8 meters. Sand beds are up to 40 cm thick.

**Interpretation.** The sedimentary structures in the rocks of this member suggest that the depositional interface was below water, above wave base, euxinic, but occasionally subaerially exposed. The characteristics of the rock types imply that they were formed in a nearshore, but reducing, shallow water environment; perhaps a fringing terrigenous mudflat.

At this point it is helpful to discuss the fluvial depositional model for the Missoula Group presented by Winston (1978). He has identified five major depositional environments on alluvial fan, distal flat, and sea margin surfaces. The rock types, in order of increasing distance from the crystalline source rocks, are: 1) conglomerate rock type, 2) coarse, crossbedded rock type, 3) finely horizontally laminated rock type, 4) red argillite rock type, and 5) green argillite rock type. He concluded that sediments were transported by braided streams on the proximal parts of the alluvial system and as sheet wash floods on the more distal parts. As the floods moved across the distal parts of the fan en route to the "Belt Sea" they passed over flats with imperceptibly
low topographic gradients. The water slowed over these very large flats and deposited its suspended load forming the fine sand to mud couplets of the red argillite rock type nearer the land and green argillite rock type farther out in the "Belt Sea". The red color reflects oxidized ferric iron in locations where the flats were well drained, and the green color reflects ferrous iron produced where the water remained over the surface for longer periods of time and the sediments were reduced below the depositional interface. Finally, Winston stated that this model "appears to apply well with minor modifications to other fluvial units of the Belt". The St. Regis Formation is one of those units (Winston, pers. comm., 1980).

The St. Regis Formation gradationally underlies the Wallace Formation. The upper part consists of the red argillite rock type. Farther up near its top, it interfingers with the green argillite rock. In the St. Regis-Wallace transition, the red argillite passes upward into green argillite. In the lowermost green member of the Wallace, green argillite passes upward into dolomitic green argillite which is later replaced by black argillite in the cyclic member farther up in the Wallace. The sedimentary processes in these rocks suggest that this progression of rock types records a major transgression by the "Belt Sea". It is important to note that this transgression lacks any distinctive marine environments.

As mentioned earlier, I believe that the dolomitic green argillite rock type was produced by evaporative precipitation of calcium carbonate over the depositional tracts where the green argillite rock type was
developing. Dolomitization was subsequent. If, during times of "Belt Sea" supersaturation part of that tract was subaerially exposed, then it did not receive any dolomite. Conversely, the submerged portions of the tract become dolomitic (see Fig. 21).

In a model that advocates the formation of dolomite by evaporitic calcium carbonate precipitation, the more seaward, deeper water depositional tracts should be the most dolomitic. The fringing environments (red and green argillites) were not dolomitic because they were subaerially exposed during evaporation and not in contact with the "Belt Sea" by the time it reached supersaturation. When precipitation was initiated while the shoreline was still over the depositional tract of the green argillite, then the submerged portion received mud size calcite as a supplement to the normal suspended load. The mixture of chemical and terrigenous sediments was at first dominated by the latter. This resulted in production of the dolomitic green argillite. As regression continued, the mixture became increasingly enriched with regard to dolomite. Ultimately, the bedded dolomite rock type was produced.

Conversely, during times of high water stand the depositional tracts of the red and green argillite rock types were indeed covered by water, but the "Belt Sea" was undersaturated with respect to calcium carbonate, and carbonate bearing sediments were not produced.

**Cyclic Member**

**Description.** The lower boundary of the cyclic member is marked by the lowest bedded dolomite. Shortly above this, the stratigraphy is
Figure 21. Origin of the dolomitic green argillite rock type.
T₁: Green argillite is deposited on the depositional tract extending from A to C during high stand. T₂: The sea is at low stand and supersaturated with respect to calcium carbonate. But, part of the depositional tract of the green argillite has been exposed subaerially, and only A-B receives the carbonate precipitate. Transformation to dolomite is subsequent.
dominated by an orderly asymmetrical repetition of rock types, reflected in weathered profiles and accompanied by a regular vertical variation in color, composition and sedimentary structures. More than two hundred cycles, ranging from one to eight meters and averaging 4 meters thick occur in the Big Hole Peak section. In the lower part of the member the usual stratigraphic sequence of rock types in an average cycle is: 1) intraclastic conglomerate rock type, 2) horizontally laminated rock subtype, 3) green argillite rock type, 4) dolomitic green argillite rock type, and 5) bedded dolomite rock type. In the middle and upper parts of the member, the coarsely coupled rock subtype substitutes for the green argillite rock type and dolomitic green argillite rock type. In the upper part of the member, the cycles become less predictable by missing one or more of the component rock types. The sand content also increases significantly, indicating the end of cyclic sedimentation and the approach of the sandy member.

The sequence of rock types in the cycles is so extraordinarily repetitive that it is possible to abstract an "ideal" cycle (see Fig. 22). This ideal cycle is nearly identical to the ideal cycles in the Helena Formation abstracted by O'Conner (1967, p. 213) and Eby (1977, p. 50). The base of the ideal Wallace cycle is marked by a scoured surface which is paved by the intraclastic conglomerate rock type. The intraclastic conglomerate is covered by the horizontally laminated rock subtype which is, in turn, succeeded by the green argillite and dolomitic green argillite rock types in the lower cycles and coarsely coupled rock subtype in the middle and upper cycles.
Figure 22. Abstracted ideal cycle from the cyclic member of the Wallace Formation with four depositional phases. Phase 1: Expansion of the Belt Lake and deposition of intraclastic packstone and horizontally laminated sand. Phase 2: Continued expansion and deposition of offshore fine sand, silt and clay. Phase 3: Contraction of Belt Lake and deposition of both chemically precipitated carbonate (now dolomite) and terrigenous fine sand, silt and clay. Phase 4: Continued contraction and rapid deposition of carbonate (now dolomite). Terrigenous sediments are minor. Maximum contraction results in the subaerial exposure of the carbonate dominated sediments.
All three of these contain intercalations of the lenticular, cross-laminated rock subtype, which is common in cycles containing the dolomitic green argillite rock type, but most abundant in those containing the coarsely coupleted rock subtype. Eventually, all three of these rock types grade upward into the bedded dolomite rock type. The top of the bedded dolomite interval is capped by local depressions filled with solution collapse breccia and thin beds of wavy cryptagalaminate which is cut by desiccation cracks that are filled with sand at the base of the overlying cycle.

The transition between the lower, terrigenous rock types and the upper, dolomitic rock types is marked by a gradational zone, 0.5 to 1.5 meters thick, in which nondolomitic lithologies become dolomitic and pass upward to dolomite. Generally, the terrigenous part of the cycle becomes thicker northwestward; at the Clark Fork section, bedded dolomite is relatively uncommon.

Finally, molar tooth structures are systematically distributed within the ideal cycle. Ribbons occur most commonly in the lower part of the cycle, pods in the transition zone, and ribbons and blobs in the upper part. O'Conner (1967) found a similar sequence of molar tooth structures in the Helena cycles, but Eby (1977) did not.

Interpretation. (Refer to Fig. 23 for a model of cyclic deposition). The "ideal" cycle represents rapid expansion of the "Belt Sea" followed by slow contraction. Expansion is documented by the development of an edgewise flat pebble conglomerate. Since the scoured surface underlying this distinctive rock type represents an erosional diastem, it is
$T_1$  
\[ \text{SEA LEVEL} \quad \text{STRANDLINE} \quad \text{DEPOSITIONAL SLOPE} \]

$T_2$  
\[ \text{SURFACE OF MIGRATION} \]

$T_3$  
\[ \text{ZONE OF COMPACTION AND LITHIFICATION} \]

$T_4$
difficult to say if the erosion took place during the rapid advance of the strandline or if it occurred while the "Belt Sea" was drawn down and the dolomite was exposed to surface runoff. During the fastest rises in sea level and accompanying migrations of the shoreline, no pieces of the dolomite were ripped up. During slower rises in sea level, pieces of the bedded dolomite rock type of the preceding cycle were ripped up and deposited as recumbent flat pebble conglomerates. The slowest expansions of the sea produced beach rosettes. The intraclasts were unbent, indicating lithification prior to rip-up probably by cementation or desiccation. However, the presence of desiccation cracks in the dolomite beds suggests that desiccation was responsible for their rigidity during transportation, deposition and subsequent compaction. Further, the presence of the molar tooth hash rock subtype which is devoid of dolomitic intraclasts, at the bases of some cycles suggests that the dolomitic sediments were still muddy when traction currents scoured the substrate, and eroded and concentrated the molar tooth fragments during expansion. In conclusion, most of the scouring probably accompanied expansion and, surface runoff during periods of low sea stand was possibly negligible because the fluvially dominated rock types did not prograde out over the subaerially exposed carbonate mud flats.

After deposition of the intraclastic conglomerate, horizontally and subhorizontally laminated sands were deposited in the swash zone. As lake expansion proceeded, these sands were covered by the sublittoral
zone and were rippled. Further expansion put the depositional locus farther out to sea. Here, suspended load and traction load sedimentation of terrigenous fine sand, silt and clay created the green argillite rock type, dolomitic green argillite rock type or the coarsely coupled rock subtype. The organic content of the coarsely coupled rock subtype indicates that the "Belt Sea" was stratified; it is clear that oxygenated water lay over deoxygenated water. The oxygenated layer supported a photosynthetic microbiota and, upon death, the remains settled to the bottom which was a favorable site for the preservation of organic matter. Silt and clay were brought from either the marginal strandline area, or, by reworking from the bottom farther seaward.

As mentioned earlier, the middle part of a cycle becomes dolomitic. I believe that this lithologic inflection point records the initiation of evaporative contraction. Concurrent with "Belt Sea" shrinkage was the concentration of its dissolved salts. Eventually, the water of the sea reached the point of supersaturation and calcium carbonate precipitated. As the mud sized precipitate accumulated on the sea floor, it was dolomitized as evidenced by its extremely fine grain size and selectivity. Several other features also point to early dolomitization. First, the matrix of packstones and grainstones containing molar tooth fragments is dolomitic whereas the fragments remain pure calcite. In fact, molar tooth structures "in situ" are nondolomitic even where the host sediment is dolomitic. The dolomitization event, therefore, must predate the episodes of scouring and formation of the molar tooth hash
rock subtype. This interpretation of early dolomitization is further supported by the fact that dolomitic rocks show no tendencies towards obliteration of primary structures and textures. Finally, Eby (1977) noted that in the Helena Formation carbonate mudstones are generally dolomitic while the more porous and permeable grainstones (oolitic and nonoolitic) are not.

In the upper part of the "ideal" cycle, the amount of siltstone in the coupled lithologies decreases significantly, and eventually, the claystone content drops too. One particularly appropriate explanation for this follows. 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. Accordingly, low stands of the "Belt Sea" correspond to climatically dry periods and high stands correspond to wet periods of the hydrographic province which surrounded the intracratonic sea. Thus, when the "Belt Sea" was drawn down, the clastic influx was negligible and terrigenous sediments did not prograde out over the exposed carbonate mud flats.

The top of the "ideal" cycle is capped by solution collapse breccia and thin, wavy cryptalgalaminate with a fenestral fabric that is split by desiccation cracks. These deposits were laid down in the littoral or supralittoral zone during the last stages of sea contraction. Ultimately they were subaerially exposed, dried and cracked. Some
atmospheric precipitation resulted in the dissolution of the more soluble salts.

Toward the top of the cyclic member, the amount of the bedded dolomite decreases and the amount of the lenticular, cross laminated rock subtype increases. The significance of this will be considered in the discussion of the sandy member.

The lower terrigenous parts of these cycles indirectly reflect numerous expansions of the "Belt Sea" by directly recording the advance of the strandline and contiguous, coeval environments in the sense of Walther (1894). On the contrary, the bedded dolomite does not represent a migratory environment on the sea floor, but a change in the hydrochemistry of the "Belt Sea". The bedded dolomite rock type "blankets" all other rock types and did not migrate; it was precipitated across the supersaturated parts of the basin during an imperceptibly short geologic time interval. Therefore, the units of bedded dolomite are chronostratigraphic.

O'Conner (1967) and Eby (1971) described cycles from the Helena Formation with terrigenous bases and dolomite tops. These cycles compare extremely closely with Wallace cycles. They noted, independently, that the terrigenous components of the cycles thickened considerably from east to west but that the dolomite components remained uniformly thick in all directions. This evidence supports the time-stratigraphic interpretation of these bedded dolomite intervals.

All the rest of the rock types in the cycles are time-transgressive and are part of a depositional system that migrated in response to
fluctuations in the level of the "Belt Sea". However, the rate at which these units transcend time must be very low. The amazing lateral continuity of even the thinnest beds suggest that the topographic gradient of the "Belt Sea" - alluvial plain complex was exceedingly low. Therefore, the slightest rise in sea level caused rapid transgression and thus moved the depositional environments very quickly.

In more than 200 expansional and contractional sequences in the cyclic member no marine environments are evident. Absent are: tidal channels with large scale bed forms and epsilon crossbedding and tidal flats with 1) bimodal cross-stratification, and 2) the common simultaneous occurrence of large-scale and small-scale bed forms in super- or juxta-position. A lagoonal origin could be argued for the coarsely coupled rock subtype. However, there are no barrier island deposits which would include: barrier beach, tidal delta, tidal channels and intertidal zone.

The Belt basin is elongate in the NW-SE direction. If the "Belt Sea" were a marine system, then the tidal currents should have been stronger than along normal coastlines and should have been more like the Bay of Fundy where geographic funneling of the tides increases their velocity.

In conclusion, there is no reason to believe that the "Belt Sea" was marine. On the contrary, the characteristics of the rock types and their vertical sequence suggests that the "Belt Sea" was actually an enormous inland sea during Wallace deposition. The Wallace Formation shares the following in common with other lacustrine deposits:
laterally persistent bedding, thin bedding, graded sedimentary couplets, extensively disturbed bedding, small-scale crossbedding, abundant evidence of synaeresis, abundant cyclical carbonate sequences, and salt casts (Klein, 1962b; Picard and High, 1972).

Lithologically, the cyclic member shares many features in common with the following lacustrine sequences: the Eocene Green River Formation of Wyoming (Bradley, 1931; Surdam and Stanley, 1979; Desborough, 1980), Early Cretaceous Peterson Limestone of Western Wyoming and Southeastern Idaho (Glass and Wilkenson, 1980), Triassic Lockatong Formation of New Jersey and Eastern Pennsylvania (Van Houten, 1964), Permo-Pennsylvanian Dunkard Group in Pennsylvania, West Virginia and Ohio (Beerbower, 1961), and Mississippian Albert Shale of New Brunswick (Greiner, 1962).

The climatic interpretation for the Wallace cycles is of great support to the overall lacustrine Wallace interpretation. Picard and High (1972) state "although such cycles are also found in marine units, the smaller size of lakes makes them more responsive to climatic (or tectonic) changes. Thus, local fluctuations that would cause only minor changes in marine regimes can lead to widespread and significant alterations in lacustrine deposition." Phanerozoic climatic, cyclic lacustrine sedimentation has been well documented from both the Lockatong Formation and Green River Formation. The Wallace cycles share a large number of similarities with the cycles from those two sequences of rocks. A comparison of the similarities and differences found between the three sets of cycles is compiled in Table 1.
<table>
<thead>
<tr>
<th>CHARACTERISTIC</th>
<th>GREEN RIVER FORMATION</th>
<th>LOCKATONG FORMATION</th>
<th>WALLACE FORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>THICKNESS (AVG.)</td>
<td>2 METERS</td>
<td>9 METERS</td>
<td>4 METERS</td>
</tr>
<tr>
<td>TOTAL NUMBER</td>
<td>16</td>
<td>80</td>
<td>200</td>
</tr>
<tr>
<td>SEQUENCE OF ROCK TYPES FROM TOP OF CYCLE TO BOTTOM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DESICCATION CRACKED, DOLOMICRITE, COMMONLY INCLUDING SALINE MINERAL CASTS AND MOLDS AND/OR MAGADI-TYPE CHERT</td>
<td></td>
<td>DESICCATION CRACKED, CARBONATE AND ANALCIME RICH MASSIVE MUDSTONE</td>
<td>DESICCATION CRACKED, DOLOLUTITE AND DOLOMICRITE, LOCAL SOLUTION COLLAPSE BRECCIA, AND CRYPTALGALAMINITE</td>
</tr>
<tr>
<td>RIPPLE CROSS-LAMINATED SANDSTONE OR KEROGEN</td>
<td></td>
<td>SYNAERESIS CRACKED, INTERBEDDED BLACK TO DARK GRAY DOLOMITIC AND CALCITIC MUDSTONE</td>
<td>SYNAERESIS CRACKED, DOLOMITIC DARK GRAY SILTSTONE AND CLAYSTONE</td>
</tr>
<tr>
<td>RICH LAMINATED CARBONATE, COMMONLY SYNAERESIS CRACKED</td>
<td></td>
<td>DOLOMITIC SILTY MUDSTONE WITH IRREGULAR LAMINAE AND SYNAERESIS CRACKS</td>
<td>INTERLAMINATED FINE SANDSTONE, SILTSTONE AND CLAYSTONE</td>
</tr>
<tr>
<td>FLAT PEBBLE CONGLOMERATE OVERLAIN BY STROMATOLITES AND OOLITES</td>
<td></td>
<td>BLACK AND GRAY MUDSTONE</td>
<td>INTRACLASTIC CONGLOMERATE OVERLAIN BY HORIZONTALLY LAMINATED SANDSTONE</td>
</tr>
<tr>
<td>ADJACENT ALLUVIAL ROCK TYPES</td>
<td>GREEN MUDSTONE AND RED MUDSTONE</td>
<td>REDDISH-BROWN MUDSTONE</td>
<td>RED ARGILLITE</td>
</tr>
<tr>
<td>CAUSE OF CYCLIC SEDIMENTATION</td>
<td>CLIMATIC FLUCTUATIONS</td>
<td>CLIMATIC FLUCTUATIONS</td>
<td>CLIMATIC FLUCTUATIONS</td>
</tr>
</tbody>
</table>

Table 1. Comparison of various aspects of the lacustrine sedimentary cycles from the Green River Formation (Surdam and Stanley, 1979), Lockatong Formation (Van Houten, 1964) and Wallace Formation (Grotzinger, this study).
Sandy Member

Description. The base of the sandy member is characterized by an increase in the amount of the lenticular, crosslaminated rock subtype and a decrease in the bedded dolomite rock type. This grades upward into the middle sandy member which is mostly thick sequences of the tripled rock subtype with occasional intercalations of the lenticular, cross-laminated rock subtype and rare occurrences of the bedded dolomite rock type. At the Clark Fork section, the amount of sand increases dramatically and is interstratified with two large lenses (1 m x 50 m) with mostly horizontally laminated fine to medium size sand. Ripple crosslamination in those two lenses is rare and some of the sand is massive and ungraded.

The uppermost part of this member, in all sections, is marked by the microlaminated rock subtype in alternating sequences with the coarsely coupled rock subtype. Stromatolites occur locally in the microlaminated rock subtype.

Interpretation. The thick sequences of the tripled rock subtype represent an environment in which turbidity currents alternated with pelagic sedimentation. The intercalated sands of the lenticular, cross-laminated rock subtype and the sands at the bases of the tripled rock subtype are broken into sedimentary boudinage (see Fig. 7). In the classification scheme of Godlewski (1980), penecontemporaneous sedimentary features are "grouped into regimes on the basis of the dynamics of deformation that led to their form". Since no compressional or passive structures such as soft sediment folds, breccias or slumps were seen, and
since sedimentary boudinage is placed in the tensional regime, the environment of deposition probably represented the upper and middle parts of a slope.

The high sand content indicates that the most northwestern Clark Fork section was closest to the sand source. Also, sublacustrine distributary channels, recorded as the large sand lenses, ushered the sand to the topographically lower parts of the sea floor. These channel deposits compare closely with modern sublacustrine distributary channels from Lake Geneva, Switzerland (Reineck and Singh, 1975) which are composed of horizontally laminated fine to medium sand that lacks small or large scale crossbeds. The massive sandstone beds also support this interpretation. Modern massive sands are commonly formed by the rapid deposition of a large amount of sand from fluidized flows (Middleton and Hampton, 1976).

Finally, the intercalations of the lenticular, crosslaminated rock subtype indicate that intrabasinal, circulatory currents played an important role in the distribution of the sand to the fringing environments of the sea.
CHAPTER IV
SYNTHESIS

The Wallace Formation represents a major transgression and regression of an intracratonic sea in a fault block basin. The lacustrine Wallace deposits spread over sea margin argillites of the St. Regis Formation which overlie the fluvial quartzites of the Revett Formation. Transgressive sediments comprise the green member, cyclic member and lower and middle parts of the sandy member. Regression is represented by the upper part of the sandy member.

The initial deposits of the transgressing lacustrine environment were green argillite and dolomitic green argillite which spread across extremely broad flats where they were mud cracked mostly by synaeresis but less commonly by dessication. Occasional longshore currents spread thin sand sheets across parts of these flats as evidenced by the intercalations of crosslaminated sand. The sea was shallow, stratified, and sediments accumulated on very broad, flat depositional surfaces above and below wave base. After the sea became well established, the climate began to influence sedimentation strongly. Alternating humid and arid climatic periods rapidly expanded and contracted the sea many times. Each expansion and contraction produced shoaling upwards cycles which were superimposed on the continuing major transgression.
The onset of each cycle marked the expansion of the sea during humid periods and increased inflow of fresh water. As the sea level rose, the strandline quickly migrated over the nearly flat, exposed carbonate and terrigenous mud flats forming intraclastic lag and horizontally laminated sand deposits. The flooded sea floor then received layers of silt, clay and organic debris. Sulphate was reduced by bacteria to form pyrite. 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. Chemicals from a crystalline source area were concentrated and precipitated in the sea by evaporation of the sea water. First, mud sized calcium carbonate was precipitated and immediately dolomitized to form beds of dolomite. Later, crystals of halite grew in the sea and fell to the bottom where they continued to grow in the interstices of the sediment. Simultaneous, evaporitive pumping of the exposed mud flats generated ephemeral salt crusts on the depositional tracts occupied by the red argillite but did not dolomitize those sediments. Gypsum and anhydrite were uncommon because sulphate was immediately reduced to form pyrite.

As the major transgression continued, Wallace sediments of the area accumulated below wave base on what was probably the upper and middle parts of a slope forming the lower and middle parts of the sandy member. The top of the Wallace records the return to shallow water deposition and the onset of a major regression in the Belt Supergroup. However, the absence of cyclic sequences indicates that the climate did not so
strongly influence sedimentation as it did during the deposition of the cyclic member. Occasionally, the sea evaporated enough to produce dolomite beds, but this was much less common than before. Continued regression resulted in eutrophication of the sea. Stromatolites developed and the water column became exceptionally rich in photosynthetic microorganisms. This produced sequences of very pure kerogen films. The sea bottom was still oxygen deficient and sulphate reducing bacteria produced much pyrite.

The demise of the "Belt Sea" is recorded by the progradation of the sea margin systems of the Snowslip Formation over the last sea beds.

Later episodes of lacustrine sedimentation may be represented by the carbonate rocks of the Shepard Formation and Mount Shields Formation above the Wallace. An earlier episode of lacustrine sedimentation may be represented by the Prichard Formation below the Wallace.
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APPENDIX A

SYNAERESIS IN THE WALLACE FORMATION
General Statement

The focus of this appendix centers on the description, illustration and interpretation of several varieties of penecontemporaneous deformation that characterize many of the Wallace rock types. I hope that this small glossary will serve as a reference for future comparisons of Wallace rocks with other Belt rocks as well as with rocks of other province.

Synaeresis Cracks

Synaeresis cracks are common in the green argillite, dolomitic green argillite, and black argillite rock types of the Wallace Formation. These structures appear to be inherent features of these rock types and occur in similar rock types found elsewhere in the Belt section.

Generally, couplets of siltstone and claystone have complexly cracked surfaces with shrinkage crack-casts that are filled with the silt of fine sand of the succeeding couplet. Individual casts are intricately crumpled and anastomose downward (see Fig. 24). Many cracks were filled from above but some were filled from below, suggesting that much of the shrinkage resulted from synaeresis after burial (see Fig. 25). Some silt filled cracks now "float" in a matrix of claystone (see Fig. 26). Commonly, these cracks lack a systematic relationship to bedding surfaces and seem to originate from several horizons unlike subaerially formed shrinkage cracks which all originate at the same horizon. Also, there is no evidence for curling of the claystone layers or for reedimentation of dried polygons. Further, the cracks stand up
Figure 24. Intricately crumpled synaeresis crack.
Figure 25. Synaeresis crack filled from below.
Arrow points to crack.
Figure 26. Silt filled synaeresis cracks floating in clay.
as sharply defined ridges above the upper surface of the cracked bed and occasionally penetrate the overlying bed, indicating that the greater compaction of the claystone layers has caused the less compactible sandy and silty mud-crack fillings to protrude above the mud-cracked surfaces as small dike-like ridges (see Fig. 27). Protruding mud crack fillings are generally not associated with desiccation cracks.

**Horizontal Deformation**

Many of the synaeresis cracks are now stretched or offset a few millimeters by shearing parallel to bedding. On a greater scale, soft sediment overthrusting has displaced silt laminae by a few centimeters (see Fig. 28) and occasionally, resulted in recumbent folds (see Fig. 29).

**Vertical Deformation**

Related to all of the dewatering features described above are zones of vertical micro-faulting and brecciation. The vertical microfaults generally offset strata by only a few millimeters. The zones of vertical brecciation generally disrupt the thicker (1-3 cm) silt and fine sand beds (see Fig. 30) or break upward and form brecciated dewatering dikes that are approximately perpendicular to the bedding. The large scale water escape structures occur along with water escape structures on a microscopic scale.

**Other Forms of Synaeresis**

These rather ubiquitous forms of dewatering include micro-dish structures and zones that look like burrows (see Fig. 31).
Figure 27. Plan view of synaeresis cracks protruding above bedding plane. Nickel for scale in top picture.
Figure 28. (Top picture) Soft sediment overthrusting. Arrows show relative movement.

Figure 29. (Bottom picture) Soft sediment recumbent folding. Folding probably resulted from movement by overriding thrust sliver. Arrows show relative movement.
Figure 30. Vertical zones of brecciation. Top picture has part of a lens cap at the bottom for scale.
Figure 31. Ubiquitous forms of synaeresis.
Top: micro-dish structures.
Bottom: Dewatering structure that looks like a burrow.
Conclusion

I believe that the characteristics of these interesting structures indicate that the sediments were deformed after burial, during dewatering and compaction. Similar features of synaeresis occur in the Triassic Lockatong Formation (Van Houten, 1964), Cretaceous Peterson Limestone (Glass and Wilkinson, 1980), Eocene Green River Formation (Bradley, 1930), Cretaceous Dakota Sandstone (Shelton, 1962), Triassic Edderfugledal Member (Clemmensen, 1978), Proterozoic Rocknest Formation (Hoffman, 1975), and Proterozoic Dismal Lakes Group (Donaldson, pers. comm., 1981).
APPENDIX B

HALITE CRYSTAL CASTS IN THE WALLACE FORMATION
Some of the most fascinating sedimentologic features of the Wallace Formation are the enormous hopper-shaped halite crystal casts at the Graves Creek Section. These occur in the coarsely coupleted subtype of the black argillite rock type.

They occur mostly as separated crystal casts with maximum dimensions of up to 10.5 cm that cut both sand and mud laminae (see Fig. 32). Casts shapes are cubic, rhomboid or rectangular and in most casts, the "face" is oriented parallel to bedding. Uncommonly, cast apices point upward through the bedding (see Fig. 33) and some apices protrude out into the sediment beyond the main body of the cast (see Fig. 34).

Regardless of the cross sectional geometry of the cast, the major three dimensional form of the casts is hopper-shaped. This growth form can be promoted by two different processes. Dellwig (1955) described the formation of hopper crystals of halite by evaporation and concentration at the surface of a brine body. When growth is initiated at the air-water interface, the crystal sinks under its own weight but is suspended by surface tension. Further growth proceeds upward and outward along the edges which results in an inverted, hollow pyramid. The crystal is then in part suspended by surface tension and in part by its own displacement of the brine. As an alternative, Raup (1970) showed that halite crystals with hopper shapes could also develop within a brine body by mixing solutions with different compositions and specific gravities.
Figure 32. Two halite crystal casts with touching corners.
Figure 33. Cross section of cast corner parallel to bedding.
Figure 34. Protruding apices of crystal casts. Arrows point to the extension beyond the main body of the cast.
In both models, the hopper crystals eventually settle to the bottom where they may continue to grow by the accretion of halite overgrowths. Because the apices grow at a faster rate than the edges and faces, they often protrude out into the sediment as described earlier. This has been described from the Dead Sea (Neev and Emery, 1967) and from the Helena Formation (Eby, 1977). Eby (1977) additionally pointed out that to preserve such perfect impressions would have required very unusual conditions. Either the sediment and overlying brine were unaffected by traction currents or wind disturbance, or the brine bodies in which the hoppers grew existed as "small, isolated and undisturbed pools on an arid mud flat". Because the Helena hoppers Eby observed were preserved in dolomitic mud, either explanation is plausible. However, all of the Wallace hoppers I observed were preserved in fine sand with minor amounts of silt and mud. Commonly, these sands are cross-bedded and are interpreted to have accumulated subaqueously under the influence of traction currents. This suggests that dissolution of the halite crystals and formation of the crystal casts occurred after deposition of the salt and sediment, below the depositional interface. Thus, the crystal casts were preserved in an environment where traction currents were active.
Figure 35. Concentric hopper structure in square (top) and rectangular (bottom) crystal casts.
KEY

GRAYISH RED QUARTZITE/CLAYSTONE
GREEN SILTSTONE/CLAYSTONE
BLACK SILTSTONE/CLAYSTONE
QUARTZITE
SEDIMENTARY SHOALING UPWARD CYCLES
MUDCRACKS
MUDCHIPS
COVER (<100 FT.)
COVER (>100 FT.)
Big Hole Peak Section

Green, slightly dolomitic, siltstone/claystone. Horiz. lam., v.vv., v.f. to med. couplets.

Green, slightly dolomitic, siltstone/claystone, v.vv., und. bed., pyrite cubes, coarse to med. couplets.

Wallace Fm.
St. Regis Fm.
Reddish-gray, quartzite/claystone, v.vv., horiz. lam.
Cycles (Type I). Intrabasaltic packstone, overlain by horizontally laminated v.f.g. sandstone, overlain by non-dolomitic light gray to black siltstone to claystone couplets, overlain by dolomitic light gray to black siltstone to claystone couplets. Cycles are separated by scarred surfaces.

Black and light gray to white, claystone/v.f.g. quartzite, horiz. lam., ripple x-lam., v.v.v. Non-dolomitic. Pyrite cubes.

Silty dolomite bed w/ lenticular bedding.

Green, non-dolomitic siltstone/claystone. Horiz. lam., v.v.v., v.v.v., fine couplets, increased percentage of claystone.

Silty Dolomite. Cross laminated, v.v., cryptagalamite (?).

Several thin (>3cm) black siltstone beds.

Dolomitic, v.f.g., quartzite. Horizontally laminated.
Cycles, Type 2

black to light gray, claystone/siltstone (with molar tooth ribs)

First Molar Tooth (vertical ribs)

Cycles, Type 2. Intraclast packstone, overlain by green, non-dolomitic siltstone/claystone, overlain by dolomitic siltstone/claystone, overlain by silty dolomite.
Cycles: Type 2. Siltstone/claystone is green. Molar tooth structures include: vertical, horizontal ribbons, horizontal pods, and blobs.

Black, dolomitic claystone. Horizontal pods, vertical ribbons.

Cycles: Type 2. Siltstone/claystone is green.
Cycles. Type 2. Horizontal pods very common at the level in a cycle where the sediments become dolomitic.

Green, non-dolomitic, siltstone/claystone; med. caplets, horizontal pods. VVV, 11.1.

Interbedded white, v.f.i. quartzite and green siltstone. Non-dolomitic, horizontally laminated, VVV.

Cycles. Type 2
cycles. Type 2. The basal packstone is now mostly composed of reworked molar tooth fragments. The horizontal pods are generally found in the level of the cycle where the sediments become dolomitic. Pyrite cubes are common. Siltstone/claystone is green.
Cycles. Type 2. Siltstone/claystone is green, but upwards in the sequence, becomes grayish.

Green, non-dolomitic siltstone/claystone. VV/V.

Cycles. Type 2. Siltstone/claystone is green. The tops of dolomite beds do not contain molar tooth structures. Otherwise, horizontal pods, vertical ribbons and blobs are common.
Cycles. Type 2. Siltstone/claystone is now light gray to black. Molar tooth structures include vertical ribbons, horizontal ribbons, blobs and pods. Couplets are medium to coarse.

← possible soft sediment folds.

← First dark siltstone/claystone (light gray to black).
Cycles. Type 2. Siltstone to claystone couplets are light gray to black. Molar tooth structures appear to be specific to certain positions in the cycles. The succession is, from cycle to top: horizontal pods, vertical ribbons; horizontal ribbons, blobs and then, at the top, no molar tooth structures at all.
Cycles. Type 2. Siltstone to claystone couplets are light gray to black, medium to coarse in thickness. The amount of sand appears to be increasing at the base of each cycle.
Cycles: Type 2. Siltstone to claystone couplets are light grey to black. Top of dolomite bed has desiccation cracked cryptagalaminite. Ripple cross beds very well developed. Ball and pillow structures very well developed in dolomite.
Cycles. Type 2.

Interbedded siltstone to claystone couplets (light gray to black) and white, horizontally or cross-laminated U.F.G. sandstone. Couplets are coarse to very coarse in thickness.

Cycles. Type 2. Siltstone to claystone couplets are light gray to black and of medium thickness.
Cycles. Type 2.

Light gray to black siltstone to claystone couplets. Fine to medium thickness.

Interbedded light gray to black siltstone to claystone couplets and white, ripple cross laminated sand.

Horizontally laminated & cross-laminated white sandstone.

Cycles. Type 2. Dark gray to black siltstone to claystone couplets. Medium thickness.

Interbedded white U.F.G. sandstone and dark gray to black siltstone/claystone graded couplets. vvv, vvv.
Cycles, Type 2. Light gray to medium gray siltstone to claystone couplets. Medium thickness.

Molar tooth structures include horizontal pads where the cycles become dolomitic, overlain by vertical ribbons and then pools. The tops of cycles are devoid of molar tooth.
Cycles, Type 2

Cover

Cycles, Type 2. Pyrite cubes abundant.

← Starved ripples.
Cycles. Type 1. Interbedded horizontally laminated white sandstone (w.s.g.) and gray to white siltstone to claystone couplets. Dolomite beds are less common in these cycles than in Type 2 cycles. Molar tooth structures are common and have a random distribution. Bedding in the sands is usually tabular but can be lenticular. Ripple cross laminae are common, as well as mudcracks and pyrite cubes.

Cycles. Type 2.
Cycles. Type 2. Light gray to black siltstone/claystone. Cycles. Type 1. Light gray to black siltstone to claystone couplets.  

Dolomite beds are more common.
Cycles, Type 2. Couplets are light gray to black siltstone to claystone of fine to medium thickness.

← very well developed climbing ripples in dolomite.

← interbedded, gray siltstone to claystone couplets and white cross laminated quartzose sandstone, non-dolomitic.

← slightly dolomitic, gray, siltstone to claystone

← interbedded, gray siltstone to claystone couplets and white cross laminated quartzose sandstone, non-dolomitic

Cycles, Type 2. Well developed molar tooth.
Cycles. Type 2. Light gray to black siltstone to claystone couplets. Medium thickness.

Light gray to black siltstone to claystone couplets. Medium to coarse thickness. Slightly dolomitic. Intercalated, lenticular u.t.g. sandstone beds.
gray to black, non-dolomitic siltstone to claystone couplets.

transitional

non-dolomitic white, cross laminated, u.f.g. quartzite.

sandy member

Cyclical member

Cycles. Type 2. Poorly developed. Usually missing either horizontally laminated sandstone, or non-dolomitic siltstone/claystone.

gray to black, dolomitic, siltstone to claystone couplets. Fine thickness of couplets.

increasing amount of dolomite

non-dolomitic, interbedded, white, cross laminated u.f.g. quartzite and gray to black siltstone to claystone couplets.

Covered
Covered

Last molartoof pods. Silty dolomite.

Increasing dolomite content.

dark gray to black siltstone to claystone couplet. Medium to coarse thickness. Generally non-dolomitic, no intraclast beds.
Coarse textures.

94 to block, silts from clay to clay (transitions of medium to

... Sandy interval. Ripple cross-laminated

... Sandy interval! Grade into siltstone! Claystone

... Fining upwards

... Dolomite bed

... Thickness

... Gravel to block, siltstone to clay shale, clayshales of common

... Sharp contact

... Sandy, cross-laminated interval

... Fining upwards
Sequences of cross laminated white quartzite, graded siltstone to claystone that fine upward are common. The sand beds frequently exhibit "pull-apart" structures. Mudcracks are common in the siltstone/claystone beds.
Starting here, most sand intervals are sharply bounded and exhibit both horizontal and ripple cross laminations. Poll apats are very common, fining upwards sequences are less common. Pyrite cubes are common. First occurrence of the tripled rock subtype.

← sandy interval. Sharp bounded.

fining upwards

← sharp boundary
Interbedded white, horizontally laminated
u.f.g. quartzite and gray to black, coarsely
cemented siltstone and claystone. Mudcracks
and pyrite cubes are very common. Commonly,
and interval of thin, epiclastic dolomite siltstone separates
the terrigenous silt from the black argillite. These
sediments then form triplets. The black argillite sharply
overlies the dolomite silt.
microlaminated siltstone and claystone.

possible stromatolites, discrete hemispheroids (2).

dark gray to black siltstone to claystone couplets.

---

first occurrence of the microlaminated rock subtype.

dark gray to black siltstone to claystone couplets, fine to medium scale.
black to light gray, siltstone to claystone couplets

mostly microlaminated black siltstone / claystone, with some coarsely cobbled siltstone / claystone interbeds. Abundant pyrite cubes and mudcracks. Dolomitic
Interbedded white, cross laminated; horizontally laminated r.f.g. sandstone and gray to black siltstone to claystone couplets of medium to coarse thickness.

---

- micro laminated, black siltstone and claystone.

---

Light gray to black siltstone to claystone couplets interbedded with white, cross laminated white sand.
dolomite bed with cryptalgalaminite (?).

Interbedded white v.f.g. quartz and gray to black siltstone to claystone coupled. Non-dolomitic

dolomite bed. Possible stromatolite (?)

dark gray to black siltstone to claystone couplets. Fine to med. thickness. Abundant nodules & pyrite cubes

dolomite bed. Well developed cross laminations.
Interbedded micro-laminated (black siltstone/claystone), light gray to black siltstone to claystone cahlets, horizontally and cross-laminated u.f.s. quartzite, and silty dolomitic. Pyrite cahes are common, molar tooth structures are rare, and mudcracks are very common. Dolomitic in part.

increasing dolomite
microlaminated siltstone/claystone couplets, dolomitic

sandy interval

light gray to black siltstone to claystone couplets. Couplets are fine to coarse thickness. Abundant pyrite cubes and mudcracks. Dolomitic
TOP OF SECTION (200 ft. above this mark are the green siltstones and claystones of the Snowslip Formation)

Dark green siltstone to claystone couplets. Pyrite cokes and mudcracks. Slightly dolomitic.

Snowslip Fm.
Wallace Fm.

Gray to black siltstone to claystone couplets. Fine to coarse thickness. Pyrite cokes, mudcracks, slightly dolomitic.
Graves Creek Section

Interbedded orange weathering dolomite and green siltstone/claystone.

- First dolomite bed, massive, first horizontal pods (molar tooth)

Interbedded green claystone and green siltstone to claystone couplets. Dolomitic. Pyrite cubes, ripple marks, cross-laminated.

- Ripple marks
- Sandy bed
- First pyrite cubes (1-3 mm)

Dolomitic, green, siltstone to claystone couplets, shows both cross-laminations and horizontal laminations.

- Sandy interval, u.f.g. quartzite, horizontally laminated
- Well developed climbing ripples

Wallace Fm.
St. Regis Fm.

Interbedded reddish gray quartzite/claystone and greenish red siltstone/claystone. Non dolomitic.
Quartzite (u.f.g) / siltstone (dolomite) / claystone triplets. Usually, 2 cm sand, 2-3 cm silt, 1-2 cm clay.

Green, dolomitic siltstone / claystone couplets. Fine to medium thickness.

Silty dolomite. Thin bedded and muddy at times. No meter tooth. Abundant pyrite cubes (2 mm).

Green, dolomitic siltstone / claystone. Each couplet is mostly claystone. Varying dolomite concentrations. Horizontal pods.
Cycles, Type 2. Very well developed, with superimposed cyclic order of molar tooth types which is: Horizontal pods at dolomite transitional zone, overlain by vertical ribbons, then blobs.

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First vertical ribbons, and blobs (molar teeth) and more horizontal pods.

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Interbedded white, horizontally bedded v.f.g. quartzite and green siltstone to claystone couplets.

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Cross laminated dolostone. Gray to black siltstone to claystone couplets, fine to coarse thickness. Pyrite cubes.

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Intrabedded bed with sand. Clasts are non dolomitic, 10 cm long (max).

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Interbedded green siltstone to claystone couplets and laminated dolomite. Pyrite cubes. Horizontal pods.
very large halite crystal casts. Up to 10cm across. Hopper shaped. Some are square, others rectangular, others rhombohedral.

Cycles. Type 2. Light gray to black siltstone to claystone couplets. Fine to medium thickness. Pyrite cubes, mud cracks, salt casts, molar tooth.

Well developed symmetrical ripples in sandy part of cycle.
Cycles, Type 2.

- well developed scour-fill erosional surface at boundary between top of cycle and bottom of next.

- Beautiful symmetrical ripples with very well developed cross-hatched laminae. Also climbing ripples farther up in the bed.

Cycles, Type 2. Abundant mole tooth structures.
Interbedded white quartzite and grey to black siltstone to claystone couplets.

Cycles. Type 2.

Interbedded, white, cross-laminated/horizontally laminated u.f.g. Quartzite and light grey to black siltstone to claystone couplets. Slightly dolomitic.
Cycles. Type 2.

Possible stromatolites. Lateral linked hemispheroids (?).

Slightly dolomitic, light gray to black siltstone to claystone couplet.

Cycles. Type 2.

Interbedded white and thin (>5mm) beds of black claystone. Non dolomitic.
Cycles. Type 1

Cycles. Type 2

dolomite with blobs and vertical ribbons

Cycles. Type 2

Gray to black siltstone to claystone couplets. Slightly dolomitic. Coarse thickness
Fining upwards sequences of horizontally laminated or cross-laminated u.f.g. quartzite, and gray to black siltstone to claystone couplets.

Small outcrop shows interbedded white, non dolomitic, u.f.g. sandy mbr., quartzite and dark gray to black siltstone to claystone couplets. Cyclic mbr.

Cycles. Type 2. Sandy parts of cycles are becoming thicker than below.
Microlaminated blade siltstone to claystone, zones of horizontal brecciation, vertical brecciation, and folding.

First occurrence of microlaminated rock subtype.

Bestial "ball & pillow" structures.

Gray to black, non dolomitic, siltstone to claystone couplets. Fine to very coarse thickness. Also, some triplets with dolomite silt laminae separating the parts of the couplets.

Interbedded white, cross laminated quartz and dark gray to black siltstone to claystone couplets. Sand beds show well developed "pull-apart" structures and are sharply banded. Some couplets have dolomite silt laminae separating the terrigenous siltstone from the black claystone (triplets).

Very dolomitic black siltstone/claystone

Increasing dolomite dark grey siltstone to claystone couplets couplets are 0.5-8.0 cm thick.

Vertical & horizontal molas tooth ribbons
**TOP OF SECTION**

Sandy interval. Cross laminated.

Green siltstone to claystone couplets. Fine to medium thickness. **vvv, ***.

Snowlips Fm.

Wallace Fm.

Dark gray to black siltstone to claystone couplets. Fine to medium thickness. Vertical ribbons, **vvv**.

Green siltite to black argillite couplets. Medium thickness, blobs, **vvv**, ribbons.

Dark gray to black siltstone to claystone couplets. **vvv**, vertical ribbons. Slightly dolomitic.

Microlaminated black siltstone/claystone. Soft sediment brecciation and bedding is abundant. Pyrite coheses
Clark Fork Section

Green, dolomitic, silts tone to claystone couplets.
microlaminated to medium thickness. uuv, cross laminar, "ball & pillow" structures, dish(2) structures.

Grayish red quartzite / claystone couplets. uuv, ccl, cross-laminations.
- sandy interval.
- dolomite bed.
- possible salt casts (1).
- cryptagalamanite (1).

- first dolomite bed.

- dolomitic
  - non-dolomitic
    - dolomitic

- green, siltstone to clayey silt clays.
  - fine to medium thickness.

- sandy intervals.
Cycles. Type 2: Green siltstone to claystone couplets. Fine to medium thickness.

Cycles. Type 2: Sand beds are lenticular or tabular and contain cross laminations or horizontal laminations, respectively. No molar tooth. Green siltstone to claystone couplets in these cycles.

← first horizontal pods, "in situ".

← molar tooth fragments in intraclastic mud.
First occurrence of light gray to black siltstone/claystone.

Nice transition from horizontal laminations to cross laminations in the white quartzite of the cycle.

Cycles. Type 2. Dolomite beds in these cycles are thinner than at Graves Creek or Bighole Peak, and the sand beds are thicker.

First occurrence of vertical ribbons, horizontal ribbons and blobs. (molar tooth).
Cycles. Type 2. Siltstone to claystone cov plts are now all gray to black. Pyritic coves, and lenticular sands.
Cycles. Type 2.

Interbedded, slightly dolomitic, white quartzite and gray to black siltstone to claystone couplets.

Interbedded, dolomitic, cross-laminated, white v.f.g. quartzite and minor gray to black siltstone to claystone couplets.
Cycles. Type 2. Very sandy.

Interbedded gray to black siltstone to claystone and white quartzite, slightly dolomitic.

White quartzite, cross laminated.

- Shop sandy
Cycles: Type 2. Sandy, more dolomite than clays. Type 1. Clays, more claystone than dolomite.

Siltstone to claystone coaly.

Cyclically bedded siltstone (silty) and gray to black shop boundy.

Dolomite bed.
Cycles. Type 2. Very sandy. Dolomite beds are very thin and sandy.

Cycles. Type 2. Very sandy. Molar tooth is uncommon.

Cycles. Type 2.

- Gray to black, bittern to claystone couplets. Medium thickness
  - Fining upwards.
- White quartz, cross laminates.

Cycles. Type 2.
Cycles. Type Z.

Interbedded, dolomitic, white, v.f. quartzite and gray to black siltstone to clayshaly coullets. Medium to coarse thickness.

- Very well developed herringbone cross

- Dolomite rip-up clasts in basal sand bed of cycle

Cycles. Type Z. *Note: The dolomitic in almost all the cyclic beds seen so far is very impure as compared to Bighole Peak or Graves Creek sections. It contains abundant sand and/or silt in mud.

- Extensively reworked dolomite bed.
Interbedded white, dolomitic quartzite and gray to black siltstone to claystone couplets. Couplets are fine to medium in thickness.

Cycles. Type 2.

Cycles. Type 2. Poorly developed. Sometimes missing the dolomitic component at the top of the cycle couplets are still gray to black siltstone to claystone.

Cycles. Type 2.
very coarse couplets interbedded with quartzite.

massive quartzite (u.g., gray).

Interbedded gray quartzite and black siltstone to claystone couplets. Couplets are U. fine to fine thickness.

finely coupleled, black siltstone to claystone

definite stromatolites. Lateral linked hemispheres.

dolomitie nodules both ribbons and pods.

Interbedded gray quartzite and gray to black siltstone to claystone.

zone of extensive sediment disruption by "nodule both".

low angle cross stratification in white sand.
well developed "pull-aparts" in sand.

Interbedded "triplets" (gray/brown), gray non-dolomite quartzite and black claystone. Sands exhibit well developed "pull-aparts".

A thick sequence of lenticular quartzite beds begins here.

well developed "triplets" with basal sand, middle dolomite silt and black claystone cap.

thick molar tooth hash bed

clastic dike with injected molar tooth fragments.

Interbedded "triplets" and non-dolomite quartzite.

intraclast beds. The intraclasts are highly deformed.
sands are now commonly "pulled-apart."

Interbedded, lenticular quartzite and gray coqulets. Pyrite is very common and parallels bedding.

← rip-up clasts in quartzite.

Interbedded, gray, horizontally laminated or massive, v. f.g. quartzite and light gray to dark gray siltstone to claystone coqulets.

↑ Fining upwards
→ tabular, horizontally laminated sandstone
← sharp boundary

↑ Fining upwards
Copper minerals (chalcopyrite, etc.) in view of siderite

Microlaminated, very dark gray to black siltstone/claystone couplets. Non-dolomitic

Interbedded quartzite - horizontally laminated

Interbedded quartzite - horizontally laminated

Interbedded quartzite - horizontally laminated

Mostly dark gray siltstone to claystone couplets, non-dolomitic, very fine to medium thickness. Ripples are uncommon, pyrite is very common.
Dolomite, gray, siltstone to claystone couplets of medium thickness. Intercalation of sand.

Interbedded greenish gray siltstone to claystone couplets and gray v.f.g. quartzite.

Interbedded quartzite to claystone couplets and siltstone to claystone couplets. Slightly dolomitic. Mudcracks uncommon. Pyrite common.

Very fine to medium thick couplets of light gray to dark gray siltstone/claystone.
Snowslip Fm. (green dolomite; green siltstone; claystone)

Top of Section

- sand bed with soft sediment (s) slump. Laminae under bed are very distorted, those on top are horizontal.

- medium couplets
- fine couplets
- very fine couplets
- very fine to coarse couplets

- medium to coarse couplets
- very fine couplets
- fine to medium couplets
- Gray to black siltstone to claystone couplets. Dolomite. Mudcracks uncommon. Pyrite common.

- interbedded greenish-gray siltstone/claystone and dolomite, gray siltstone/claystone. V. Fine to medium couplet thickness. Vvv, minor sand lenses (as boundaries.)

brecia

minor fault