PETROLOGY OF THE UPPER NOUNAN - WORM CREEK SEQUENCE,
UPPER CAMBRIAN NOUNAN AND ST. CHARLES FORMATIONS,
SOUTHEAST IDAHO

by

Lillian Donley Wakeley

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Geology

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1975
Full fathom five thy coral lies,
Of his sclerites spar is made:
The pearls of mollusc calcitize,
Naught skeletal that doth fade
But shall its ions rearrange
Into something new and strange:
Algae hourly ring each shell
With a micritic rind 'neath the ocean swell.

Fakespar
(Marine Geol. 5:470)
ACKNOWLEDGMENTS

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Lillian Donley Wakeley
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The upper member of the Nounan Formation and the Worm Creek Member of the St. Charles Formation, both late Cambrian in age, were studied in the Bear River Range and the Fish Creek Range in southeast Idaho. Lithology and sedimentary structures of these units were compared with characteristics of similar modern sediments and ancient rocks, to determine the environments of deposition and effects of diagenesis for the interval studied.

On the basis of widely traced marker horizons, the two-member interval is divided into three parts, with parts 1 and 2 comprising the upper member of the Nounan Formation, and part 3 equal to the Worm Creek Member.

A marker of mixed-fossil lime packstone at the base of part 1 is overlain by mixed-fossil and lithiclast lime grainstones and cryptalgal boundstones. Sedimentary structures within these units suggest that part 1 was deposited in shallow subtidal and intertidal environments.
An oolitic lime and/or dolomite grainstone marks the base of part 2, and suggests shallow subtidal conditions. Part 2 is comprised of interbedded limestones and dolostones, with dolostone becoming predominant up section. The mixed-fossil, oolitic, and lithiclast packstones and grainstones, and cryptalgal boundstones of this part include sedimentary structures which indicate shallow, subtidal accumulation. The percentage of non-carbonate sand increases near the top of part 2, and sedimentary features suggest that water depth decreased slightly as terrigenous influx increased.

The base of part 3 (Worm Creek Member) is marked by sandstones and quartizes, cemented with carbonate minerals and/or quartz overgrowths. Carbonate deposition resumed above these terrigenous units in the southern and central parts of the study area, while terrigenous sediments continued to accumulate in the north and northwest. This suggests that the source of terrigenous sand was north or northwest of the study area.

Radial-fibrous cement rims on carbonate grains indicate early subsea cementation in limestones. Dolomite in "birdseye" structures and in reworked lithiclasts, both in limestones, suggests that a minor amount of syngenetic dolomite formed, although there are no beds of primary dolomite.

Dolostone units do not have the sedimentary structures typical of supratidal environments of syngenetic dolomitization, and have the coarsely crystalline texture and other characteristics of secondary dolomite. Dolomitization in a zone of mixing of fresh water and sea
water is a probable explanation of all dolostones in the sequence. Dolomite-embayed quartz and feldspar grains and overgrowths in some quartzites of part 3 suggest that dolomitization continued after lithification of some rock units.

(137 pages)
INTRODUCTION

General Statement

This report summarizes a study of the environments of deposition and diagenesis of the upper member of the Nounan Formation and the Worm Creek Member of the St. Charles Formation in southeast Idaho. This sequence is underlain by the middle member of the Nounan Formation, and overlain by the remainder of the St. Charles Formation.

Although these members are assigned to two different Upper Cambrian formations, they were studied as a unit. They exhibit a transition from predominantly carbonate deposition to predominantly terrigenous deposition, and are overlain and underlain by carbonate rocks. There was a stratigraphic problem associated with this interval, because previous workers have not been consistent in locating the contact between the Nounan and St. Charles Formations. These factors, combined with sufficient accessibility in the study area, made this interval ideal for paleoenvironmental study.

Purpose of Investigation

The objectives of this study were: (1) to reconstruct the environments of deposition as indicated by lithology and organic and non-organic sedimentary structures; (2) to determine the sequence of diagenetic events, including dolomitization; (3) to summarize the paleogeographic setting, including areas of differential subsidence
and directions of terrigenous sediment transport; and (4) to establish regional criteria for definition and recognition of the units studied.

Location of Study Area

The Preston quadrangle, southern parts of the Bancroft and Soda Springs quadrangles, and the western edge of the Montpelier quadrangle comprise the study area (Figure 1). The area is bounded on the south by the Utah-Idaho state line, extending from long. 112° 00' W. (near Clarkston Mountain) in the west to long. 111° 25' W. in the east (almost to Bear Lake), a distance of 48 km. The northern boundary extends between the same longitude lines, along lat. 42° 45' N. A distance of 78.5 km separates the state line from the northern boundary, forming a rectangle of 3768 square km. Farther north, the units are covered by the Snake River Basalt Plateau. South of the study area, Gardiner (1974) studied all members of the Nounan Formation, and Bircher (in preparation) analyzed the Worm Creek Member.

Six sections were measured in the Bear River Range, the northernmost extension of the Wasatch Range which continues northward from Utah. Outcrops in this block-faulted range generally dip westward on the east side and eastward on the west side, into the Logan Peak syncline, but dips are locally anomalous because of numerous faults. Eight other locations in this range were considered for field study, but were not measured because of faults and poor exposure. Two additional sections were measured in northeast-dipping rocks in the Fish Creek Range, west of Gem Valley.
Of the eight sections measured, five were on southward-facing slopes, one on an east-west ridge crest, and two on steep (45°) west- or northwest-facing slopes. At six sections, at least 80 percent of the two members was exposed and not obviously faulted. At the Oneida Narrows and Paris Canyon Sections (4 and 3), talus and extensive faulting prohibited accurate measurements.

Forest Service and county roads provided access by pick-up truck to within 1 km of all sections. The final kilometer on foot usually entailed a considerable climb (300 to 1000 m).

**Geologic Setting**

In southeast Idaho, the Cambrian section above the Brigham Formation consists of approximately 1615 m of carbonate rocks sporadically interrupted by thin shale and sandstone units (Hintze, 1973). Upper Cambrian rocks, comprising the Nounan and St. Charles Formations, are characterized by sedimentary structures which indicate shallow-water environments, according to many authors (Lucia, 1972; Heckel, 1972; Blatt et al., 1972). The study area was part of the Cordilleran miogeosyncline during Paleozoic time, with the craton to the east (Kepper, 1972, p. 525).

Lochman-Balk (1970) summarized a series of four late Cambrian marine transgressions which affected the environment of deposition and sediment sources of southeast Idaho. The westernmost margin of the craton was in western Wyoming. West of this line was a belt of supra-tidal to tidal stromatolite reefs, tidal flats, and sublittoral lagoons,
of mostly carbonate but with some terrigenous sediment, which fluctuated across the study area as sea level rose and fell. In late Trempealeauan time, the fourth major regression locally ended late Cambrian deposition.

According to Hanson (1953), the proportion of terrigenous material increases upward in the Upper Cambrian rocks of southeast Idaho. He stated that central Idaho was the source of terrigenous sand which was transported eastward and southward to sites of shallow-marine deposition during Dresbachian time. In his judgment, gradual uplift caused the seas to be restricted from northern Utah and southeast Idaho at the close of Dresbachian time. This presumably resulted in an hiatus between the Nounan Formation and the overlying St. Charles Formation.

Hanson explained the Worm Creek Member as a nearshore deposit from an early Franconian transgression (the second onlap of Lochman-Balk, 1970), with the sand source still in central Idaho.

Kepper (1972, p. 525) inferred the presence of a north-trending linear shoal in Utah and Nevada, separating a deeper water open-shelf environment to the west from a shallow-shelf-and-lagoon environment to the east. This idea is compatible with the conclusions of Lochman-Balk (1970) and Hanson (1953). The study area is located on the shallow, eastern side of this postulated shoal.

Coulter (1956, p. 36) briefly summarized deformation in the Bear River Range. He correlated the folding and high-angle faulting in this region with the late Cretaceous Laramide Orogeny of Eardley (1944). Williams (1948) considered the Bear River Range a part of the Bannock Thrust mass, with overriding movement from west to east having caused the north-south trending folds (cf. Crittenden, 1961).
Field and Laboratory Methods

The geologic maps of Armstrong (1969), Davis (1969), Oriel (1968), and Oriel and Platt (1968) provided information on the locations of supposedly complete sections of the study interval (Appendix A, Figure 1). The Cub River Section (2) was located from aerial photographs. Lack of exposure was a problem at many potential section sites, but well-exposed sections were located 11 to 22 km apart. Two sections are composite: the Worm Creek Member was measured at a location within 3 km of the measured upper Nounan to complete the Cub River and Densmore Creek Sections (2 and 7). Although somewhat irregular, the grid established over the study area by measured sections permitted adequate thickness and lithologic control (Appendix A, Figures 2, 3 and 4).

Forty days were spent in the field between 30 May and 1 October, 1974. During this time, eight stratigraphic sections were sampled, described, and measured. Completion of the field work at each section required four to seven days.

Three sections were measured with a Brunton compass, an Abney level, and a staff approximately 1.5 m (5 feet) long, using the method described by Kottlowski (1965, p. 61-64), modified by holding the staff vertically and making the requisite trigonometric corrections. A steel tape 15.2 m (50 feet) long was used with the above equipment to measure four sections. One section was measured using both methods. Samples were taken at stratigraphic intervals of 3 to 5 m, with extra samples taken where lithologic change was frequent.
The described lithologic features (Appendix C) included general rock types, grain sizes and types, colors (Goddard, 1963), bedding thicknesses and types, and natures of contacts. Sedimentary features, such as cross- and parallel laminae, ripple-marks, channeled bedding, oolites, and color and texture mottling were noted. Cryptalgal structures and trace- and body fossils constitute the recorded organic sedimentary structures. Other general features of the sections, including thicknesses of covered intervals, general trends of cross-laminae, sizes of all structures, and locations of ledge-forming units, were recorded (Appendix C).

After completion of the field work, hand specimens collected at each field location were further described and compared. The study of 38 thin sections (Appendix B, Tables 1 and 2) of stratigraphically significant samples from the St. Charles Canyon, Williams Canyon, and McPherson Canyon Sections (1, 5, and 6) provided petrographic detail. The method described by Mueller (1967, p. 36) was used to isolate insoluble residues from these and other samples to determine percentage. Thirty-one residues (Appendix B, Table 1) and ten whole-rock samples (Appendix B, Table 2) were analyzed by X-ray diffraction to determine the composition of detrital constituents. Samples were powdered to pass through a 120-mesh sieve onto glass slides coated with petroleum jelly. They were scanned from 4 to 60° 2θ at 1° per minute on a Siemens Crystaloflex-4 diffractometer, using nickel-filtered CuKα radiation at 35 kv and 18 ma.
Physical correlation among sections was accomplished by comparing stratigraphic sections (Appendix A, Figure 5). These pictorially display the vertical and lateral distributions of the lithologic features listed above. The construction of isopachous maps of each member (Appendix A, Figure 2), and of lithofacies maps showing percent carbonate and non-carbonate (Appendix A, Figure 3) and percent dolomite in carbonate rocks (Appendix A, Figure 4), provided additional information for paleoenvironmental and paleogeographic interpretation.
PREVIOUS WORK

The Nounan and St. Charles Formations were first defined by Walcott (1908a, p. 6). The Nounan type locality is the east slope of Soda Peak, west of the town of Nounan, Idaho. Accessibility and exposures are poor at this site. Walcott (1908b, p. 153) measured a better exposed section in Blacksmith Fork Canyon, Cache County, Utah, where the formation is 312 m (1041 feet) thick. According to Williams (1948, p. 1134), the Nounan is Croixian in age, in part or entirely. Hintze (1973, p. 16) specifically assigned this formation to the Dresbachian Stage.

Several workers have measured sections of the entire Nounan Formation in north-central Utah. Gardiner (1974) measured ten sections in that area, and in his report on these data summarized the findings of other workers in the same region (p. 7-8).

Few studies in southeast Idaho have included data on the Nounan Formation. Mansfield (1929, p. 17), in a general report about the Portneuf quadrangle, described the Nounan as a "massively bedded, whitish or light gray, somewhat coarsely crystalline dolomitic limestone, in beds about 18 inches thick." Darker colored beds of similar lithology and thickness alternate with these, to total about 91 m (300 feet).

Hanson (1953) briefly discussed the Nounan Formation in northern Utah and southeastern Idaho. He divided the formation into a lower, massive dolostone member and an upper limestone member. His discussion of the environment of deposition is summarized under Geologic Setting.
 According to Coulter (1956, p. 16), the Nounan Formation is 300 m (985 feet) thick east of Franklin, Idaho. He reported a thickness of 181 m (594 feet) for the upper part, above the massive dolostones. This interval was informally designated the upper member of the Nounan Formation by Gardiner (1974, p. 24), and that designation is used in this paper, with slight modification (see Contacts and Marker Horizons).

Oriel and Platt (1968 sheet 2) reported a thickness of 206 to 305 m (675 to 1000 feet) for the entire Nounan Formation in the Preston quadrangle. In the Bancroft quadrangle, the Nounan was reported to be 206 m (675 feet) thick (Oriel, 1968). Armstrong (1969) indicated a thickness of 184 m (603 feet) in the Soda Springs quadrangle. These thicknesses were supposed to represent the entire Nounan Formation.

St. Charles Canyon, west of the town of St. Charles, Idaho, is the type locality of the St. Charles Formation (Walcott, 1908a). This formation is entirely Croixian in age according to Williams (1948), but is assigned to only the Franconian and Trempealeauan Stages by Hintze (1973, p. 16). The first section was measured in Blacksmith Fork Canyon, where the "basal sandstone" unit is 50.6 m (166 feet) thick (Walcott, 1908b, p. 193). This "sandstone" unit was formally named the Worm Creek Member of the St. Charles Formation by Richardson (1913, p. 406). The name is derived from Worm Creek, in Bear Lake County, Idaho (p. 408). Richardson reported a maximum thickness of 91.5 m (300 feet) for the Worm Creek, which he described as a massive gray quartzite (p. 407).
The Worm Creek Member has also been mentioned in a few general studies of areas of southeast Idaho. Thicknesses of 45.7 to 91.4 m (150 to 300 feet) were reported for the Worm Creek Member in the Chesterfield and Bear River Ranges (Mansfield, 1927, p. 17; 1929, p. 56). Coulter (1956) gave 51.8 m (170 feet) as the thickness of this member east of Willow Flat, Idaho. The section descriptions of these workers show that the Worm Creek Member is readily distinguished in the areas they studied.

Inability of workers to agree on the location of the contact between the upper member of the Nounan Formation and the Worm Creek Member of the St. Charles Formation has caused confusion about the actual thicknesses of these units. Deiss (1938) failed to recognize the Worm Creek Member, and thus reported no quartzites or sandstones at the base of the St. Charles Formation. This led to errors in his reported thicknesses of the Nounan, St. Charles, and Ordovician Garden City Formations (as explained by Williams, 1948, p. 1135).

The thickness of the Nounan Formation in the Preston quadrangle, 206 m reported by Oriel and Platt (1968), is only part of the total thickness. Likewise, their supposed 274.5 m (900 feet) of Worm Creek is too thick. Their general section description shows that at some locations they chose the Nounan-Worm Creek contact at a sandstone unit within the upper Nounan, and mapped a considerable thickness of upper Nounan rocks as Worm Creek Member. This situation is repeated in the Bancroft quadrangle (Oriel, 1968) where again the Nounan at some locations is far too thin and the Worm Creek too thick, when compared with the present study and earlier work (Mansfield, 1929).
Armstrong's (1969) composite stratigraphic section of the Nounan and St. Charles Formations in Cheatbeck Canyon, Caribou County, Idaho, clearly shows that he identified the contact between the upper Nounan and Worm Creek Members at a stratigraphic position different from that used in the original definition of the Worm Creek Member. He reported 212 m (695 feet) of Worm Creek, over half of which matches the description of the upper Nounan in the present study and in the earlier works of Mansfield (1927 and 1929), Hanson (1953), Coulter (1956), Hansen (1964), and Gardiner (1974).

Most workers agree that the Worm Creek Member thins toward the south through southeast Idaho (Oriel and Platt, 1968; Hanson, 1953; Coulter, 1956; Haynie, 1957) and continues thinning southward through north-central Utah (Hanson, 1953; Williams, 1948; Bircher, in preparation). The magnitude of this lateral thickness change has been overestimated in the literature because of the lack of agreement with the original definition of the contact between the upper Nounan and the Worm Creek Member.
In the carbonate rock classification of Leighton and Pendexter (1962, p. 51), a limestone is a rock composed of more than 50 percent carbonate of which 50 percent or more is calcite. Dolostone is a carbonate rock composed of 50 percent or more dolomite. A quartz sandstone, which breaks through rather than around grains and was cemented with silica which was precipitated in optical continuity around the detrital quartz grains, is a quartzite (Pettijohn et al., 1972, p. 169). Sandstone is consolidated sand-sized terrigenous material in which the insoluble residue equals or exceeds 50 percent (Lumsden, 1974). In samples from the present study, the dominant insoluble mineral is quartz, and the cement is dolomite or calcite.

A limestone or dolostone which includes 10 to 50 percent quartz sand is modified by the term "sandy." The modifiers "dolomitic" or "calcareous" indicate that a rock contains 10 to 50 percent dolomite or calcite, respectively. A feldspathic sandstone or quartzite consists of 50 percent or more quartz sand, and 10 to 50 percent sand-sized feldspar in its insoluble grain fraction.

Because all rocks in this study have been diagenetically recrystallized or replaced, no attempt is made to indicate this fact in rock names, unless the depositional texture is not recognizable. The textural carbonate rock classification of Dunham (1962, p. 117) is used with appropriate modifiers (Table 3).
Grain-size terminology used in this report is taken from Leighton and Pendexter (1962, p. 52). Grain-size terms are applied to the recognizable constituents of carbonate rocks, and to all non-carbonate rocks.

Folk's (1965, p. 25) crystal-size terminology for recrystallized carbonate material is applied to all carbonate rocks in this study.

The terminology of Aitken (1967) is used to distinguish among structures of algal origin. All of these structures are presumed to have been formed by the sediment-binding activities of non-calcareous blue-green and green algae.

Cryptalgalaminae are planar to slightly crenulated, laterally continuous laminations. These are distinguishable from non-organic sedimentary laminae by the presence of irregularly connected filament traces, "birdseye" structures disrupting the laminae, and associated lithiclasts between sets of laminae (p. 1170). In this paper, single laminae of 2 mm or less between upper and lower boundaries are termed "thin." Those greater than 2 mm are "thick."

A thrombolite is a mottled, clotted, irregular algal-formed structure in which filaments and laminae are not clearly visible (Aitken, 1967, p. 1171).

Domal stromatolites resemble cryptalgalaminae, but are not planar. The laminae are parallel, forming blister-shaped bodies of low relief (p. 1166). Those seen in this study are either continuous chains of small domes, or are local features, grading laterally into cryptalgalaminae.
Columnar stromatolites are non-linked, vertically stacked, arched hemispheroids of constant or slightly variable diameter (Aitken, 1967, p. 1168). In the present study, however, some columnar cryptagal structures were linked, by what were apparently domal stromatolite layers, at infrequent intervals.

The abbreviated form of the algal-stromatolite terminology of Logan et al. (1964) is used wherever possible to further clarify structure types.

The descriptive terms for the configurations of beds, laminae, and laminasets of Campbell (1967) are used for clastic rocks. These terms are also applied to cryptagal structures, where appropriate, in the section descriptions (Appendix C).
STRATIGRAPHY, ROCK TYPES AND SEDIMENTARY STRUCTURES

General Statement

Based on rock types and sedimentary structures, the upper Nounan and Worm Creek sequence can be subdivided into three major parts. The upper Nounan is divided into a lower fossiliferous limestone part, and an upper interbedded limestone and dolostone part, in which the percentage of non-carbonate material is generally higher (Appendix A, Figure 6). The quartzites and dolostones of the Worm Creek Member comprise the third part of the sequence. Sandstone and/or shale beds are included in one or both of the lower parts in five measured sections. In the St. Charles Section (1) the Worm Creek includes a shale bed.

Stratigraphic relations, lithologic characteristics, and sedimentary structures of these three parts will be described, beginning with the lower limestone part. Following this is a comparison, among parts and sections, of important characteristics, including insoluble minerals.

Detailed descriptions of measured sections are given in Appendix C, and stratigraphic relations among sections are shown in Appendix A, Figure 5.

Contacts and Marker Horizons

In this study, the contact between the middle and upper members of the Nounan Formation was chosen at the base of the first limestone unit above the massive light gray dolostone of the middle member (described
by Gardiner, 1974, p. 24). Here, the gross lithology, darker rock color, decreased bedding thickness, and decreased slope contrast sharply with the light-gray dolostone immediately below. However, south of the present study area, there is usually no limestone directly above these middle dolostones, and a sandstone unit often marks the base of the upper member (same reference). Possibly, the top of the white dolostones is the most reliable criterion for this contact, because it is readily recognizable at all locations.

A sparsely fossiliferous limestone unit, with beds composed of fragmented and microscopic skeletal debris, is present in all sections at which the base is exposed (at Section 4, the contact is under Bear River or faulted out). Another marker horizon forms the base of part 2. This is an oolitic lime grainstone, which grades upward into mixed-fossil, oolitic, or lithiclast-grain-supported rocks, or oolitic dolomite grainstones.

A third marker horizon is a very light gray (N8) cryptalgal dolomite boundstone, present in every section near the top of part 2 (Appendix A, Figure 5).

Although five sections include sandstone units within part 2, they are not in stratigraphically related positions in the sections, and are not considered marker units (Appendix A, Figure 5).

The contact between the upper Nounan and Worm Creek members is readily recognized in the field, at a sandstone and/or quartzite unit which marks an abrupt end of carbonate deposition. The basal unit of the Worm Creek Member is an unequivocal marker, although it is probably time transgressive.
The contact between this sequence and the upper part of the St. Charles Formation is marked in each section by at least two of five significant changes. In Sections 1, 2, 4, 5, and 6, the carbonate lithology changes from dolostone to limestone. Fossils become abundant above this contact in the same five sections, and above Sections 2, 4, and 5, Billingsella is present. This genus of brachiopod is not present in the Nounan Formation or Worm Creek Member. Limestone lithiclasts are present just below the contact in Sections 5 and 6. In seven sections, sandstone and sandy carbonates end at this contact (Section 8 has a conglomerate of reworked quartzite 1 m thick just above the contact), and the crystal size in carbonates becomes coarser in the overlying rocks.

The upper Nounan and Worm Creek Members are mappable, easily recognized in the field, and represent depositional conditions different from those of the underlying and overlying rocks. The quartzite conglomerate at the Worm Creek-upper St. Charles contact in Section 8 suggests at least a local hiatus at the end of Worm Creek deposition. For these reasons, the two members of this report could be considered a single formation. Because the criteria for recognizing the contact between the Worm Creek Member and the upper St. Charles member are not the same in all sections, a mappable definition of this contact cannot be easily established. For mapping purposes, it is probably more desirable to maintain the present definitions, with the contact between the Nounan and St. Charles Formations at the easily distinguished base of the Worm Creek Member.
Lower Limestone: Part 1

In sections 1 through 7 the units of part 1 are predominantly limestone. Section 7 includes one dolostone unit 2.7 m thick at the base of part 1, and part 1 of Section 3 includes 20.8 m of dolostone. In Section 8, 75.9 m of dolostone and 12.2 m of limestone form part 1. This part averages 88 m thick, with a minimum of 77 m in Section 3, and a maximum of 102 m in Section 6. The thickness of part 1 of Section 4 given in this report is probably less than the actual thickness, because the base is covered or missing (Appendix C).

Mud-supported, grain-supported, and organically bound rocks are interbedded throughout part 1. These rocks are all dark colored, (N3 to N5), suggesting the presence of reduced iron minerals, possibly related to the former presence of organic matter. All beds were diagenetically recrystallized, and the resulting crystal size is extremely variable, although depositional fabrics are usually recognizable. Beds range from 3 to 20 cm in thickness.

Non-organic sedimentary features in mud-supported rocks include rounded lithiclasts in all sections, and even parallel laminae and low-amplitude (<6 cm) channeled bedding each in two sections. Organic sedimentary structures in these units include burrows in seven sections and feeding traces in six, pellets and oncolites each in three sections, and broken trilobite and echinoderm fossils in all sections.

In grain-supported rocks, low-angle cross laminae (<12°; McKee, 1964) (in four sections), round and/or elongate lithiclasts (all sections), and oolites (six sections) comprise the non-organic sedimentary
features. Abundant trilobite and echinoderm fossils are in grain-supported rocks in all sections. Non-branching, vertical burrows are present in seven sections. Pellets are abundant, infilling burrows and within lithiclasts and matrix material (seen in thin section), in rocks from at least three sections. Oncolites, present in one section, complete the list of organic features.

Organically bound rocks include abundant cryptalgalaminae, which are commonly thick (>2 mm, in six sections), but locally thin (<2 mm, in two of the same and two additional sections). Domal stromatolites are present in two sections, and thrombolites recognizable in seven, usually very near the base. These cryptalgal rocks include even parallel laminae and "birdseye" structures, each in two units of different sections. Most structures listed in mud- and grain-supported rocks are present in beds which are locally interbedded with cryptalgalaminate rocks.

The insoluble material present in this part ranges from 2.0 to 20.4 percent by weight of the sample, and averages 7.5 percent for 18 samples tested. One calcareous sandstone in Section 5 is 75.3 percent insoluble material.

Quartz and plagioclase were identified by X-ray diffraction in all analyzed samples. Illite is present in seven carbonate mudstones, packstones, and grainstones. Several samples also include chlorite. Hematite is a component of two packstones and one grainstone. Clay minerals are usually associated with rocks containing fossils and lithiclasts. Other minerals, including limonite (from several lithologies)
and pyrite (in mudstone only), were found in thin sections from part 1 of Sections 1 and 5 (Appendix B, Table 1).

Mineralogy of the insoluble fraction of some samples was not determined, because of the small amounts of residue remaining after the samples were dissolved. One whole-rock sample from this part of Section 1 was analyzed, with only calcite and illite abundant enough (>5%) to be recorded.

Limestones and Dolostones: Part 2

Dolostone comprises over half of this part of every section, with the exception of Section 4 in which there is no dolostone. In Section 8, these units are all dolostones. In general, thicker limestone units are located near the base, dolostone becoming the dominant rock type up section. The uppermost carbonate unit is consistently dolostone, with the exception of Section 4. Part 2 of Section 6 includes one shale bed.

Section 2 has the maximum thickness for this part, 177 m. The minimum, 71 m at Section 4, is probably less than the actual thickness. The two parts of the upper Nounan are only approximately defined for this latter section, because there are no dolostones, oolites are present in most beds, and the section is faulted. The average thickness of part 2 is 119 m.

Bedding thicknesses range from 6 to 47 cm, with one anomalous unit of beds which average 71 cm thick. These units are lighter colored than the limestones of part 1, range from N5 to N9, and include many pinkish beds (hues 5R and 5YR).
Diagenetic alteration has destroyed many original fabrics. In most thin sections of dolostones, little or no indication remains of the depositional texture or the nature of the original grains. Many structures are recognizable only on weathered outcrop surfaces, or on wet and magnified hand specimens. Still, these observations reveal the former abundance of sedimentary features.

In many dolostone units, it is difficult to determine whether the rock was originally grain-supported or mud-supported. Oolites are present in all measured sections, either in dolostones (two sections), limestones (two sections), or both rock types (four sections). Six sections include beds of elongate lithiclasts, and rounded lithiclasts are locally abundant in six sections. Broken fossils are present in all sections, as a constituent of limestone beds (at five), in dolostone beds (at one), or within beds of both rock types (at two localities). All these features suggest that many beds were originally grain-supported.

Direct evidence of mud-supported rocks is lacking in dolostones. Their former presence is assumed for beds with little evidence of grains in hand specimens or thin sections.

Organic sedimentary structures such as non-branching, vertical burrows, which are uncommon in part 2, and epistratal traces parallel to bedding, noted at all localities, do not indicate whether the rock was mud- or grain-supported, although epistratal traces are more common on muddy substrates (Seilacher, 1967). Low-angle cross-laminae (present at seven localities), channeled bedding surfaces (two localities),
and current ripple-marks (one locality) are non-organic structures which may suggest accumulation of grain-supported sediments, but can be associated with mud-supported layers on tidal flats (Heckel, 1972). Even parallel laminae are not diagnostic (present at four sections).

Evidence of cryptalgal boundstone is obvious and abundant. Thin cryptalgal laminae are present at all localities, thick laminae at five. Columnar stromatolites (SH-C and SH-V of Logan et al., 1964) are visible on weathered surfaces in two sections, domal stromatolites (LLH-C and LLH-S) in two. Elongate lithiclasts with visible cryptalgal laminae, and round to elongate oncolites (SS-C and SS-1), are each present at three localities.

The insoluble residues, isolated from 17 carbonate rock samples in this part of the section, average 12.5 percent, by weight, of the samples. The range is 1.1 to 45.0 percent. Not all isolated residues were analyzed by X-ray diffraction (Appendix B, Table 1).

As in part 1, quartz and plagioclase are present in every sample tested. The clay minerals illite and chlorite are present in some boundstones and crystalline dolostones. Microcline was identified in one crystalline dolostone sample, and hematite is present in one grain-supported (?) dolostone. All minerals found by X-ray diffraction or in thin sections are listed in Appendix B, Table 1.

Five carbonate whole-rock samples from part 2 were analyzed to determine the presence of minor carbonate components. Three samples are dolostones. No other carbonate mineral was detected, although one sample contains hematite. One limestone from Section 1 included a
detectable amount (>5%) of dolomite. The other, from Section 4, contains only quartz in addition to the major component (Appendix B, Table 2).

**Terrigenous Rocks and Dolostones: Part 3**

The base of part 3 is sandstone, 1 to 3 m thick, usually dolomitic. Only at Sections 3 and 4, where the contact between this part and the underlying interbedded limestones and dolostones is faulted, was this sandstone not observed. Above the base is a thick (3 to 36 m) quartzite sequence, above which is dolomitic sandstone, and dolostone. In Section 1, some dolostone beds are present within these terrigenous units. Average thickness for part 3 is 61.9 m, the thickness ranging from a maximum of 99 m at Section 7 to 29 m, the (faulted) minimum, at Section 4.

Shale is present within a unit of sandstone and shale 1 m thick at the base of this part in Section 2. There is also a shale bed 1 m thick near the top of Section 1, and a few shaly partings among quartzite and dolomitic sandstone beds at this locality. These units are not present in measured sections to the north, although Bircher (oral communication) found a persistent shale bed near the top of the Worm Creek Member south of the present study area.

Light-colored rocks are common, most sandstone and quartzite beds ranging from N6 to N8, with pinkish gray (5 YR 8/1) feldspathic quartzite beds in every section. Dolostones are usually medium light or light gray (N6 or N7). Medium or coarsely crystalline dolostones and medium- and coarse-grained quartzites predominate. Part 3 of Sections 6, 7,
and 8 includes more coarse-grained terrigenous beds than does this part of the other sections. Bedding thickness ranges from 12 to 34 cm in quartzites and from 5 to 19 cm in dolostones and sandstones.

Feeding traces are locally present on shale bedding surfaces. Many quartzite and sandstone beds at seven sections have burrows either perpendicular or oblique to bedding (not observed in Section 4, where quartzite is not exposed). In some beds, the depositional laminae were contorted or obscured by burrowing. Some quartzite beds in Section 8 have channeled contacts. Low-amplitude (<1 cm) current ripple-marks were observed in quartzite beds in Sections 5 and 6; ripple-marks in Section 1 are flat topped.

Above the ubiquitous feldspathic quartzite units at the bottom of part 3, original fabrics in most dolostones are well preserved relative to fabrics in rocks of part 2. Beds of elongate lithiclasts in two sections, rounded lithiclasts in one, and oolites at two localities are inorganic evidence of grain-supported rocks. Broken fossils are visible in hand specimens from two localities, and in thin sections from a third. Cryptalgal structures are common in these dolostones, three sections including thin, and one, both thick and thin cryptalgalaminae. In addition, Section 3 has one bed of domal stromatolites (LLH-C). One dolomitic limestone bed is present below the shale unit near the top of this part of Section 1.

Most samples collected from this part are terrigenous rocks. Insoluble residues were isolated from only five hand specimens. A sample of the shale at the base of this part in Section 2 was 90 percent
insoluble residue that contained microcrystalline quartz, plagioclase, illite, and hyalophane. Taken from the uppermost unit of Section 1, a calcareous siltstone includes quartz and plagioclase in its 60 percent insoluble material. A dolomitic quartzite, from just above the lowermost quartzite unit in this section, is 70 percent non-carbonate. From Section 5, quartz, plagioclase, and illite were identified in a dolomitic sandstone with 79 percent insoluble residue. An echinoderm lithiclast dolomite wackestone (?) is 12 percent insoluble residue, containing quartz, hematite, and chlorite (identified in thin section only).

Thin sections from other samples in this part show that some units which appear to be feldspathic quartzites contain up to 20 percent dolomite. One thin section made from quartzite of the basal unit of the Worm Creek Member in Section 5 has a matrix of sericite.

Four whole-rock samples from part 3 of Sections 1, 2, 5, and 7 were analyzed by X-ray diffraction. Two of these are feldspathic quartzites, composed of quartz and plagioclase. One is a dolomitic sandstone, containing the same two minerals plus dolomite, and one is a shale, containing feldspars, chert, illite and chlorite. Other minerals comprise less than 5 percent of the rock, and do not appear in the X-ray records. Microcline and zircon were observed in thin sections of these and other terrigenous rocks.
Insoluble Residues

Distribution of insoluble residues

For the 36 carbonate-rock samples from which insoluble residues were isolated, insoluble material averages 10.0 percent by weight. The average value for 15 dolostone samples is 13.4 percent. The 21 limestone samples average 7.6 percent. Although a difference appears to exist, it is not statistically significant (P > .05; Students' t-test, Zuwaylif, 1969, p. 170) for this small sample; the difference might be significant with a larger sample.

Considering all analyzed dolostone samples from Sections 1 and 5, there is no significant correlation between the percentage of detrital material in a sample and its position in the section (P > .05; linear regression, Zuwaylif, 1969, p. 235). No significant correlation exists between these factors using only the data from Section 1. However, the samples from Section 5, considered alone, show a significant positive correlation (P > .05) between percent of insoluble material and distance up section (Appendix A, Figure 6). The reason for this difference in Sections 1 and 5 is discussed with Source of Terrigenous Sediments.

The apparent but non-significant difference in the mean values of insoluble material in dolostones and limestones exists for at least two reasons. Dolostones come from higher in the section than do limestones, and the percentage of insoluble material is greater near the Worm Creek contact (also observed by Gardiner, 1974). This does not indicate that only units high in insoluble material were dolomitized. There is much overlap in the percentages of detrital minerals for the two carbonate
rock types. The high percentage of insoluble residue from most samples taken within 50 m of the top of part 2 contribute to the large mean value, although the variability is high (insoluble material ranges from 1.1 to 45.0 percent, standard deviation = 13.4, for 15 dolostone samples from two sections).

Five of the seven cryptalgal boundstones analyzed in this study are dolostones. This fact contributes to the high mean percentages of insoluble minerals in dolostones, because boundstones average 25.2 percent insoluble residue, far higher than the overall average or the average for dolostones. The two lime boundstones are 21.8 and 18.9 percent insoluble residue, much higher than the average for limestones, which again indicates no preferential dolomitization of impure limestones.

Mineralogy of insoluble residues

Quartz, feldspars, clay minerals, and hematite were identified by X-ray diffraction in this study. Quartz is present in all but one of the samples analyzed by X-ray diffraction, and is probably present throughout the sequence. Seen in thin sections, quartz grains are equant (L/W averaging < 1 1/2:1; Folk, 1965), subangular to subrounded (Powers, 1953, in Folk, 1968), and average 0.1 mm in diameter. Some grain boundaries are difficult to distinguish, due to embayment by dolomite. Most grains are single crystals, with straight to strongly undulose extinction (Folk, 1968). Some have quartz overgrowths. A few composite grains are present, especially in terrigenous rocks. All feldspar grains seen in thin sections are single-crystal grains. Some
albite twinning and infrequent microcline twinning are visible in thin sections.

No clay minerals are identifiable in thin sections. Hematite is obvious in many thin sections, although it is not usually abundant enough or crystallized well enough to show on diffraction records. Limonite is also common in thin sections, especially concentrated along stylolites and in algal boundstones. Pyrite is present in one thin section from part 1 of Section 5.
INTERPRETATION OF DEPOSITIONAL ENVIRONMENTS

General Statement

Interpretations of environments of deposition of carbonate rocks include the symposia of LeBlanc and Breeding (1957), Friedman (1969), Rigby and Hamblin (1972), Laporte (1974), and many other works. In this section, studies of both modern sediments and ancient rocks provide a basis for interpreting the environmental conditions indicated by the characteristics listed previously. These conditions are synthesized into an analysis of the succession of changes which produced this Upper Cambrian sequence.

Carbonate Rock Units

Chemical requirements of carbonate deposition

Revelle and Fairbridge (1957, p. 250) summarized the chemical and physical requirements for precipitation of calcium carbonate in marine environments. Increased temperature lowers the solubilities of CaCO_3 and CO_2, thus increasing the concentration of carbonate (CO_3^{2-}). Evaporation increases the concentration of dissolved calcium and other ions. Both photosynthesis and bacterial production of weak bases raise the pH of sea water, which increases the concentration of carbonate ions. Availability and movement of nuclei and catalysts in sea water supersaturated with Ca^{++} and CO_3^{2-} also favor precipitation, as do some organic processes, but these factors are not yet quantifiable.
The conditions under which calcium carbonate is forming at present are probably similar to those required in the past, although the present rate of production is not assumed for all geologic time. According to Revelle and Fairbridge (1957, p. 240), rates of solution and precipitation have probably undergone cyclic oscillations, due to changes in:

- the abundance and kinds of marine organisms, and the resultant rates of calcium carbonate withdrawal;
- the areal extent and mean temperature of shallow seas;
- the state of weathering of exposed land masses, and the amount of orogenic activity.

Shallow seas located in what is now the western United States probably were warm during late Cambrian time, when this area was located between lat. 0° and 15° S. (Seyfert and Sirkin, 1973, p. 204). Therefore, the conditions in the study area during the late Cambrian are assumed to have been similar to those in modern tropical areas.

**Cryptalgal structures**

Cryptalgal structures are more variable in appearance than any other depositional characteristic of the carbonate units. The most abundant structure type, they are present in all three parts of every section (except part 3 of Section 4, most of which was omitted by faulting). The following discussion will show that the forms of cryptalgal structures result from physical conditions of the environment in which the algae grew.

Blue-green and green algae, which range in age from the Precambrian to the Recent, are bathymetrically limited by the depth of light penetration, usually 100 m. Other limiting factors include extremes of
temperature, chemical toxicity, ultraviolet radiation, rapid sedimentation or current rates (Awramik, 1971), and prolonged desiccation (Kendall and Skipworth, 1968). Modern stromatolites seldom extend to 100 m, even where all non-organic factors are favorable, because of abundant algae-eating metazoans. In pre-mid-Ordovician time, however, burrowing and grazing molluscs had not achieved their present diversity and abundance, and algae probably filled the entire photic marine realm (Garret, 1970; Awramik, 1971). When interpreting Cambrian cryptalgal structures, the possibility of growth in shallow to moderate subtidal environments should be considered.

The energy of the environment is a meaningful basis for interpretation of cryptalgal structures. Discontinuous and/or even, parallel to wavy (Campbell, 1967) cryptalgalaminae are the most abundant structure type, present in 51 percent of all carbonate units. This growth morphology is associated with low-energy conditions in both ancient rocks (Aitken, 1967; Chafetz, 1973) and modern sediments (Gebelein, 1969; Logan, 1961; Logan et al., 1964). In the present study, the bathymetric position of cryptalgal accumulations is determined by morphology, and by association with other sedimentary structures.

Aitken's (1967, p. 1176) model showed cryptalgalaminae forming in the supratidal zone, associated with desiccation cracks, "birdseyes" of sparry calcite or dolomite (discussed under Lithiclasts and "Birdseye" Structures), and elongate lithiclasts derived from the cryptalgal layers. Chafetz (1973), Frost (1974), Howe (1966), Logan (1961), Shinn et al (1969), Laporte (1967) and Schenk (1967) all agreed with
Aitken's interpretation of this association. Zenger (1972, p. 114) and Lucia (1972) added evaporite crystal molds to the list of structures often associated with cryptagalaminae and diagnostic of supratidal conditions. Hanselman et al. (1974) reported that algal mats in tidal areas are normally devoid of terrigenous material. These features are conspicuously absent from cryptagalamine rocks in the present study, with the exception of "birdseye" structures in one thin (<10 cm) limestone bed in each of two sections.

Gebelein (1969, p. 55-56) described "flat to slightly rippled continuous" algal mats as the most common type in subtidal environments along the Bermuda coast. Blue-green algae bind sediment with an organic sheath which is absent only where sediment movement is too rapid for establishment of an algal mat (surface current velocity > 20 cm/sec). Thin laminae (<1 cm) form in shallow subtidal areas. The thickness of laminae increases (to > 2 cm) in water ranging from 6.0 to 10.5 m in depth, with a decrease in the rate of sediment movement (Gebelein, 1969).

In the present study, undisrupted thin (<2 mm, this paper) laminae grade vertically into their thicker (>2 mm) counterparts through distances of 5 to 10 m, a configuration which may have resulted from differences in depth similar to those described by Gebelein.

Decreased erodability of mat-bound sediment enhances preservation of an established mat. Neumann et al. (1970, p. 294) found that intact mat surfaces withstood three to nine times the maximum tidal-current velocity (13 cm/sec) recorded at Abaco, Bahamas. In flume studies, unbound grains moved at current velocities of 20 cm/sec (erosion threshold for sand with 0.1 mm diameter from Hjulstrom's diagram, in Krumbein
and Sloss, 1963, p. 203). Velocities of 60 to 100 cm/sec were required to continuously erode subtidal mats. A similar relationship between algal-bound sediment and stability may have allowed Cambrian mats to become cryptalgalaminae.

Reworking of algal sediments by burrowing and grazing organisms greatly reduces the likelihood of preservation of modern subtidal algal mats, in which burrowers often destroy individual laminae and create a massively bedded sediment (Neumann et al., 1970). Breaks caused by burrows or projections through the mat also reduce by half the velocity required for erosion (Scoffin, 1970, p. 269). Because of the relative paucity of subtidal burrowers in Cambrian seas (Garret, 1970), the late Cambrian subtidal cryptalgalaminae in this study were resistant to erosion and were preserved intact.

Thin sections of cryptalgalaminae provide further evidence of energy conditions and sediment-transport. Fine (0.1 mm) quartz sand is present in both cryptalgal and carbonate mud layers, but is approximately 20 times more abundant in the cryptalgalaminae, a relationship also noticed by Gardiner (1974, p. 27). The appreciably greater percentage of insoluble material in boundstones, discussed previously, corroborates the preferential trapping of non-carbonate particles of this size by algal mats. Available carbonate grains were apparently smaller than sand-size. Fine sand can be transported by water moving 10 to 20 cm/sec, a realistic rate for tidal currents (Neumann et al., 1970). There was apparently not enough energy to carry larger particles into mat-bound areas. Silt and clay-sized particles were carried past the mat in suspension, the organic algal sheath preferentially trapping
larger particles near their threshold of deposition. Therefore, non-carbonate particles were deposited in quantity only where mats trapped them to create thin, irregular laminae of sand, organic matter, and algal lime mud (Stockman et al., 1967).

The greater concentration of terrigenous material in cryptalgal laminae is also evidence that the algae were subtidal, as contrasted to the terrigenous grain-poor aspect of tidal-flat algae, discussed previously.

The non-cryptalgal, relatively sand-free laminae may represent seasonal periods of quieter or deeper water, non-channel conditions, when sand-sized material did not reach the mats. Deposition of carbonate mud probably dominated these periods and the water may have been too cloudy and the sedimentation rate too rapid for algae to thrive. Slower current rates alone may have been sufficient to cause rapid deposition of mud, or the carbonate precipitation rate may have been suddenly extreme, in conditions similar to the non-organic aragonite precipitation described by Cloud (1962, p. 19) and Friedman (1975). In either case, alga-free (lighter colored) laminae (>8 mm thick) represent relatively instantaneous deposits, possibly related to quieter or deeper water during storm seasons. The cryptalgal layers (laminae 1 to 7 mm thick in layers 0.5 to 3 cm thick) probably took longer to accumulate, being limited by rates of algal growth and terrigenous influx.

Water depth and energy also control the formation of other, more complex, cryptalgal structures. Domal stromatolites (LLH-S and some compound forms of Logan et al., 1964) form in modern intertidal flats with moderate to high energy, and a high sedimentation rate (Kendall
and Skipworth, 1968; Logan et al., 1964; Illing et al., 1965). Logan et al. (1964, p. 75) suggested that this form is restricted to protected areas where wave action is slight, the lateral extent of these colonies being determined by tidal amplitude and slope of the substrate. Chafetz (1973) and Aitken (1967) agreed with this energy interpretation. Contrarily, Gebelein (1969, p. 67) observed domal stromatolites in very high-energy subtidal areas, where domes become streamlined with the current. In the present study, however, domal stromatolites are not streamlined, and probably formed in protected intertidal environments.

Columnar stromatolites (SH-C and SH-V) also have been observed forming in both subtidal (Gebelein, 1969) and intertidal areas (Logan, 1961; Logan et al., 1964; and others). Gebelein (1969, p. 57) observed colonies of this morphotype in water depths and energy conditions intermediate between those of streamlined domal stromatolites (shallow, high energy) and cryptagalaminae (deeper, low energy). Those he saw were small (6 cm high), and showed an upward increase in diameter (SH-V). Columnar stromatolites in the present study are up to 40 cm high, with a constant 4 cm diameter (in part 2 of Section 8). These dimensions suggest an intertidal origin. A small tidal amplitude is suggested by the low relief (<2 cm) of individual layers in the columns.

Thrombolites are a puzzling cryptagal structure, in which algal layers are rarely well preserved. The clotted texture, which lends a mottled appearance to the enclosing rock, is recognizable in the lower units of part 1 in seven of the sections measured in this study. In hand specimens, it is difficult to distinguish between clotted thrombolites
and burrow mottling. Thin sections of these rocks reveal sediment- or pellet-filled burrows and trilobite fragments between clots, patchy recrystallization and dolomitization (discussed further with diagenesis), and other characteristics outlined by Aitken (1967, p. 1171) for recognizing thrombolites in Cambrian and Ordovician rocks. In his interpretation, these structures form below the tidal range, in areas where mats are not continuous. The environment may have been similar to that in the modern Florida backreef, where blue-green algae are patchily distributed due to the local disruptive effects of projections above the substrate (Frost, 1974), although grazing organisms also effect patchy distribution of algal mats in modern environments.

Physical requirements for the formation of oncolites (SS-C and SS-I) are summarized by Logan et al. (1964). The most important factors required for this form of algal growth are permanent submergence and either repeated or continuous agitation. The rarity of this morphotype in the present study area suggests that most of the time areas of subtidal algal growth were relatively quiet.

Trace fossils

Frey (1973) summarized the definitions and uses of trace-fossil terms. A burrow is "an excavation made within unconsolidated sediment," excluding intrastratal trails (p. 10). This usage includes the dwelling structures (domichnia) of Seilacher (1964) which are "simple, bifurcated, or U-shaped structures perpendicular or inclined to bedding ..." and "provide more or less permanent domiciles, mostly for semisessile, suspension-feeding animals" (in Frey, 1973, p. 12).
Seilacher (1967, p. 418) further stated that this burrow type is prominent in shallow environments. Rhoads (1967, p. 475) found that deep (up to 30 cm) vertical burrows are characteristic of intertidal conditions in modern environments, where they provide protection from extremes of temperature and salinity, and from desiccation.

Although burrows are rare, difficult to recognize, and never exceed 5 cm in length in the carbonate rocks of the present study, it is likely that these non-branching, vertical or oblique burrows, in late Cambrian time, were excavated in shallow subtidal or intertidal environments.

The epistratal traces observed in the study area are crawling traces (repichnia) and grazing traces (pasichnia) (Seilacher, 1953, in Frey, 1973, p. 13). Because the identities of the metazoans which left these traces are not known, no attempt is made by the present author to distinguish which activity was the cause of a particular trace. Seilacher (1967) acknowledged that these categories overlap, because both can result from the activities of metazoans traveling at or near the sediment-water interface in shallow water. Traces are associated with shallow to intermediate, subtidal environments, in both modern sediments (Seilacher, 1967, p. 418; Rhoads, 1967, p. 475) and ancient rocks (Laporte, 1969, p. 110; Howard, 1972, p. 216).

In this study, burrows perpendicular and oblique to bedding surfaces are associated with both grain- and mud-supported rocks which contain lithiclasts, fossil debris, and pellets, and locally have channeled contacts. The sediment within burrows is usually of a
different color or grain size than the enclosing rock, and was probably introduced later (McKee, 1964), although this relationship is difficult to prove in rocks completely recrystallized. The association of sedimentary features listed above with vertical burrows, common in part 1 of the present study, was found by Laporte (1969) in other ancient rocks. He interpreted this assemblage (including desiccation cracks) as an indicator of a highly variable, tidal-flat environment.

In contrast, epistratal traces are common on bedding surfaces of units which include subtidal cryptalgalaminae in the present study. Between these boundstones are oolitic and mixed-fossil grainstones. This association of lithologies provides further evidence that horizontal traces are most common in subtidal rocks (Laporte, 1969). Seilacher (1967, p. 421) stated that the gradation from intertidal protection burrows to subtidal surficial grazing tracks corresponds to the trend from suspension- to bottom-feeding, in response to the availability of food at higher and lower energy levels. This relationship between trace-fossil types and water energy and depth is displayed in the late Cambrian carbonate rocks of this study.

Observations of modern sediments have shown that bottom-dwelling metazoans are capable of totally reworking bottom sediments, and effectively destroying all evidence of the original bedding (Neumann et al., 1970; Piper and Marshal, 1969; Rhoads, 1967). Although most biogenic activity is restricted to the upper 2 to 3 cm of sediment, disturbance can extend as deep as 30 cm if conditions are favorable. In the present study, there is no evidence of deep or total reworking in carbonate rocks. The paucity of metazoans, mentioned with Cryptalgal
Structures, is a likely cause of relatively undisturbed sediments, although an intermittently rapid sedimentation rate also may have limited metazoan activity.

Biogenic pellets are also considered to be trace fossils (Frey, 1973, p. 7). This grain type is recognized by its small (commonly <0.15 mm) and constant size (Beales, 1965), and dark color, presumed to indicate fecal origin (Illing, 1954). Pellets are associated with many environments; they indicate shallow to extremely shallow water (Beales, 1965), perhaps with partly stabilized sandy substrates (Illing, 1954). Hanselman et al. (1974) interpreted ancient pelletal lime mudstones and wackestones as indicators of low turbulence and sedimentation, but assumed no fixed water depth. Laporte (1967) recognized pelletal mudstone in ancient supratidal, intertidal, and subtidal rocks, indicating that pellets can be transported from their site of origin to other environments.

In the present study, pellets are seen only in thin sections, infilling burrows, within lithiclasts (of pelletal mudstone), or rarely, in matrix material of oolitic and/or mixed fossil packstones. They are considered to be equivocal indicators of environment. Where pellets fill vertical burrows, the enclosing rocks are probably intertidal. Pelletal mudstones probably formed in quiet, subtidal areas. Pellets in oolitic packstones suggest mixing of sediments after the grains formed.
Body fossils

Segments of trilobites (class Trilobita) and plates of cystoids (class Cystoidea) comprise the megascopic fauna recognized in carbonate rock units. Other fragments resemble the valves of inarticulate brachiopods and spicules of sponges, but these were not positively identified. These same fossil types, plus sections of echinoderm spines and coralline algae, are seen in thin sections.

Trilobites apparently were exclusively marine (Shrock and Twenhofel, 1953, p. 579), and Cambrian forms were primarily vagrant bottom-dwellers (Tasch, 1973, p. 529). Individuals in this study probably represent either Aphelapsis, or Genevievellla, two common genera in Upper Cambrian rocks. Most Cambrian genera inhabited quiet environments, including shallow subtidal areas and protected bays, and lived in water less than 30 m deep (Tasch, 1973, p. 529). Trilobites dominate the fauna preserved in these rocks, because their molts added several exoskeletons per individual to the sediment (Lechman, 1957, p. 124), and possibly because few other vagrant organisms were available to move into the area during periods of favorable salinity or sedimentation rates.

Thoracic and pygidial segments of trilobites in these rocks are often the only fossil type on a particular bedding plane, and are usually oriented convex (dorsal side) upward. This orientation is hydraulically stable in moderate and high-energy environments, where exoskeletons are moved by wave action after the death of the organism (Schäfer, 1972, p. 163). The common condition of skeletons being
separated into several small parts might also suggest wave washing. However, when trilobites molted, they shed the outgrown test by crawling out between the cephalon and thoracic sections, leaving it fragmented into three or more parts, with the dorsal side of the thorax and pygidium upward (Harrington, 1959, p. 111). Therefore, the broken and convex-upward aspect of these exoskeletons does not necessarily indicate strong currents, and may suggest very quiet water.

Rocks containing trilobite molts with other fossil debris, lithiclasts, and oolites, suggest an environment different from that indicated by the molts alone. These mixtures are transported death assemblages, the components of which were washed together after the individual grain types had formed elsewhere (Lochman, 1957, p. 124). Some may be storm deposits.

The molts usually are concentrated in small sandy lenses and are not present in cryptagalaminae. They are present between cryptagal beds, however, as are the debris lenses. This suggests a variety of bottom conditions existing at one time through a large area (Lochman, 1957, p. 123), and frequent lateral migration of environments.

Crystoids apparently inhabited shallow, subtidal marine environments (Sinclair, 1957), where they thrived in quiet, clear-water areas, attached to firm substrates on which fine mud slowly accumulated (Lochman, 1957, p. 125). They fed on fine detrital fragments which they filtered from their surroundings (Sinclair, 1957).

Because cystoid plates dissociated when the animal died, the presence of single plates does not indicate turbulent water. However,
cystoid plates sometimes were transported by waves and currents, and deposited in mixed-debris lenses, as described previously.

Coralline algae, identified in one thin section, also indicate very shallow water (Friedman and Sanders, 1970).

The types and aspects of the body fossils in these carbonate units are compatible with the shallow environments indicated by cryptalgal and other structures.

**Oolitic rocks**

Bathurst (1971, p. 295-316) summarized the four physical and chemical conditions required for the growth of oolites, and the nature of that growth. Oolites are considered to be indicators of shallow water (1 to 3 m) (Bathurst, 1967, p. 448 and 464). The basic requirements of formation are water supersaturated with CaCO₃, available nuclei, agitation of those nuclei, and a mechanism for keeping grains within the lateral confines of these conditions (hydraulic and topographic factors in marine environments) (Bathurst, 1967, p. 450). Similar conditions were probably required for the growth of oolites in late Cambrian time, although they may have formed in slightly deeper water (Lochman, 1957, p. 146).

Clean oolitic grainstones, which in this study commonly exhibit low-angle cross-lamination, must have been deposited in agitated, shallow subtidal environments, where the oolites formed (similar to the oolite shoals of the modern Bahamian Platform, as described by Newell and Rigby, 1957, p. 54). Oolitic, mixed-fossil packstones and grainstones may have accumulated in marine-sand belts or tidal-bar
belts (Ball, 1967), also shallow subtidal. Mixtures of oolites with lithiclasts and pelletal mud suggest periodic transport of oolites into quieter or shallower water (Bathurst, 1967).

The lower average percentage of insoluble material in oolitic grainstones (4.0 percent compared to an average of 10.0 percent for all carbonate rocks) is a function of the high energy of the environment in which these rocks accumulated. Thin sections reveal that the average grain size of insoluble mineral grains (0.1 mm) is much smaller than the average size of oolites (0.7 mm). There was sufficient energy and time to remove most of the fine, non-carbonate particles from areas of oolite accumulation.

**Lithiclasts and "birdseye" structures**

Lithiclasts form in modern tidal flats, where carbonate mud and algal stromatolites shrink and crack when dry, to form flat, cohesive mud chips. These chips are reworked by tidal currents, transported short distances, and deposited in high-energy areas such as intertidal channels (Lucia, 1972, p. 168). Beds and lenses of imbricated elongate lithiclasts often form as supratidal storm deposits (Ball et al., 1967). Because of these modes of formation, lithiclast accumulations are commonly interpreted as supratidal or intertidal deposits.

No desiccation cracks were found in this study. In areas with a low seaward gradient or with fluctuating energy conditions, such cracks could be difficult to preserve. The upper layers of mud might be reworked as lithiclasts soon after they dried. Thus, desiccation cracks could be a continuous source of lithiclasts, rather than a preservable structure.
Subaerial exposure is not required for the formation of flat lithiclasts. Jindrich (1969) observed these structures forming by current erosion and accumulating in the mouths of subtidal channels in the Florida Keys. Lochman (1957, p. 143) stated that lithiclasts can accumulate in water up to 30 m deep. Considering the abundance of subtidal rocks in the present study, this origin for lithiclasts is possible. However, observed lithiclasts do not infill channels, are often imbricated, and are not laterally associated with other subtidal deposits such as cryptalgalaminia, undisturbed trilobite molts, or well sorted oolitic grainstones. For these reasons, most flat-lithiclast rocks studied are assumed to be intertidal, high-energy, essentially instantaneous storm deposits.

Smaller, rounded lithiclasts can have a similar origin, but increased transport commonly causes them to break apart and lose their original bedded character (Jindrich, 1969). Their smaller size makes them more susceptible to reworking.

In this study, small rounded lithiclasts are associated with mixed-fossil debris and oolites. Some were composed of dolomite when they were deposited (explained under Diagenesis). As stated previously, these mixed deposits represent high energy, shallow subtidal and intertidal accumulations, and considerable transport of grains.

"Birdseye" structures are perhaps the only unequivocal non-organic indicator of supratidal rocks. Shinn (1968) studied modern and ancient "birdseyes," and experimented with their formation. He determined that sediment shrinkage and gas bubbles are the most likely
causes (p. 217). "Birdseyes" sometimes form in intertidal (intermittently exposed) sediments, but never in subtidal sediments, which are too soft to prevent gas escape (p. 221).

In the present study, "birdseye" structures are only present in two thin (<10 cm) cryptalgal lime boundstones. They are elongate parallel to bedding, range from 0.7 to 3.5 mm in length, and comprise up to 20 percent of the rock. Both of the "birdseye" beds are overlain by elongate-lithiclast accumulations, and clearly indicate uncommon, supratidal deposition.

Other non-organic structures

Low-angle (<12°) cross-laminae, parallel laminae, and asymmetrical ripple-marks are present in carbonate rocks of sand-sized particles. These rocks are usually oolitic, mixed-fossil, or lithiclast grainstones. With the exception of oolitic grainstones, which are relatively pure carbonate, they usually contain more than 6 percent non-carbonate material. The environment indicated by these structures is the same regardless of the composition (carbonate or non-carbonate) of the grains. Because these structures are relatively rare in the carbonate rocks and extremely common in the terrigenous units, discussion of their origin is deferred until the next section.

Channeled bedding-plane contacts can originate by the erosive action of unidirectional, possibly tidal or wind-driven currents. These channels are commonly near the intertidal-marine boundary (Lucia, 1972), but can extend into subtidal areas, as noted by Jindrich (1969).
Maximum depth of channels observed in the present study is 6 cm. If their formation is assumed to have been intertidal, a small tidal amplitude is indicated.

**Terrigenous Rocks**

**Chemical implications of insoluble minerals**

Clay minerals of the illite group are the most common clays identified by X-ray diffraction in the insoluble residues of carbonate rock samples. Deer et al. (1963) described the probable source minerals and chemical requirements for formation of illite-type clays. Illites are usually weathering products of feldspars, and are often deposited with terrigenous material. Illites are very stable in marine and other alkaline environments, although they are sometimes partially weathered during transport in fresh water.

Chlorite is also present in many insoluble residues. According to Powers (1957), chlorite commonly forms in marine environments, principally from the diagenesis of montmorillonite or weathered illite.

Kahle (1965) suggested the possibility of a relationship between insoluble minerals, especially clays, and the formation of dolomite. The experimental work of Hatfield and Rohrbacker (1966) and Lumsden (1974) indicate that insoluble materials do not facilitate dolomitization. The results of the present study corroborate these findings (discussed under Distribution of Insoluble Residues).

Quartz in these late Cambrian rocks is terrigenous, except where it is cement in quartzites, or is locally microcrystalline. The
feldspars (mainly oligoclase) in non-carbonate units are also terrigenous; their rounded grain boundaries suggest considerable transport. Many grains exhibit albite or microcline twinning, characteristic of an igneous origin (Folk, 1968, p. 86). Feldspars in the carbonate units are difficult to recognize because of their small size and similarity to quartz, but are probably terrigenous. Because these minerals are stable in many environments, they do not provide definite information about water chemistry.

The presence of hematite and limonite in these rocks is probably related to post-depositional oxidation of reduced iron minerals.

**Structures in sandstones and quartzites**

The most common, non-organic, primary sedimentary structure in non-carbonate rocks of this study is low-angle (<12°) planar cross-lamination, in laminasets of even, parallel laminae 20 to 50 cm thick. The great lateral extent of these structures, in most quartzite and sandstone beds of part 3 throughout the study area, suggests deposition in a tide- or wind-dominated foreshore-beach, marine-sand belt, or tidal-bar belt, modern environments in which cross-laminae are common (Goldring and Bridges, 1973; McKee, 1964; Ball, 1967). The laminae are probably the internal structure of dunes or sand waves, structures which form in the lower flow regime (Simons et al., 1965, p. 38).

Even parallel laminae ("flat horizontal stratification" of McKee, 1964, p. 278) are common in modern tidal flats, in lagoons, and in shallow-marine environments (McKee, 1964; Reineck, 1972). Those in the
present study probably are not counterparts of plane beds of the transition from lower to upper flow regime (high-energy environments). They are present in every sandstone unit and may represent periods of rapid sediment influx in very shallow water.

Ripples form under low-energy conditions in the lower flow regime (Simons et al., 1965). According to McKee (1964), ripples are characteristic of many environments; they can form in lagoons, on tidal flats, and landward of or within sand belts, and in some non-marine environments. Asymmetrical and flat-topped ripple-marks were recognized in the late Cambrian rocks of the present study. Asymmetrical ripples probably were formed by longshore or tidal currents. Transport to the south or southeast is suggested by orientations of some ripple-marks in Sections 1, 5, and 6. Flat-topped ripple-marks, present in Section 1, originally may have been either current or oscillation ripples. The ripple crests probably were flattened by wind during subaerial exposure.

Calcitic and/or dolomitic sandstone units 1 to 12 m thick are present in part 2 of Sections 2, 6, 7, and 8. These units are not traceable among sections, and represent local terrigenous accumulations. All of these sandstone units include even parallel laminae, and some have low-angle cross-laminae also. Because these units are underlain and overlain by marine carbonates, and cemented with carbonate, it is presumed that they were deposited in a marine environment. In contrast to the terrigenous rocks of part 3 which locally were burrowed extensively (discussed later), these thin sandstones of part 2 contain no
burrows or other trace fossils. The fact that burrowing organisms were present, to some extent, to leave trace fossils in other terrigenous and some carbonate beds, but did not burrow in these local sand accumulations, suggests that the sand in these beds was deposited and buried rapidly.

Storm waves and currents, and rip currents are capable of carrying sand offshore and depositing it as sheets in marine environments (Goldring and Bridges, 1973). River floods, or unusually high tides followed by strong outrush can also carry sandy sediments far seaward of bays to effect geologically instantaneous deposition of thin sandstones in a marine carbonate sequence. One or all of these mechanisms could have deposited these thin terrigenous beds in part 2.

The calcitic and dolomitic sandstones do not represent any long-term changes in sedimentation. Carbonate precipitation persisted to cement them. Contrarily, many quartzite units in part 3 are carbonate-free; some that are dolomitic did not receive this dolomite until after cementation (as shown by dolomite-embayed quartz overgrowths, discussed under Diagenesis of Terrigenous Rocks).

Carbonate-free quartzites, especially common in the northern part of the study area (Sections 6, 7, and 8) indicate a temporary cessation of carbonate deposition. In the other sections, and continuing southward, this cessation was intermittent, as shown by the presence of some carbonate-rich beds intercalated with the quartzites of part 3. Some change in the source area probably caused the increased influx of sand-sized terrigenous quartz and feldspar. The provenance change could
have been increased relief, changes in run-off patterns, or increased exposure with closer proximity, and may have caused more acidic run-off to decrease the pH of nearshore water to a level that inhibited carbonate production.

The quartzites of part 3 in all sections are burrowed locally. Most non-branching burrows are perpendicular to bedding surfaces, although a few are oblique. All have constant 3 to 6 mm diameters, and range in length up to 12.5 cm. These are probably the protection dwelling structures (domichnia) of Seilacher (1967). Some beds are completely burrow churned ("bioturbation structure" of Frey, 1973, p. 9), and neither individual burrows nor original laminae are distinguishable. Below these burrowed layers, parallel or cross-laminae are usually visible in the remainder of the bed. These bioturbated horizons indicate a local, temporary cessation of deposition, probably in areas with currents which transported any incoming sediment without significantly eroding previous deposits. This cessation gave shallow infaunal organisms sufficient time to rework the sediment, probably in shallow-marine rather than intertidal areas (Rhoads, 1967). Burrows are the only fossils in quartzite beds, although epistratal traces are present on the surface of two sandstone beds of part 3 (Sections 2 and 8).

Shales

Because they cannot be traced among sections, all shale beds in this study represent local conditions. South of the study area, Bircher (oral communication, 1973) found a persistent shale marker bed at the
top of the Worm Creek Member (part 3). Section 1, the southernmost of the present study, is the only section which includes this unit.

Shale beds in this study are dark colored (N3 and N2), apparently because of the presence of iron sulfides. These shales are either overlain or underlain by sandstone or quartzite beds. They contain little carbonate (<10 percent in one sample), and are composed of microcrystalline quartz (identified by binocular microscope), oligoclase, and locally hyalophane. The association with cross-bedded terrigenous rocks suggests deposition in or near shallow water. Fine grain size and reduced iron minerals suggest quiet water. The shales probably accumulated in local lagoons caused by sand or other barriers, where suspended terrigenous material limited the growth of calcareous biota and the formation of carbonate sediment. Soft-bodied bottom-feeding organisms left traces on bedding surfaces, and these are the only fossils in shale beds.
Thin sections of most grain-supported limestones show evidence of early cementation. The fabrics of radial-fibrous cement rims, with crystals oriented perpendicular to grain boundaries, are still visible, even where recrystallized and included in large crystals of pseudospar. This type of cement is typical of non-organic marine cementation, either in beachrock or in submarine crusts (Bathurst, 1971, p. 371; Land, 1970; Boyer, 1972; Fischer and Garrison, 1967; Folk, 1974). These rocks include abundant intertidal characteristics, as previously described, and do not have the borings, micritization, and irregular surfaces of hardgrounds (Bathurst, 1971, p. 373). For these reasons, the cement rims probably represent syngenetic precipitation of aragonite or high-magnesium calcite (>10% Mg), in an intertidal or shallow subtidal environment, in which abundant Mg prevented the sideward growth of large, blocky crystals (Folk, 1974; Folk and Land, 1975).

Mud-supported rocks were also being cemented at this time, but not as rapidly or obviously (they have no rim cements). Cementation in muddy environments can be inhibited by reduced flux of dissolved carbonate, and the prevention of overgrowths by organic films (Boyer, 1972), and this may have happened in the rocks of the present study.
Because there is no evidence of subaerial exposure soon after early cementation, it is probable that most of the loss of porosity occurred anagenetically. The sparsely cemented sediments were buried as deposition continued. Heating of the sediments and their connate brines might have caused a relative increase in CO$_3$\textsuperscript{-} and a decrease in the solubility of carbonate minerals, to effect slow precipitation of cement (MacKenzie and Bricker, 1971, p. 243; Land, 1973; Purdy, 1968).

The development of iron-mineral coatings on skeletal grains, and the growth of small pyrite and magnetite crystals (observed in three thin sections) were probably early changes in the sediment. Reducing conditions may have been enhanced by buried organic matter, and permitted crystallization of reduced iron minerals.

Syngenetic dolomite formed periodically, probably by replacement of less stable carbonate phases (Degens, 1965, p. 121) and by filling voids. In the two previously mentioned cryptalgal lime boundstones which contain "birdseye" structures, the "birdseyes" are filled with clear dolomite spar, and there is no apparent dolomite in the rest of the rock. If this dolomite formed in a hypersaline environment, it is unlikely that only the "birdseyes" would have been dolomitized. The clarity of these structures may suggest fresh-water diagenesis (the "limpid dolomite" of Folk and Land, 1975, p. 65), later recrystallization having obscured the original crystal shapes but having maintained this stable (pure and non-ferroan) mineral phase.

Further evidence for limited syngenetic dolomitization comes from small, rounded clasts, consisting of iron hydroxides and carbonate
rhombohedrons (seen in 10 thin sections). Evamy (1969), Folkman (1969), and Al-Hashimi and Hemingway (1973) described this relationship as a product of the replacement of ferroan dolomite by calcite. According to Evamy (1969), ferroan carbonates can form locally below the water table where organic matter causes a reducing environment. Ferrous iron is substituted into the carbonate lattice in these conditions, and if dolomitization takes place in the same environment, the ferrous iron is included in the dolomite. Later, when the relatively unstable ferroan dolomite is epigenetically replaced by calcite in an oxidizing environment, the iron becomes oxidized and will no longer fit into the carbonate crystal lattice. The iron is ejected from the lattice, and the result is an association of rhombohedral calcite crystals surrounded by hematite and limonite. A similar sequence of events may have caused this association in rocks of the present study. Resultant grains originally would have been ferroan calcite, were syngenetically replaced by dolomite (before being reworked), then epigenetically replaced by calcite.

The early dolomitization from which these lithiclasts were derived must have been spatially and temporally localized. There are no beds of this type of dolomite. The only evidences are clasts and small patches in limestones of part 1 which have retained much of their depositional fabric. Because the small amount of ferroan dolomite was reworked as lithiclasts, it probably formed supratidally. Short-lived areas of evaporative pumping of brine into organic-rich near-surface sediments could have formed this patchy dolomite prior to erosion.
(Hsü and Siegenthaler, 1971; Milliman, 1974). The small amounts of surface evaporites that should have formed by this mechanism could have been dissolved by fresh water or by normal-marine water during spring tides.

Secondary changes

The exact timing of recrystallization of skeletal grains and oolites from aragonite and Mg-calcite to calcite cannot be determined, because all rocks have been wholly recrystallized. There is no evidence for the dominant subsea micritization reported by Purdy (1968, p. 185). This lack may suggest that deposition was rapid and micritization thus prevented, or that micrite was destroyed by later recrystallization to pseudospar. Recrystallization is documented for all types of grain fabrics.

Most of the original carbonate material was probably aragonite and Mg-calcite, which recrystallized to calcite soon after the sediment lost contact with the marine environment through burial (Friedman, 1964). This first recrystallization was, in many units, solution and precipitation on a small scale, which maintained some fine textures such as oolite layers and echinoderm pores (same reference). Thin sections of lime packstones and grainstones show large crystals which cover several grains or parts of grains and cement patches, and within which are ghosts of other crystal boundaries cutting across grains. This combination indicates the occurrence of at least two periods of recrystallization.
The models of dolomitization by seepage refluxion (Deffeyes et al., 1965) and evaporative pumping (Hsü and Siegenthaler, 1971) share several characteristics which make them unlikely to have been the origin of dolostone units in this sequence. To form dolomite through a large area, both models require vast tidal flats, where evaporation exceeds precipitation, so that concentrated brines form. The dolomite is usually supratidal, in surface crusts associated with desiccation cracks, "birdseye" structures, elongate lithiclasts, evaporite minerals, and supratidal algal structures (Shinn et al., 1965; Nicholi, 1974; Milliman, 1974, p. 309). In ancient rocks, the former presence of evaporites is evidenced by crystal molds (Lucia, 1972). Supratidal dolomitization cuts across bedding planes (Deffeyes et al., 1965), and affects only the shoreward, intertidal sediments of an environment (Zenger, 1972).

In modern areas of carbonate precipitation where no dolomite is forming, there are usually no evaporite minerals (Cloud, 1962). In the present study, dolostone beds are devoid of evaporite crystal molds, and all other supratidal structures. The dolostones include oolitic grainstones, even parallel-cryptalgalaminate boundstones, and mixed-fossil-, rounded lithiclast-, and oncolite grain-supported rocks. There is no evidence of a supratidal or syngenetic origin for these dolostones.

In most cases, thin sections of these dolostones show little of the original structures. These rocks are composed of very coarsely crystalline anhedral dolomite. There are no reduced iron minerals,
and rocks are light colored. These characteristics have been used to identify late or secondary, intensive dolomitization in ancient rocks (Leighton and Pendexter, 1962; Evamy, 1967; Whitcombe, 1970; Nicholi, 1974).

Section 4 has no dolostone, and rocks are dark-colored, with clearly visible structures, so it is not likely that they were ever dolomitized. Section 4 includes the same types of structures that are present in the rest of the study area, indicating no environmental difference to account for this lack of dolomite. This suggests that not all dolomitization was related to a single event, and that major dolomitization was not syngenetic.

Dolomitization in a zone of mixing of ground water and sea water may be an applicable model. Hanshaw et al. (1971) experimentally determined that the Mg/Ca ratio attained in brackish-water zones is adequate for dolomitizing sediments, other conditions being favorable, in areas where there is no great evaporation or concentration of Mg. Given sufficient time and a circulating supply of water, dolomite can replace calcite in mixed fresh and salt water with a Mg/Ca value slightly greater than 1:1. This mixture can be attained in areas of periodic water-mixing during storms (schizohaline environment of Folk and Land, 1975), in areas of gradual subsidence which allows mixing, or at the contact of a freshwater lens with salt water along a coast (Badiozamani, 1973). Initially, replacement in this manner would not destroy textures (Land, 1973). Given the amount of time required to complete extensive dolomitization in this way, and the likelihood
of aggrading recrystallization in deep epigenetic environments, massive coarsely crystalline dolostone would form.

Sea-level, climatic, and tectonic changes could cause lateral migration of this mixed-water zone (Hanshaw et al., 1971). Meteoric solutions could easily infiltrate permeable carbonate sediments. Mixtures of salt and fresh water in meteoric environments could move laterally to appreciable depths, where increased temperature increases the rate of dolomite formation with an even lower requirement of Mg$^{++}$ (Land, 1973). This is a sufficient mechanism for large-scale dolomitization of subtidal and intertidal carbonate rocks, and may be the method by which all dolostones in the present study were formed.

Figure 4 shows that the percentage of dolomite (and therefore of dolostone) in each section generally increases northward and eastward, directions which are presumed to have been shoreward. Apparently, more of the section was dolomitized in areas adjacent to the sources of fresh water. The dolomitized rocks do not represent a shallower water facies, however, as indicated by the structures they contain.

Stylolites, present in most carbonate units in this study, are visible in hand specimens and thin sections. They commonly separate areas of different textures, and are usually marked by concentrations of iron hydroxides. Beginning their formation early in subsurface diagenesis, stylolites are an important source of early cement (Park and Schot, 1968). Insoluble minerals become concentrated along these surfaces as the thickness of carbonate sediment is reduced (Bathurst, 1971, p. 471). This is a possible origin of the shaly partings within and between beds in the upper units of part 3, Section 1.
Terrigenous Rocks

Cementation occurred in approximately the same way in carbonate-cemented quartz sandstones that it did in carbonate rocks. The sudden dominance of detrital sediments inhibited carbonate precipitation during deposition of much of the Worm Creek Member, and the resulting rocks were cemented with quartz and feldspar overgrowths. The cementation possibly began syngenetically: authigenic Na-plagioclase forms easily in contact with sea water, which serves as a source of Na$^+$ ions (Degens, 1965, p. 50). The quartz overgrowths formed by optically continuous chemical precipitation (Pettijohn et al., 1972, p. 216).

Some of the quartzites are locally dolomitic. Seen in thin sections, dolomite crystals often embay or partially replace both quartz grains and overgrowths. The dolomite was introduced into the quartzite after lithification by quartz overgrowths, during later dolomitization.

Shale beds locally contain chert, but no detrital quartz. The chert is probably anagenetic, possibly having formed by solution of quartz grains during deep burial, and re-precipitation.
PALEOGEOGRAPHIC SETTING

Site of Deposition

The sequence studied was deposited on a broad, shallow shelf, probably with a low seaward gradient and tidal range. This is indicated by the low amplitude of domal and columnar stromatolites, and channels, and the abundance of subtidal rocks with a paucity of intertidal and supratidal deposition. The greatest thickness of carbonate material is in a north-south-trending region in the center of the study area (Appendix A, Figure 2). This region possibly experienced more rapid differential subsidence, which resulted in thicker accumulation of shelfal carbonates.

The water depth at any location probably changed repeatedly, on a small scale with seasonal changes in run-off and wind, and on a larger scale with tectonic movements. There are no obvious unconformities in the sequence, suggesting that all changes in water depth and sediment influx were gradual. There is no proven hiatus between the upper Nounan and Worm Creek members. The percentage of terrigenous material in the rocks does not change greatly across this planar contact, and there are no indicators of a change in water depth. However, the contact is very sharp, except perhaps in Sections 3, 4, and 7, where it is not exposed, and may represent a period of shoaling and non-deposition as the terrigenous-sediment source became dominant.

Deposition of the Worm Creek Member (part 3) possibly started first in the northwest, after which the sand gradually spread southward
across the study area and into Utah. As the sand source began to diminish, deposition ceased first in the south. This is a probable cause of very thin (<25 m) accumulations in north-central Utah (Hanson, 1953).

In most of the study area (Sections 1 through 6), carbonate deposition resumed above the quartzites prior to deposition of the upper St. Charles. The rocks in the upper units of part 3 are not everywhere the same, and reflect local environmental differences. No carbonates were deposited in the Worm Creek Member in Sections 7 and 8, probably because terrigenous deposition continued, in the northwest part of the study area, after it had ceased elsewhere (Appendix A, Figure 3).

Source of Terrigenous Sediments

The total percentage of terrigenous material in the upper Nounan-Worm Creek sequence, and the thickness of the Worm Creek Member, both increase toward the north or northwest in the study area (Appendix A, Figures 2 and 3). In Sections 7 and 8, the Worm Creek (part 3) includes no carbonate rock units (Appendix A, Figure 5), and the quartzites in Section 6, 7, and 8 show a marked increase in grain size, compared to those in part 3 in the other five sections (sorting and rounding were not numerically compared). These factors indicate a source area to the north or northwest, in central Idaho, which is consistent with the conclusions of previous workers (Gardiner, 1974; Bircher, oral communication; Hanson, 1953; James, 1972).
The rocks of the source area were at least partially igneous, indicated by the abundance and grain sizes of single-crystal quartz and feldspar grains (Folk, 1968, p. 71). The rocks were sialic, including oligoclase, microcline, and hyalophane. The larger oligoclase crystals may suggest that two distinct rock types were being eroded in the source area. The microcline crystals are apparently more rounded, and may be from reworked arkosic sands (Bircher, in preparation).

In Section 5, the percentage of terrigenous material in carbonate rocks of part 2 increases significantly up section toward the Worm Creek contact (Figure 5). Field evidence suggests this same relationship in part 2 of Sections 6, 7, and 8, although isolation of more insoluble residues is needed to prove it. In Section 1, however, there is no correlation between percent terrigenous material and distance up section. The percentage of insoluble material in the carbonates fluctuates widely through parts 1 and 2. Section 1 also has a greater total percentage of non-carbonate material than have Sections 2 through 5, and locally reverses the trend of decreasing percent terrigenous sediment with increasing distance from the postulated sediment source to the northwest (Appendix A, Figure 3). These facts may suggest that a second, sporadic source of terrigenous material was exposed to erosion east or southeast of the study area during accumulation of the upper Nounan member (parts 1 and 2). However, the mineralogy and grain size of the terrigenous material deposited in Section 1 are similar to those of the other sections. The terrigenous influx in Section 1 could be attributable to concentration by longshore currents, or to a fluvial connection to the same, northwest, sediment source.
SUMMARY OF ENVIRONMENTAL AND DIAGENETIC CONDITIONS

All rock types and characteristics in this Upper Cambrian sequence indicate shallow-marine, intertidal, or lagoonal deposition. The fossiliferous limestones of part 1 include vertical burrows, low-angle cross-laminae, lithiclasts (some formerly dolomite), and a few "birds-eye" structures and thrombolites. Shallow subtidal conditions prevailed, with infrequent shifts to supratidal and intertidal deposition. An oolitic grainstone unit, at the base of part 2, marks the beginning of predominantly subtidal conditions.

The interbedded limestones and dolostones of part 2 include thick sequences of cryptalgalaminae, mostly deposited subtidally. Local thin sandstones up to 12 m thick probably were deposited subtidally during storms (in four sections). Beds and lenses of imbricated, elongate lithiclasts also may be storm deposits. Small stagnant lagoons are suggested by local dark colored shales. The terrigenous influx gradually increased through time, although carbonate deposition still dominated through part 2.

Thick cross-laminated and locally burrowed quartzite beds represent a cessation of carbonate deposition at the base of part 3. An increase in the supply of terrigenous sand overwhelmed carbonate production, and possibly lowered the pH of the coastal water enough to allow some beds to be quartz-cemented, although carbonate was locally and/or temporarily available to cement some sandstones.
Carbonate deposition resumed in the study area south of Sections 6, 7, and 8 after the main terrigenous influx, and interbedded sandstones and dolostones above the quartzite suggest an intermittent and dwindling supply of terrestrial sand. Cryptalgalaminae and parallel laminae in the carbonates of part 3 suggest shallow subtidal deposition.

Recent tidally dominated areas include a wide range of conditions, and provide an ideal setting for the deposition of many sediment types (Matter, 1967). Coastal areas are very sensitive to minor changes, such as winds, storms, and seasonal changes in sea level. These and many other factors contribute to the complexity of the rock record of shoreline and nearshore areas at present, as they probably did for the late Cambrian sequence of the present study.

Considering the size of the study area and the fact that these units extend much farther southward and westward, it is improbable that a single tidal-flat and adjacent shallow-marine environment covered this region throughout the length of time required for deposition of a sequence up to 335 m thick. Water depth probably changed repeatedly at any one location, within the general framework of shallow subtidal deposition.

Early diagenesis of carbonates included subsea, rim cementation in medium and coarse-grained rocks, and production of a minor amount of intertidal and supratidal syngenetic dolomite. Aggrading recrystallization affected all carbonate units, probably during a later period. Quartzites and sandstones probably were cemented syngenetically, by quartz and feldspar overgrowths and by carbonate minerals, respectively.
Dolomitization probably occurred in a zone of mixed fresh water and sea water, and may have begun syngenetically. It persisted until a much later time, to produce all dolostone units in the sequence and cause dolomite embayment of quartz and feldspar grains and overgrowths in some quartzites of part 3.
REFERENCES CITED


APPENDICES
Figure 1. Index map showing outcrops of Nounan Formation and Worm Creek Member (in black), locations of measured sections (numbered), and geologic map sources (lettered).
Figure 2. Thicknesses of the upper Nounan member (parts 1 and 2: solid lines, contour interval = 25 m) and Worm Creek Member (part 3: dashed lines, contour interval = 10 m).
Figure 3. Total percentages of carbonate and non-carbonate material, based on thickness and weight percent, covered intervals omitted (parts 1 and 2: contour interval for non-carbonate material = 5%).
Figure 4. Total percentage of dolomite in carbonate rocks, based on thickness and dolomite percentage of each unit, upper Nounan member (parts 1 and 2).
Figure 5. Generalized geologic section showing stratigraphy, rock types, and colors of upper Nounan and Worm Creek Members in Bear River and Fish Creek Ranges, southeast Idaho.
Figure 6. Percent insoluble material in sample vs. distance from base of section, with linear regression from part 2 of Section 5.
Appendix R

Tables
Table 1. Petrographic, X-ray, and insoluble-residue data of dissolved-rock samples, with composition of insoluble minerals

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Section</th>
<th>Unit</th>
<th>Rock Name</th>
<th>% Insoluble</th>
<th>Composition (non-carbonate fraction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-0A</td>
<td>1</td>
<td>1</td>
<td>Fxn lithiclast lime packstone</td>
<td>3.0</td>
<td>quartz, oligoclase, illite (X, t.s.)</td>
</tr>
<tr>
<td>A-OB</td>
<td>1</td>
<td>1</td>
<td>Cxn pellet-lithiclast mixed-fossil lime packstone</td>
<td>2.0</td>
<td>quartz, oligoclase, hematite, chlorite (X), limonite (t.s.)</td>
</tr>
<tr>
<td>A-OC</td>
<td>1</td>
<td>1</td>
<td>Vfxn lime mudstone</td>
<td>7.6</td>
<td>quartz, oligoclase, illite (X), hematite (t.s.)</td>
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<tr>
<td>A-9B</td>
<td>1</td>
<td>2</td>
<td>Vfxn and Cxn lithiclast mixed-fossil lime wackestone and mudstone</td>
<td>2.3</td>
<td>quartz, oligoclase (X), hematite, limonite (t.s.)</td>
</tr>
<tr>
<td>A-15A</td>
<td>1</td>
<td>2</td>
<td>Mxn lithiclast trilobite lime grainstone</td>
<td>3.6</td>
<td>quartz, oligoclase (X), hematite (t.s.)</td>
</tr>
<tr>
<td>A-17</td>
<td>1</td>
<td>2</td>
<td>Mxn lithiclast trilobite lime grainstone</td>
<td>2.9</td>
<td>quartz, limonite (t.s.)</td>
</tr>
<tr>
<td>A-18</td>
<td>1</td>
<td>3</td>
<td>Fxn sandy crystalline limestone</td>
<td>29.4</td>
<td>quartz, oligoclase, chlorite (X), hematite, limonite (t.s.)</td>
</tr>
<tr>
<td>A-19A</td>
<td>1</td>
<td>4</td>
<td>Cxn and Cgr lithiclast lime packstone</td>
<td>4.6</td>
<td>quartz (t.s.)</td>
</tr>
<tr>
<td>A-22B</td>
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<td>5</td>
<td>Fxn lithiclast oolite lime packstone</td>
<td>3.3</td>
<td>quartz, oligoclase (X)</td>
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<tr>
<td>A-25A</td>
<td>1</td>
<td>5</td>
<td>Mxn cryptalgal lithiclast trilobite lime boundstone</td>
<td>21.8</td>
<td>quartz, oligoclase, chlorite (X), limonite (t.s.)</td>
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</table>
Table 1. (continued)

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<tr>
<th>Sample No.</th>
<th>Section</th>
<th>Unit</th>
<th>Rock Name</th>
<th>% Insoluble</th>
<th>Composition (non-carbonate fraction)</th>
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</thead>
<tbody>
<tr>
<td>A-28A</td>
<td>1</td>
<td>6</td>
<td>Mxn sandy crystalline limestone</td>
<td>14.8</td>
<td>quartz, oligoclase (X)</td>
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<tr>
<td>A-35</td>
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<td>7</td>
<td>Mxn crystalgal dolomite boundstone</td>
<td>30.8</td>
<td>quartz, oligoclase, illite, chlorite (X, t.s.)</td>
</tr>
<tr>
<td>A-36A</td>
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<td>7</td>
<td>Vcxn lithiclast dolomite packstone</td>
<td>3.4</td>
<td>(not determined)</td>
</tr>
<tr>
<td>A-41A</td>
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<td>7</td>
<td>Cxn oolite dolomite grainstone (altered to crystalline dolostone)</td>
<td>1.4</td>
<td>quartz, oligoclase, microcline, illite (X, t.s.)</td>
</tr>
<tr>
<td>A-45A</td>
<td>1</td>
<td>7</td>
<td>Cxn crystalline dolostone</td>
<td>4.4</td>
<td>quartz, oligoclase, illite, chlorite (X, t.s.)</td>
</tr>
<tr>
<td>A-49A</td>
<td>1</td>
<td>8</td>
<td>Vcxn mixed-fossil lime grainstone</td>
<td>2.3</td>
<td>quartz, oligoclase, hematite (X, t.s.)</td>
</tr>
<tr>
<td>A-53</td>
<td>1</td>
<td>9</td>
<td>Fxn sandy crystalline dolostone</td>
<td>18.6</td>
<td>quartz, oligoclase, chlorite (X)</td>
</tr>
<tr>
<td>A-59</td>
<td>1</td>
<td>10</td>
<td>Vcxn crystalline dolostone</td>
<td>1.1</td>
<td>quartz, oligoclase, illite (X), limonite (t.s.)</td>
</tr>
<tr>
<td>A-66</td>
<td>1</td>
<td>13</td>
<td>Fxn to Mxn crystalgal lithiclast dolomite boundstone</td>
<td>15.8</td>
<td>quartz, oligoclase, illite (X), limonite (t.s.)</td>
</tr>
<tr>
<td>A-71</td>
<td>1</td>
<td>14</td>
<td>Mgr dolomitic sandstone</td>
<td>70.2</td>
<td>quartz, oligoclase, illite (X, t.s.)</td>
</tr>
</tbody>
</table>
Table 1. (continued)

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Section</th>
<th>Unit</th>
<th>Rock Name</th>
<th>% Insoluble</th>
<th>Composition (non-carbonate fraction)</th>
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</thead>
<tbody>
<tr>
<td>A-90</td>
<td>1</td>
<td>19</td>
<td>Fgr calcareous siltstone</td>
<td>59.7</td>
<td>quartz, oligoclase, illite (X, t.s.)</td>
</tr>
<tr>
<td>E-0</td>
<td>5</td>
<td>1</td>
<td>Vfxn and Mxn mixed-fossil lime wackestone and cryptalgal boundstone</td>
<td>9.5</td>
<td>quartz, oligoclase (X), limonite, hematite (t.s.)</td>
</tr>
<tr>
<td>E-9</td>
<td>5</td>
<td>1</td>
<td>Vfxn sandy lime mudstone</td>
<td>13.2</td>
<td>quartz, oligoclase, illite (X), hematite, limonite, pyrite (t.s.)</td>
</tr>
<tr>
<td>E-5</td>
<td>5</td>
<td>1</td>
<td>Vfxn, locally Cxn, lithiclast trilobite lime wackestone</td>
<td>4.2</td>
<td>quartz, oligoclase, goethite (?) (X, t.s.)</td>
</tr>
<tr>
<td>E-12B</td>
<td>5</td>
<td>2</td>
<td>Vcxn oolite lump lime grainstone</td>
<td>4.5</td>
<td>quartz, oligoclase, illite (X, t.s.)</td>
</tr>
<tr>
<td>E-15A</td>
<td>5</td>
<td>3</td>
<td>Vcxn oolite mixed-fossil lime packstone</td>
<td>5.9</td>
<td>quartz, oligoclase, hematite (X, t.s.)</td>
</tr>
<tr>
<td>E-17</td>
<td>5</td>
<td>3</td>
<td>Cxn oolite mixed-fossil lime grainstone</td>
<td>4.4</td>
<td>quartz, oligoclase, illite, chlorite (X)</td>
</tr>
<tr>
<td>E-17C</td>
<td>5</td>
<td>3</td>
<td>Vcxn oolite lithiclast mixed-fossil lime grainstone</td>
<td>9.7</td>
<td>quartz, oligoclase, chlorite, illite (X), limonite (t.s.)</td>
</tr>
<tr>
<td>E-20A</td>
<td>5</td>
<td>4</td>
<td>Fgr calcareous sandstone and Fxn cryptalgal boundstone</td>
<td>75.3</td>
<td>quartz, oligoclase (X), hematite (t.s.)</td>
</tr>
<tr>
<td>E-17C</td>
<td>5</td>
<td>5</td>
<td>Cxn oolite lithiclast dolomite grainstone</td>
<td>1.8</td>
<td>(not determined)</td>
</tr>
<tr>
<td>Sample No.</td>
<td>Section</td>
<td>Unit</td>
<td>Rock Name</td>
<td>% Insoluble</td>
<td>Composition (non-carbonate fraction)</td>
</tr>
<tr>
<td>------------</td>
<td>---------</td>
<td>------</td>
<td>----------------------------------</td>
<td>-------------</td>
<td>---------------------------------------------------------------------------</td>
</tr>
<tr>
<td>E-24</td>
<td>5</td>
<td>6</td>
<td>Mxn crystalline limestone</td>
<td>7.1</td>
<td>quartz, oligoclase (X), hematite, limonite (t.s.)</td>
</tr>
<tr>
<td>E-33B</td>
<td>5</td>
<td>7</td>
<td>Mxn and Fxn oolite lime grainstone</td>
<td>8.4</td>
<td>quartz, oligoclase, chlorite (X, t.s.)</td>
</tr>
<tr>
<td>E-40</td>
<td>5</td>
<td>8</td>
<td>Cxn crystalline dolostone</td>
<td>5.3</td>
<td>(not determined)</td>
</tr>
<tr>
<td>E-49</td>
<td>5</td>
<td>10</td>
<td>Cxn crystalline dolostone</td>
<td>8.1</td>
<td>(not determined)</td>
</tr>
<tr>
<td>E-54</td>
<td>5</td>
<td>12</td>
<td>Mxn sandy cryptalgal dolomite boundstone</td>
<td>10.0</td>
<td>(not determined)</td>
</tr>
<tr>
<td>E-59</td>
<td>5</td>
<td>13</td>
<td>Mxn sandy cryptalgal dolomite boundstone</td>
<td>34.7</td>
<td>(not determined)</td>
</tr>
<tr>
<td>E-63</td>
<td>5</td>
<td>13</td>
<td>Mxn sandy cryptalgal dolomite boundstone</td>
<td>45.0</td>
<td>(not determined)</td>
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<tr>
<td>E-75A</td>
<td>5</td>
<td>16</td>
<td>Vcxn lithiclast mixed-fossil dolomite wackestone (?)</td>
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<td>quartz, hematite, goethite (X), limonite (t.s.)</td>
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<tr>
<td>E-81</td>
<td>5</td>
<td>17</td>
<td>Vfgr calcareous sandstone</td>
<td>79.3</td>
<td>quartz, oligoclase, illite (X), limonite (t.s.)</td>
</tr>
<tr>
<td>B-33</td>
<td>6</td>
<td>5</td>
<td>Mxn lithiclast pellet lime grainstone</td>
<td>3.1</td>
<td>quartz, oligoclase, hematite illite (X, t.s.)</td>
</tr>
<tr>
<td>Sample No.</td>
<td>Section</td>
<td>Unit</td>
<td>Rock Name</td>
<td>% Insoluble</td>
<td>Composition (non-carbonate fraction)</td>
</tr>
<tr>
<td>------------</td>
<td>---------</td>
<td>------</td>
<td>-----------</td>
<td>-------------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td>C-23</td>
<td>7</td>
<td>6</td>
<td>Vfxn, locally Cxn, cryptalgal lime boundstone</td>
<td>18.9</td>
<td>quartz, limonite (t.s.)</td>
</tr>
</tbody>
</table>

**Grain size**
- Vcgr - very coarse grained
- Cgr - coarse grained
- Mgr - medium grained
- Fgr - fine grained
- Vfgr - very fine grained

**Crystal size**
- Vcxn - very coarsely crystalline
- Cxn - coarsely crystalline
- Mxn - medium crystalline
- Fxn - finely crystalline
- Vfxn - very finely crystalline

**Mineral identification**
- X - by X-ray diffraction
- t.s. - in thin section
Table 2. Petrographic and X-ray data from whole-rock samples

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Section</th>
<th>Unit</th>
<th>Rock Name</th>
<th>Composition (whole rock)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-22B</td>
<td>1</td>
<td>5</td>
<td>Vfxn lithiclast lime packstone</td>
<td>calcite, illite quartz (t.s.)</td>
</tr>
<tr>
<td>A-29B</td>
<td>1</td>
<td>6</td>
<td>Cxn mixed-fossil lime grainstone</td>
<td>calcite, dolomite (X)</td>
</tr>
<tr>
<td>A-32</td>
<td>1</td>
<td>6</td>
<td>Cxn oolite lithiclast dolomite packstone</td>
<td>dolomite (X)</td>
</tr>
<tr>
<td>A-43</td>
<td>1</td>
<td>6</td>
<td>Cxn to Vcxn crystalline dolomite</td>
<td>dolomite, quartz (t.s.)</td>
</tr>
<tr>
<td>A-56</td>
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<td>10</td>
<td>Mxn to Cxn crystalline dolostone</td>
<td>dolomite (X)</td>
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<tr>
<td>A-69</td>
<td>1</td>
<td>13</td>
<td>Mxn sandy crystalline dolostone and cryptalgal boundstone</td>
<td>dolomite, quartz, hematite (t.s.)</td>
</tr>
<tr>
<td>A-70</td>
<td>1</td>
<td>14</td>
<td>Mgr dolomitic quartzite</td>
<td>quartz, oligoclase, microcline, dolomite (t.s.)</td>
</tr>
<tr>
<td>A-75</td>
<td>1</td>
<td>16</td>
<td>Cxn sandy cryptalgal dolomite boundstone</td>
<td>dolomite, quartz, oligoclase, limonite (t.s.)</td>
</tr>
<tr>
<td>A-76A</td>
<td>1</td>
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<td>Gcr feldspathic quartzite</td>
<td>quartz, oligoclase (X)</td>
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<td>A-81</td>
<td>1</td>
<td>17</td>
<td>Mgr dolomitic quartzite</td>
<td>quartz, oligoclase, dolomite, microcline (t.s.)</td>
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<td>A-85B</td>
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<td>18</td>
<td>Vcxn mixed-fossil dolomite wackestone</td>
<td>dolomite, hematite, quartz, chlorite (t.s.)</td>
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<tr>
<td>Sample No.</td>
<td>Section</td>
<td>Unit</td>
<td>Rock Name</td>
<td>Composition (whole rock)</td>
</tr>
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<td>---------</td>
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<td>--------------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>F-71A</td>
<td>2</td>
<td>15</td>
<td>shale</td>
<td>oligoclase, illite, chlorite, hyalophane (X), microcrystalline quartz (binocular microscope)</td>
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<tr>
<td>D-15</td>
<td>4</td>
<td>8</td>
<td>Mxn crystalline limestone</td>
<td>calcite, quartz (X)</td>
</tr>
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<td>E-64</td>
<td>5</td>
<td>14</td>
<td>Cgr feldspathic quartzite</td>
<td>quartz, oligoclase, microcline, sericite, zircon (t.s.)</td>
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<tr>
<td>E-71</td>
<td>5</td>
<td>15</td>
<td>Mgr feldspathic quartzite</td>
<td>quartz, oligoclase, dolomite (X)</td>
</tr>
<tr>
<td>B-22</td>
<td>6</td>
<td>4</td>
<td>Vfxn, locally Vcxn, cryptalgal dolomite boundstone</td>
<td>dolomite, limonite, quartz (t.s.)</td>
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<tr>
<td>C-59</td>
<td>7</td>
<td>14</td>
<td>Cxn oolite dolomite grainstone</td>
<td>dolomite, hematite (X)</td>
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<td></td>
<td></td>
<td></td>
<td>(altered to crystalline dolostone)</td>
<td></td>
</tr>
<tr>
<td>C-84</td>
<td>7</td>
<td>13</td>
<td>Cgr feldspathic quartzite</td>
<td>quartz, oligoclase (X)</td>
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Table 3. Classification of carbonate rocks. From Dunham, 1962

<table>
<thead>
<tr>
<th>DEPOSITIONAL TEXTURE RECOGNIZABLE</th>
<th>DEPOSITIONAL TEXTURE NOT RECOGNIZABLE</th>
</tr>
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<tbody>
<tr>
<td>Components not bound together during deposition</td>
<td>Original components were bound together during deposition</td>
</tr>
<tr>
<td>Contains mud (clay and fine silt sizes)</td>
<td>Lacks mud and is grain-supported</td>
</tr>
<tr>
<td>Mud-supported</td>
<td>Grain-supported</td>
</tr>
<tr>
<td>Less than 10% grains</td>
<td>More than 10% grains</td>
</tr>
<tr>
<td>Mudstone</td>
<td>Wackestone</td>
</tr>
<tr>
<td></td>
<td>Packstone</td>
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<tr>
<td></td>
<td>Grainstone</td>
</tr>
<tr>
<td></td>
<td>Boundstone</td>
</tr>
<tr>
<td></td>
<td>Crystalline limestone or dolostone</td>
</tr>
<tr>
<td>(Subdivided according to classification designed to bear on physical texture or diagenesis)</td>
<td></td>
</tr>
</tbody>
</table>
Appendix C

Measured Stratigraphic Sections
# EXPLANATION OF STRATIGRAPHIC SECTIONS

## ROCK SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Rock Type</th>
<th>Column Headings</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Dolostone" /></td>
<td>Dolostone</td>
<td>1 - cryptalgalaminae</td>
</tr>
<tr>
<td><img src="image" alt="Limestone" /></td>
<td>Limestone</td>
<td>2 - columnar or domal stromatolites</td>
</tr>
<tr>
<td><img src="image" alt="Quartzite or Sand" /></td>
<td>Quartzite or Sand</td>
<td>3 - oncolites</td>
</tr>
<tr>
<td><img src="image" alt="Shale" /></td>
<td>Shale</td>
<td>4 - fossils</td>
</tr>
<tr>
<td><img src="image" alt="Poorly Exposed" /></td>
<td>Poorly Exposed</td>
<td>5 - vertical or oblique burrows</td>
</tr>
<tr>
<td><img src="image" alt="Covered" /></td>
<td>Covered</td>
<td>6 - epistratal traces</td>
</tr>
<tr>
<td><img src="image" alt="Color" /></td>
<td>Color</td>
<td>7 - rounded lithiclasts</td>
</tr>
<tr>
<td><img src="image" alt="N7 - N9" /></td>
<td>N7 - N9</td>
<td>8 - elongate lithiclasts</td>
</tr>
<tr>
<td><img src="image" alt="N2 - N6" /></td>
<td>N2 - N6</td>
<td>9 - &quot;birdseye&quot; structures</td>
</tr>
<tr>
<td><img src="image" alt="Low-Angle Cross-Laminae" /></td>
<td>Low-Angle Cross-Laminae (&lt; 12°)</td>
<td>10 - oolites</td>
</tr>
<tr>
<td><img src="image" alt="Parallel Laminae" /></td>
<td>Parallel Laminae</td>
<td>11 - low-angle cross-laminae (&lt; 12°)</td>
</tr>
<tr>
<td><img src="image" alt="Parallel Laminae" /></td>
<td>Parallel Laminae</td>
<td>12 - parallel laminae</td>
</tr>
</tbody>
</table>
Section 1

Location: St. Charles; measured east to west along ridge crest, north of U.S. Forest Service St. Charles Canyon Road, S/2, sec. 18, T. 15 S., R. 43 E., Bear Lake County, Idaho.

Upper member, St. Charles Formation

Sharp, planar contact

Worm Creek Member, St. Charles Formation

Part 3

<table>
<thead>
<tr>
<th>Unit</th>
<th>Thickness in meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 19:</td>
<td>Limestone, medium gray (N5), weathers dark yellowish brown (10 YR 4/2), finely crystalline, dolomitic throughout, few fossil fragments in most limestone; shale bed 1 m thick near top, with epistral traces; calcareous sandstone bed 2 m thick at top; beds average 5 cm, 80 percent covered.</td>
</tr>
<tr>
<td>Unit 18:</td>
<td>Dolostone, light gray (N7) to very light gray (N8), weathers light olive gray (5 Y 6/1), coarsely crystalline, fossils and lithiclasts 2 cm long, thin cryptalgalaminae, burrows oblique to bedding, lower 3 m sandy, beds average 5 cm, 80 percent covered.</td>
</tr>
<tr>
<td>Unit 17:</td>
<td>Quartzite and dolomitic sandstone, light gray (N7) to very light gray (N8), weathers several colors in hue 10 YR, medium to coarse grained, few thin shale partings, even parallel and cross-laminae, burrows perpendicular to bedding, flat-topped ripple marks in float, beds average 16 cm, 6-m cliff near top of unit.</td>
</tr>
<tr>
<td>Unit 16:</td>
<td>Dolostone, medium gray (N5), weathers light olive gray (5 Y 6/1), medium crystalline, sandy cross-laminae between cryptalgalaminae, beds average 19 cm, upper half covered.</td>
</tr>
<tr>
<td>Unit 15:</td>
<td>Sandstone, medium light gray (N6), weathers yellowish gray (5 Y 8/1), medium grained, dolomitic, lithiclast conglomerate near top, thick sandy cryptalgalaminae in upper half, beds average 19 cm, exposed in ledges.</td>
</tr>
<tr>
<td>Unit 14:</td>
<td>Quartzite, very light gray (N8), weathers grayish orange (10 YR 7/4), medium grained, cross-laminae, some burrow-churned layers, cryptalgal dolostone bed 18 cm thick near top, dolomitic sandstone at</td>
</tr>
</tbody>
</table>
Upper member, Nounan Formation

Part 2

Unit 13: Dolostone and sandstone, medium light gray (N6), weathers light olive gray (5 Y 6/1), medium crystalline, dolostones sandy and sandstones dolomitic, lithiclast beds throughout, small current ripplemarks and cross-laminae between beds of thin cryptagalminae, epistratal traces, beds average 6 cm, exposed in ledges .. 12.7

Unit 12: Dolostone, medium light gray (N6), weathers pale yellowish brown (10 YR 6/2), medium crystalline, quartz sand content increases upward, oolites, oncrites, cryptalgal clasts (SS-I) locally, thin cryptagalminae throughout, beds average 11 cm, exposed in ledges .. 13.1

Unit 11: Dolostone, light gray (N7), weathers light gray, finely crystalline, few thin cryptagalminae and fossiliferous layers, beds average 14 cm, upper part covered .. 1.5

Unit 10: Dolostone, very light gray (N8), weathers yellowish gray (5 Y 8/1), medium crystalline, thin cryptagalminae in one bed, beds average 19 cm, exposed in 2 to 3-m cliffs .. 19.1

Unit 9: Dolostone, light olive gray (5 Y 6/1), weathers grayish orange pink (5 YR 7/2), medium crystalline, sandy throughout, current ripple marks and cross-laminae, beds average 7 cm, 70 percent covered .. 8.8

Unit 8: Limestone, medium light gray (N6), weathers light gray (N7), coarsely crystalline, fossiliferous throughout, oolites, lithiclasts, and thick sandy cryptagalminae locally, beds average 5 cm, exposed in cliffs .. 7.3

Unit 7: Dolostone, medium light gray (N6), weathers pale to moderate yellowish brown (10 YR 6/2 to 5/4), coarsely to very coarsely crystalline, few fossiliferous beds in upper part, oolites and oolitic lithiclasts throughout middle, thin cryptagalminae in lower beds, beds average 14 cm, exposed in ledges .. 12.2

Thickness in meters

base, beds average 32 cm, cliffs 2-3 m .. 5.3

Subtotal 54.2
Unit 6: Limestone and dolostone, medium gray (N5), light gray (N7) locally, weather light olive gray (5Y 6/1), coarsely crystalline, oolites throughout, fossils and lithiclasts locally, few sandy beds, thin cryptalgalaminae in lower part, burrows oblique to bedding, beds average 9 cm, alternating ledges and covered intervals ........................................ 21.2

Part 1

Unit 5: Limestone, medium (N5) to medium dark gray (N4), weathers light olive gray (5Y 6/1), finely and medium crystalline, rounded lithiclasts 2-6 mm, thick cryptalgalaminae throughout, beds average 7 cm, 50 percent covered ........................................ 13.6

Unit 4: Limestone, medium gray (N5), weathers medium light gray (N6), finely and medium crystalline, thrombolites throughout, lithiclasts and oncolites (SS-C) locally, beds average 10 cm, 50 percent covered . 8.7

Unit 3: Limestone, light brown (5 YR 6/4), weathers grayish orange pink (5 YR 7/2), medium crystalline, 30 percent quartz and feldspar sand, even parallel laminae, beds average 3 cm, 60 percent covered . 2.9

Unit 2: Limestone, medium dark gray (N4) to medium gray (N5), weathers medium light gray (N6), medium crystalline in upper part, finely crystalline lower part, fossiliferous throughout, oncolites in uppermost beds, few thrombolites near middle, beds average 9 cm, exposed in series of 0.5 m ledges ............................... 45.3

Unit 1: Limestone, color extremely variable, finely crystalline in part, pellets, and fossils locally, mostly sandy, two beds of fine calcareous quartz silt, beds average 10 cm, poorly exposed near base ........... 7.2

Subtotal 203.6

Total 257.8

Sharp, planar contact

Middle member, Nounan Formation
Section 2

Location: Cub River; upper Moulan measured on northwest-facing slope, 1.6 km west of Willow Flat Campground, 1.6 km south of Thomas Spring, south of Cub River and Cub River Road, SE/4, sec. 10, and SW/4, sec. 11, T. 15 S., R. 41 E., Franklin County Idaho; Worm Creek measured on west-facing slope, 1.3 km south of Willow Flat Campground, east of Hillyard Canyon Road, SE/4, sec. 11, T. 15 S., R. 41 E., Franklin County, Idaho.

Upper member, St. Charles Formation

Sharp, planar contact

Worm Creek Member, St. Charles Formation

Part 3

<table>
<thead>
<tr>
<th>Unit</th>
<th>Thickness in meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 18: Sandstone, light brownish gray (5 YR 6/1), weathers dark yellowish brown (10 YR 4/2), medium grained, dolomitic throughout; shale, light olive gray (5 Y 5/2), fine grained, epistral traces; dolostone, colors same as sandstone, coarsely crystalline; even parallel laminae throughout, beds average 6 cm; exposed in discontinuous ledges</td>
<td>6.6</td>
</tr>
<tr>
<td>Unit 17: Quartzite, very light gray (N8) and pinkish gray (5 YR 8/1), medium grained, more feldspathic upward; sandy dolostone and dolomitic sandstone interbeds, light gray (N7), fine grained; all weather pale yellowish brown (10 YR 6/2), even cross- and parallel laminae, few vertical burrows; one coarsely crystalline sandy dolostone bed near top includes fossils and small lithiclasts; beds average 28 cm, 40 percent exposed in ledges</td>
<td>23.3</td>
</tr>
<tr>
<td>Unit 16: Quartzite, very light gray (N8), weathers pinkish gray (5 YR 8/1), coarse grained, feldspathic, even cross- and parallel laminae, beds average 20 cm, 50 percent exposed in ledges</td>
<td>2.8</td>
</tr>
<tr>
<td>Unit 15: Sandstone, medium light gray (N6), medium grained, dolomitic throughout, cross laminae locally, bedded in discontinuous pods, some darker and clayey; thin discontinuous, even, non-parallel interbeds of shale, medium gray (N5), epistral traces; laminae pinch out laterally in 10 to 12 cm, continuous exposure</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Subtotal 33.7
Upper member, Nounan Formation

Part 2

Unit 14: Dolostone, medium light gray (N6), weathers light gray (N7), coarsely crystalline, thin cryptalgal laminae and lithiclast beds locally, beds average 19 cm, lower half covered . . . . . . . . . . . . . . . . . 5.7

Unit 13: Limestone, light gray (N7) at base, remainder medium dark gray (N4), coarsely crystalline, imbricated lithiclasts, fossils, and cryptalgal laminae locally; interbedded dolostones and dolomitic limestones, medium crystalline, even parallel laminae; beds average 13 cm, exposed in 2.5-m cliffs and small ledges . . . . . . . . . . . . . . . . . 43.4

Unit 12: Dolostone, medium gray (N5) at base, medium light gray (N6) above, weathers light olive gray (5 Y 6/1) and yellowish gray (5 Y 8/1), medium crystalline, thin cryptalgal laminae in upper part, faint oolites and elongate lithiclasts in lower part, beds average 22 cm, exposed in continuous cliffs . . . . . . . . . . . . . . . . . 7.7

Unit 11: Dolostone and limestone interbeds, medium light gray (N6) and very light gray (N8), medium crystalline, small domal stromatolites (LLH-S), rounded lithiclasts, and even parallel laminae locally, beds average 13 cm, cliff in lower 9 m, 1-m ledges above . . . . . . . . . . . . . . . . . 18.9

Unit 10: Dolostone, very light gray (N8) and very coarsely crystalline in upper half, medium gray (N5) and medium crystalline below, fossiliferous, elongate lithiclasts locally; sandstone, light gray (N7), medium grained, dolomitic, even parallel laminae, 2.5 m thick at base of unit; beds average 12 cm, exposed in continuous cliff . . . . . . . . . . . . . . . . . 8.9

Unit 9: Dolostone, medium dark gray (N4) at top, light gray (N7) and very light gray (N8) toward base, color change within one bed, medium to coarsely crystalline, thick cryptalgal laminae and 1-mm oolites in upper part, beds average 23 cm, lower 20 m partly covered, remainder is continuous cliff . . . . . . . . . . . . . . . . . 33.8
Unit 8: Limestone, medium gray (N5) to medium light gray (N6), several reds (hue 10 R) and yellows (hue 10 YR) locally, weathers light gray (N7), medium crystalline, abundant cryptalgalaminae throughout, columnar stromatolites (SH-C) in one bed, fossils and lithiclasts locally abundant, burrows and epistral traces common, beds average 15 cm, exposed in 2-m cliffs .................................. 18.5

Unit 7: Dolostone, medium light gray (N6) and light gray (N7), weathers light gray, coarsely crystalline, fossils and 1-to-2-mm lithiclasts abundant in lower half, oolites abundant locally, even parallel laminae, uppermost bed is medium crystalline and structureless, beds average 9 cm, exposed in continuous cliff ...................... 13.3

Unit 6: Dolostone, medium light gray (N6), weathers light olive gray (5 Y 6/1), coarsely crystalline, elongate lithiclasts through lower four-fifths, oolites in cross-laminae locally through lower third, fossiliferous and sandy beds in middle of unit, beds average 37 cm, cliff in upper 18.3 m .... 26.6

Part 1

Unit 5: Dolostone, medium light gray (N6), weathers light gray (N7), medium and coarsely crystalline, thin cryptalgalaminae in upper part, even cross- and parallel laminae in middle and lower parts, beds average 14 cm, 1.5-m ledges ..................... 13.9

Unit 4: Limestone, medium gray (N5), weathers medium light gray (N6), beds alternate finely and coarsely crystalline, coarse beds fossiliferous, cross-laminated, lithiclasts locally, one oolite bed near top, epistral traces in fine beds, beds average 15 cm, 60 percent exposed in discontinuous ledges .................. 17.7

Unit 3: Limestone, medium dark gray (N4), weathers light gray (N6), finely and medium crystalline, rounded lithiclasts and fossils common, thick cryptalgalaminae and epistral traces locally, few 4-mm oncolites (SS-C) near base, beds average 16 cm, 60 percent exposed in discontinuous ledges .... 36.8

Unit 2: Limestone, dark gray (N3), weathers medium dark gray (N4), finely crystalline, large thrombolites, medium grained (silty) in upper 1.2 m, epistral...
traces, beds average 14 cm, 3.6-m cliff continuous into unit above, poorly exposed below . . . . . . 2.9

Unit 1: Limestone, pale red (5R 6/2) and moderate red (5 R 5/4), weathers moderate red, sandy throughout, thinly laminated domal stromatolites (LLH-S), vertical burrows in few beds, beds average 8 cm, 80 percent covered . . . . . . . . . . 2.7

Subtotal 250.8
Total 284.5

Contact covered, probably sharp

Middle member, Nounan Formation
Section 3

Location:  Paris Canyon; measured on southeast-facing slope, north of Paris Canyon Road, 4.5 km west of the town of Paris, NE/4, sec. 11 and SE/4, sec. 2, T. 14 S., R. 42 E., Bear Lake County, Idaho.

Upper member, St. Charles Formation

Contact Faulted

Worm Creek Member, St. Charles Formation

Part 3

<table>
<thead>
<tr>
<th>Unit 16:</th>
<th>Dolostone, light gray (N7), weathers light olive gray (5 Y 6/1), medium crystalline, calcareous and sandy throughout, beds average 14 cm, poorly exposed and faulted</th>
<th>11.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 15:</td>
<td>Dolostone, medium dark gray (N4), weathers medium light gray (N6), medium crystalline; limestone bed 60 cm thick at top of unit, same color and crystal size, vertical burrows filled with sand and pellets, few oolites; thin cryptagalaminae throughout unit, domal stromatolites (LLH-C) locally, beds average 19 cm, few ledges 60 cm thick</td>
<td>2.7</td>
</tr>
<tr>
<td>Unit 14:</td>
<td>Quartzite, very pale orange (10 YR 8/2), weathers yellowish gray (5 Y 8/1), medium grained, feldspathic, even cross- and parallel laminae, float only, some breccia, base faulted</td>
<td>24.3</td>
</tr>
</tbody>
</table>

Subtotal 38.7

Upper member, Nounan Formation

Part 2

<table>
<thead>
<tr>
<th>Unit 13:</th>
<th>Dolostone, light gray (N7), weathers yellowish gray (5 Y 8/1), coarsely crystalline, sandy throughout, few vertical burrows, beds average 47 cm, exposed in discontinuous 65 cm ledges, upper half covered</th>
<th>15.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 12:</td>
<td>Limestone, medium light gray (N6), weathers light gray (N7), coarsely crystalline, epistral traces, few fossils and rounded lithiclasts, thin cryptagalaminae locally, few randomly distributed oolites, beds average 18 cm, exposed in discontinuous ledges</td>
<td>2.1</td>
</tr>
<tr>
<td>Unit</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Dolostone, medium light gray (N6) and light gray (N7), weathers yellowish gray (5 Y 8/1), coarsely crystalline, oolites concentrated in darker laminae parallel to bedding, few faint elongate lithiclasts, beds average 25 cm, lower one-fourth covered, upper part exposed in ledges.</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Limestone, medium light gray (N6), weathers light gray (N7), medium and coarsely crystalline, fossiliferous, few rounded lithiclasts, thin cryptalgal laminae and epistratal traces in medium crystalline beds, beds average 11 cm, exposed in 65-cm ledges.</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Covered, float is coarsely crystalline limestone.</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Limestone, medium gray (N5) to medium light gray (N6), weathers medium gray, medium crystalline, some beds of rounded and elongate lithiclasts, oolites surround clasts, beds average 15 cm, nine-tenths of unit covered.</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Dolostone, mottled light gray (N7) and medium gray (N5), medium crystalline with few oolites in lighter areas, coarsely crystalline with abundant oolites in darker areas, few rounded lithiclasts, nine-tenths of unit covered.</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Dolostone, medium light gray (N6) and light gray (N7), weathers light gray, medium crystalline, faint oolites, few elongate lithiclasts, beds average 35 cm, exposed in 60-cm ledges, lower 10 m covered.</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Limestone, medium dark gray (N4) and medium gray (N5), weathers medium light gray (N6) and light olive gray (5 Y 6/1), medium to coarsely crystalline, pellet-filled burrows and burrow-churned beds in upper part, few thin cryptalgal laminae and rounded lithiclasts in lower part, beds average 10 cm, exposed in 40- to 60-cm ledges.</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Limestone, medium dark gray (N4), weathers medium light gray (N6), most beds medium crystalline, some beds coarsely crystalline and lithiclast conglomerate, fossils, vertical burrows locally, beds average 9 cm, 50 percent exposed in ledges.</td>
<td></td>
</tr>
</tbody>
</table>
Unit 3: Dolostone, light gray (N7), weathers yellowish gray (5 Y 8/1), medium crystalline, thin crypt-algalaminae separated by even parallel laminae, rounded lithiclasts locally, beds average 14 cm, exposed in two ledges, 30 cm each . . . . . . . . 8.2

Unit 2: Dolostone, light gray (N7), weathers same, coarsely crystalline, calcareous throughout, faint oolites and vertical burrows, beds average 20 cm, lower 9 m covered but float continuous . . 12.6

Unit 1: Limestone, medium dark gray (N4), weathers medium light gray (N6), few thrombolites, fossiliferous locally, sandy vertical burrows, beds average 14 cm, exposed in 30-cm ledges . . . . . . . . . . 21.6

Subtotal 174.6
Total 212.7

Contact covered, in interval 15 m thick

Middle member, Nounan Formation
Section 4

Location: Oneida Narrows; measured in near-vertical beds on west-facing slope, 5.6 km northeast of town of Riverdale, 1 km north of Idaho State Highway 36, east of Bear River and Oneida Narrows Road, SW/4, sec. 16, T. 14 S., R. 40 E., Franklin County, Idaho.

Upper member, St. Charles Formation

Contact faulted

Worm Creek Member, St. Charles Formation

<table>
<thead>
<tr>
<th>Part 3</th>
<th>Thickness in meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 10: Quartzite, pinkish gray (5 YR 8/1) and light gray (N7), weathers light brown (5 YR 6/4), coarse grained, even cross- and parallel laminae, feldspar up to 30 percent; uppermost bed is calcareous sandstone, pale red (5 R 6/2), medium grained; most beds of both rock types badly brecciated, beds average 19 cm, 80 percent covered or breccia</td>
<td>29.1</td>
</tr>
</tbody>
</table>

Upper member, Nounan Formation

Part 2

| Unit 9: Limestone, medium dark gray (N4) and medium gray (N5), weathers medium light gray (N6), medium and coarsely crystalline, fossiliferous, oolites and rounded lithiclasts locally, cross-laminated in part, burrows and epistratal traces, some beds sandy, beds average 21 cm, poorly exposed in ledges | 32.2 |
| Unit 8: Limestone, medium light gray (N6), weathers light gray (N7), finely crystalline, no structures, beds average 40 cm, exposed in 1 m ledges, 60 percent covered | 5.7 |
| Unit 7: Limestone, dark gray (N3) and medium dark gray (N4), weathers medium light gray (N6), interbedded finely crystalline and very coarsely crystalline, fossils, rounded lithiclasts, and oolites in coarse beds, thin cryptalgalamnæ in fine beds, beds average 18 cm, exposed in 7.6-m cliff only | 20.0 |
| Unit 6: Covered interval, limestone talus | 13.3 |
| Unit 5: Limestone, light gray (N7) and pale red (5 R 6/2), weathers light gray, very coarsely crystalline, fossiliferous, rounded lithiclasts, thick |
cryptagalaminæ locally, beds average 22 cm, lower half in cliff, upper half poorly exposed ... 21.8

Unit 4: Limestone, medium light gray (N6) and pale red (5 R 6/2), weathers light gray (7), interbedded finely and coarsely crystalline, coarse beds fossiliferous, fine beds include thin cryptagalaminæ, burrows, and epistratal traces, beds average 20 cm, exposed in continuous cliff ... 19.7

Unit 3: Limestone, medium dark gray (N4), weathers medium light gray (N6), finely crystalline, coarsely crystalline and sandy locally, few rounded lithiclasts, abundant oolites, beds average 13 cm where measurable, exposed in continuous cliff ... 9.7

Part 1

Unit 2: Limestone, dark gray (N3) and medium gray (N5), weathers medium gray, dark beds coarsely crystalline, abundant oolites, fossils, and rounded lithiclasts; lighter beds medium crystalline, abundant thrombolites and thin cryptagalaminæ with cross-laminæ between, rock types alternate; beds average 15 cm, exposed in continuous cliff ... 14.8

Unit 1: Covered, limestone talus, measured below unit 2 to river ........... 23.9

Thickness estimated by measuring across Bear River ... 29.0

Subtotal 190.1

Total 219.2

Contact covered, faulted, or both

Middle member, Nounan Formation
SECTION 4
Section 5

Location: Williams Canyon; measured on south-facing slope, north side of Williams Canyon Trail, 4.8 km east of Idaho State Highway 34 and village of Perry, S/2, sec. 22, T. 12 S., R. 41 E., Franklin County, Idaho.

Upper member, St. Charles Formation

Contact mostly covered, sharp where exposed

Worm Creek Member, St. Charles Formation

<table>
<thead>
<tr>
<th>Part 3</th>
<th>Thickness in meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 17: Dolostone, medium light gray (N6), weathers pale yellowish brown (10 YR 6/2), finely and medium crystalline, 30 to 45 percent fine quartz sand, elongate-lithiclast conglomerate locally, even parallel laminae, beds average 17 cm, exposed in small ledges</td>
<td>11.8</td>
</tr>
<tr>
<td>Unit 16: Dolostone, light gray (N7), weathers pale to dark yellowish brown (10 YR 6/2 to 4/2), coarsely and very coarsely crystalline, 5 to 20 percent quartz sand throughout, small lithiclasts in parallel laminae, beds average 12 cm, exposed in cliffs</td>
<td>7.0</td>
</tr>
<tr>
<td>Unit 15: Quartzite, pinkish gray (5 YR 8/1), weathers pale red (5 R 6/2) and several other colors in hues 5 YR and 10 YR, coarse grained, even cross- and parallel laminae, burrows locally, asymmetrical ripplemarks in float, beds average 34 cm, exposed in cliffs</td>
<td>16.7</td>
</tr>
<tr>
<td>Unit 14: Quartzite, greenish gray (5 GY 6/1) and pinkish gray (5 YR 8/1), weathers pale yellowish brown (10 YR 6/2), medium grained, dolomitic sandstone in part, cross-laminae, few burrows, beds average 18 cm, exposed in discontinuous ledges, upper half covered</td>
<td>17.6</td>
</tr>
</tbody>
</table>

Subtotal 54.0

Upper member, Nounan Formation

Part 2

<p>| Unit 13: Dolostone, medium light gray (N6), weathers moderate yellowish brown (10 YR 5/4), medium crystalline, 5 to 45 percent fine to medium grained quartz sand throughout, thick cryptalgal laminae, epistratal traces, beds average 16 cm, exposed in ledges | 30.8 |</p>
<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
<th>Thickness in meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Dolostone, light gray (N7), weathers light olive gray (5 Y 6/1), medium crystalline, thin cryptagalaminae and small rounded lithiclasts throughout, few cross-laminae locally, few silty burrows oblique to bedding, beds average 28 cm, exposed in 2-m cliffs</td>
<td>16.3</td>
</tr>
<tr>
<td>11</td>
<td>Limestone, medium dark gray (N4), weathers medium gray (N5), finely crystalline, cryptagalaminae thicken upward in section, beds average 29 cm, continuous exposure</td>
<td>3.0</td>
</tr>
<tr>
<td>10</td>
<td>Dolostone, pale red (10 R 6/2) and very light gray (N8), weathered color variable, coarsely crystalline, slightly sandy, cryptagalaminae thin upward in section, beds average 32 cm, exposed in 4.5-m cliff</td>
<td>7.3</td>
</tr>
<tr>
<td>9</td>
<td>Limestone, pale red (10 R 6/2) and very light gray (N8), weathers light gray (N7), finely crystalline, fossil fragments up to 4 mm long, few thin cryptagalaminae, beds average 26 cm, exposed in discontinuous cliffs</td>
<td>7.3</td>
</tr>
<tr>
<td>8</td>
<td>Dolostone, very light gray (N8) to white (N9), weathers very pale orange (10 YR 8/2), finely and medium crystalline, thin cryptagalaminae and domal stromatolites (LLH-S) locally, beds average 21 cm, exposed in 0.5-to 1-m ledges</td>
<td>29.6</td>
</tr>
<tr>
<td>7</td>
<td>Limestone, most beds medium light gray (N6), weather grayish orange (10 YR 7/4), one bed dark gray (N3), finely crystalline with local patches very coarsely crystalline, fossils throughout, dark bed has 1-mm oolites, epistral traces on bedding surfaces, beds average 20 cm, exposed in 2-m cliffs</td>
<td>21.2</td>
</tr>
<tr>
<td>6</td>
<td>Limestone, medium light gray (N6), weathers grayish orange pink (5 YR 7/2), finely crystalline, fine quartz sand locally, beds average 12 cm, 70 percent covered</td>
<td>12.1</td>
</tr>
<tr>
<td>5</td>
<td>Dolostone, medium dark gray (N4), weathers pale yellowish brown (10 YR 6/2), medium crystalline, oolites and small lithiclasta throughout, few 12-cm interbeds of fossiliferous limestone, beds average 12 cm, 60 percent covered</td>
<td>9.0</td>
</tr>
</tbody>
</table>

Part 1
<table>
<thead>
<tr>
<th>Unit</th>
<th>Thickness in meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 4: Limestone, medium dark gray (N4), weathers several colors in hue 10 YR, medium and coarsely crystalline, fossils and small lithiclasts at base, burrows oblique to beds, wavy nonparallel sandstone lenses locally, beds average 12 cm, exposed in discontinuous ledges</td>
<td>6.0</td>
</tr>
<tr>
<td>Unit 3: Limestone, dark gray (N3) to medium dark gray (N4), weathers medium light gray (N6), very coarsely crystalline, oolites and fossils throughout, lithiclast beds and thrombolites locally, beds average 17 cm, exposed in 0.5-m ledges</td>
<td>18.1</td>
</tr>
<tr>
<td>Unit 2: Limestone, medium dark gray (N4), dark gray (N3) at base, weathers medium light gray (N6), finely crystalline, rounded lithiclasts and fossils locally, branching epistratal traces, some channeled beds, beds average 16 cm, exposed in 30-cm ledges</td>
<td>20.8</td>
</tr>
<tr>
<td>Unit 1: Limestone, medium gray (N5), weathers medium light gray (N6) and light gray (N7), finely crystalline with coarsely crystalline fossiliferous patches throughout, silty burrows and rounded lithiclasts locally between thick cryptagalaminæ, beds average 15 cm, exposed in discontinuous ledges</td>
<td>228.1</td>
</tr>
</tbody>
</table>

Subtotal 228.1

Total 282.1

Contact sharp, low relief (5-10 cm)

Middle member, Nounan Formation
SECTION 5
Section 6

Location: McPherson Canyon; measured on south-facing slope, 5.6 km southeast of town of Grace, 0.8 km east of Cache National Forest Boundary, north of the McPherson Canyon Road, SW/4, sec. 9, T. 10 S., R. 41 E., Caribou County, Idaho.

Upper member, St. Charles Formation

Sharp contact with low relief (1 to 5 cm)

Worm Creek Member, St. Charles Formation

Part 3

<table>
<thead>
<tr>
<th>Unit</th>
<th>Thickness in meters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unit 19:</strong> Dolostone, medium light gray (N6), weathers light gray (N7), medium crystalline, 1-mm oolites locally, few thin cryptagalaminae, beds average 10 cm, 70 percent covered</td>
<td>4.3</td>
</tr>
<tr>
<td><strong>Unit 18:</strong> Quartzite, very light gray (N8) and grayish pink (5 R 8/2), weathers grayish orange pink (5 YR 7/2), medium to coarse grained, feldspathic, even parallel and cross-laminae, few current ripple marks, vertical burrows up to 7.5 cm long, 1 cm diameter, some burrows oblique to bedding, beds average 21 cm, poorly exposed</td>
<td>55.0</td>
</tr>
<tr>
<td><strong>Unit 17:</strong> Sandstone, grayish orange pink (5 YR 7/2), weathers pale yellowish brown (10 YR 6/2), medium and very coarse grained, smaller grains feldspar, dolomite cement, even cross- and parallel laminae, beds average 20 cm, 50 percent covered</td>
<td>5.7</td>
</tr>
<tr>
<td><strong>Unit 16:</strong> Quartzite, grayish red (10 R 4/2) at base, very light gray (N8) above, medium grained, feldspathic, burrows perpendicular and oblique to bedding, even parallel laminae, beds average 20 cm, 50 percent covered</td>
<td>11.5</td>
</tr>
<tr>
<td><strong>Unit 15:</strong> Quartzite, colors include pale red (10 R 6/2), grayish red (10 R 4/2), and pinkish gray (5 YR 8/1), coarse grained, feldspathic, even parallel and cross-laminae, 3-m calcareous sandstone bed at base, beds average 23 cm, covered between 1-m ledges</td>
<td>22.9</td>
</tr>
</tbody>
</table>

Upper member, Nounan Formation

Part 2

Unit 14: Dolostone, medium dark gray (N4) at base, grayish
Thickness
in meters

orange pink (5 YR 7/2) up section, weathers light
olive gray (5 Y 6/1), finely crystalline, fine
quartz sand increases upward, epistral traces
locally, few 3-mm lithiclasts, beds average 8 cm,
70 percent covered ........................................ 14.3

Unit 13: Limestone, medium dark gray (N4) and light brown
(5 YR 6/4), weathers medium gray (N5), burrows
perpendicular to bedding, even cross- and parallel
laminae, fossils, and rounded lithiclasts locally,
beds average 6 cm, 50 percent covered ............... 2.9

Unit 12: Dolostone, medium light gray (N6), weathers light
olive gray (5 Y 6/1), medium crystalline, thin
cryptalgalaminae, epistral traces; feldspathic
sandstone 0.8 m thick at base, grayish pink (5 R
8/2), medium grained; beds average 16 cm, covered
between 0.5-m ledges ........................................ 9.4

Unit 11: Dolostone, very light gray (N8), weathers very pale
orange (10 YR 8/2), medium crystalline, few very
coarsely crystalline beds, thin cryptalgalaminae,
beds average 28 cm, exposed in 0.7-m ledges .......... 16.3

Unit 10: Quartzite, grayish pink orange (5 YR 7/2), weathers
light brown (5 YR 6/4), very coarse grained at base,
medium grained upward, even parallel and cross-
laminae, beds average 15 cm, 70 percent covered ... 12.9

Unit 9: Dolostone, medium light gray (N6), weathers pale
yellowish brown (10 YR 6/2), medium crystalline,
few beds very coarsely crystalline, few thin
cryptalgalaminae; very light gray (N8) sandstone
bed underlain by shale bed near top of interval,
0.6 m each; beds average 16 cm, exposed in widely
spaced 30-cm ledges ......................................... 25.2

Unit 8: Limestone, dark gray (N3) and olive gray (5 Y 4/1),
weathers moderate yellowish brown (10 YR 5/4),
coarsely to very coarsely crystalline, epistral
traces locally, fossiliferous in lower half,
elongate lithiclasts in upper half, beds average
11 cm, 50 percent covered .................................. 5.8

Unit 7: Limestone, medium dark gray (N4) and grayish orange
(10 YR 7/4), weathers light gray (N6), medium and
finely crystalline, cryptalgalaminae throughout,
form lithiclasts (some SS-I) locally, few rounded
lithiclasts in some beds, burrows and epistral
traces common, oolite bed at top of interval,
shaly fossiliferous bed at base, beds average 12 cm,
Part 1

Unit 6: Dolostone, medium gray (N5), few beds light gray (N7), weathers light olive gray (5 Y 6/1), medium crystalline, light gray beds coarsely crystalline, calcareous at base, burrows throughout, oncolites (SS-C) and rounded lithiclasts locally, beds average 19 cm, exposed in ledges .......... 13.9

Unit 5: Limestone, medium dark gray (N4), weathers medium light gray (N6), coarsely crystalline, rounded lithiclasts bedded locally, few throughout, oncolites (SS-C) in upper part, few thin cryptagalaminae at base, sandy burrows in lower half, beds average 16 cm, 40 percent covered .......... 16.7

Unit 4: Limestone, dark gray (N3) and grayish orange (10 YR 7/4), weathers medium light gray (N6), medium crystalline, thin sandy cryptagalaminae throughout 90 percent, "birds-eye" structures in one bed, cryptagal lithiclasts (some SS-I) locally, small rounded lithiclasts locally abundant, fossils and pellets in one bed near base, upper one-fourth oolitic, one dolostone bed at top, beds average 12 cm, well exposed in 30-cm ledges .......... 25.0

Unit 3: Limestone, dark gray (N3), weathers medium gray (N5), medium crystalline, silty burrows oblique to bedding, epistratal traces throughout, rounded lithiclasts abundant in lower three-fourths, oolites abundant near base, beds average 13 cm, well-exposed in 0.5-to-1-m ledges .......... 31.2

Unit 2: Limestone, medium dark gray (N4) and dark yellowish orange (10 YR 6/6), weathers light gray (N7), finely crystalline, thrombolites, fossils, few rounded lithiclasts locally, burrows oblique to bedding, beds average 13 cm, well exposed in ledges .......... 20.0

Unit 1: Limestone, medium dark gray (N4), weathers medium light gray (N6), medium crystalline, burrows and epistratal traces throughout, fossils locally abundant, dolostone bed 2.3 m thick at top, beds average 18 cm, 80 percent covered .......... 8.6

Subtotal 235.6

Total 335.0
Sharp, planar contact

Middle member, Nounan Formation
Location: Densmore Creek; upper member, Nounan Formation, measured on southwest-facing slope, north of Densmore Creek, 8 km south and 1.6 km west of village of Turner, SE/4, sec. 36, T. 10 S., R. 39 E. and SW/4, sec. 31, T. 10 S., R. 40 E., Caribou County, Idaho; Worm Creek Member, St. Charles Formation, measured on ridge crest, 2.5 km northwest of above site, east of Beaver Basin, SE/4, sec. 26, T. 10 S., R. 39 E., Caribou County, Idaho.

Upper member, St. Charles Formation (?)

Contact covered, probably faulted

Worm Creek Member, St. Charles Formation

Part 3

Unit 20: Dolomitic sandstone upper 5 m, quartzite below, weathered moderate yellowish brown (10 YR 5/4), dark yellowish orange (10 YR 6/6) and grayish red (10 R 4/2), medium grained, feldspathic, burrow-churned beds, beds average 15 cm, lower part poorly exposed, faulted at top . . . . . . . . 17.5

Unit 19: Quartzite, weathered grayish orange pink (5YR 7/2) and grayish orange (10 YR 7/4), coarse grained, feldspathic, even parallel and cross-laminae, contorted bedding locally, some burrow-churned beds, beds average 32 cm, covered locally, exposed in 60-cm ledges . . . . . . . . . . . . . . . . . . . . 35.3

Unit 18: Quartzite, very light gray (N8) and pinkish gray (5 YR 8/1), weathers pale brown (5 YR 5/2) and grayish orange (10 YR 7/4), medium to coarse grained, feldspathic; sandstone near base, light gray (N7), medium grained, dolomitic; even cross- and parallel laminae throughout, beds average 12 cm, exposed in discontinuous ledges . . . . . . 38.2

Subtotal 91.0

Upper member, Nounan Formation

Part 2

Unit 17: Dolostone, medium light gray (N6), weathers pale yellowish brown (10 YR 6/2), medium crystalline, 25 percent quartz sand, thick cryptalgal laminae, beds average 33 cm, 70 percent exposed in ledges 11.2
Thickness in meters

Unit 16: Sandstone, medium light gray (N6) at top, yellowish gray (5 Y 8/1) below, weathers pale yellowish brown (10 YR 6/2), coarse grained at base, medium grained above, feldspathic at base, dolomite increases upward, even parallel and cross-laminae, beds average 23 cm, exposed in 60-cm ledges .......................... 8.8

Unit 15: Dolostone, light gray (N7), weathers light gray, medium crystalline, thin cryptalgalaminae, rounded lithiclasts locally, beds average 21 cm, exposed in 65-cm ledges .............................. 11.9

Unit 14: Dolostone, very light gray (N8) and grayish pink (5 R 8/2), weathers yellowish gray (5 Y 8/1), coarsely crystalline, few faint oolites in medium gray (N5) patches, beds average 22 cm, exposed in ledges 1 m thick ................................. 17.8

Unit 13: Dolostone in upper half, medium light gray (N6), weathers light gray (N7), medium crystalline, thin sandy cryptalgalaminae; sandstone below, light gray (N7), weathers same, medium grained, dolomitic, even cross- and parallel laminae, beds average 25 cm, basal 3 m covered, remainder exposed in 70-cm ledges .......................... 11.9

Unit 12: Dolostone, medium light gray (N6), weathers pale yellowish brown (10 YR 6/2), medium crystalline, 30 percent quartz sand, epistratal traces locally, beds average 3 cm, two 30-cm ledges in unit ... 11.9

Unit 11: Limestone, light gray (N7), weathers same, coarsely crystalline, fossils locally abundant, cross-laminae locally, thick cryptalgalaminae in upper 1.5 m, beds average 71 cm, exposed in 2-m cliffs .......................... 10.4

Unit 10: Limestone, medium gray (N5), weathers medium light gray (N6), very coarsely crystalline, lithiclasts, oolites and coated grains with round and elongate oncolites (SS-C) locally, fossils in separate beds, beds average 23 cm, covered in middle of interval, poorly exposed ......................... 27.3

Unit 9: Dolostone, light gray (N7), weathers same, coarsely crystalline, near 50 percent quartz and feldspar sand, even cross- and parallel laminae, beds average 18 cm, 20 percent exposed ............................. 8.6

Unit 8: Limestone, mottled medium dark gray (N4) and medium light gray (N6), coarsely crystalline, oolites obvious
in dark areas, faint to absent in light areas, burrows oblique to bedding, few oncolites (SS-C), beds average 22 cm, very poorly exposed 3.0

Part 1

Unit 7: Covered, dip slope and gully, limestone talus 15.8

Unit 6: Limestone, medium dark gray (N4) and medium gray (N5), weathers medium light gray (N6), finely and medium crystalline, thrombolites and thin cryptagalaminae disrupted locally by "birdseye" structures, sparsely fossiliferous in mottled beds, burrows locally, beds average 12 cm, exposed in discontinuous ledges, poorly exposed near base 23.7

Unit 5: Limestone, dark gray (N3) and medium dark gray (N4), weathers medium gray (N5), finely and coarsely crystalline, rounded lithiclasts (N2) and fossils in coarse beds, thin cryptagalaminae, burrows and epistral traces in fine beds, beds average 20 cm, 70 percent exposed in ledges 21.2

Unit 4: Limestone, medium dark gray (N4) and light olive gray (5 Y 6/1), weathers medium light gray (N5), medium crystalline, thin cryptagalaminae, thrombolites, and fossils, burrows locally, beds average 24 cm, 30 percent exposed in 60-cm ledges 5.9

Unit 3: Limestone, dark gray (N3) and medium dark gray (N4), weathers medium light gray (N6), very coarsely crystalline in upper 6 m, thick cryptagalaminae, burrows, bedded lithiclasts, few channeled beds; remainder finely crystalline, domal stromatolites (LLH-S) and thrombolites, vertical burrows, beds average 13 cm, 60 percent exposed in 26-cm ledges 20.0

Unit 2: Limestone, medium dark gray (N4), weathers medium light gray (N6), finely crystalline, cross-laminae, burrows, fossils, and small lithiclasts locally, beds average 10 cm, poorly exposed 5.3

Unit 1: Dolostone, medium light gray (N6), weathers pale yellowish brown (10 YR 6/2), medium crystalline, sandy, thin cryptagalaminae, beds average 18 cm, 50 percent exposed 2.7

Subtotal 217.4

Contact covered, probably faulted

Total 308.4

Middle member, Nounan Formation
Section 8

Location: Fish Creek Basin; measured on southwest-facing slope and crest of the first hill northwest of Fish Creek Basin, 8.4 km southeast of Lava Not Springs, NW/4, sec. 8, t. 10 S., R. 39 E., Bannock County, Idaho.

Upper member, St. Charles Formation

Sharp planar contact

Worm Creek Member, St. Charles Formation

Part 3

<table>
<thead>
<tr>
<th>Unit 20:</th>
<th>Quartzite, very light gray (N8), weathers pinkish gray (5 YR 8/1), alternating coarse and fine grained beds, feldspathic, fine beds have vertical burrows, even parallel and cross-laminae throughout, beds average 26 cm, middle 5 m covered, remainder exposed in ledges</th>
<th>Thickness in meters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>18.7</td>
</tr>
</tbody>
</table>

| Unit 19: | Quartzite, grayish pink (5 R 8/2) and yellowish gray (5 Y 8/1), weathers pinkish gray (5 YR 8/1), and light red (5 R 6/6), medium grained, feldspathic, vertical burrows 5 mm diameter, up to 12.5 cm long, some beds burrow-churned, cross-laminae in non-burrowed beds, channelled beds locally, beds average 24 cm, exposed in 1-m ledges | 32.0 |

| Unit 18: | Quartzite, very light gray (N8), weathers yellowish gray (5 Y 7/2), fine grained, feldspathic, no structures, beds average 13 cm, exposed in 2-m cliff | 5.4 |

| Unit 17: | Quartzite, light gray (N7), weathers light brownish gray (5 YR 6/1) and pale red (10 R 6/2), coarse grained, few fine grained beds with sharp contacts, cross and even parallel laminae throughout, burrows in upper part, beds average 23 cm, 50 percent exposed in 1.5-m ledges | 28.9 |

| Unit 16: | Sandstone, light gray (N7) and very light gray (N8), weathers very light gray, medium grained, dolomic, burrows, epistratal traces on one bed, cross-laminae locally; sandy dolomitic bed at top of unit, medium light gray (N6), few thin cryptalgal laminae, beds average 13 cm, 50 percent exposed in discontinuous ledges | 10.4 |

Subtotal 95.4
Upper member, Nounan Formation

Part 2

Unit 15: Dolostone, medium gray (N5) in upper one-third, light gray (N7) below, medium crystalline, sandy with cross-laminae throughout, channeled and contorted bedding near top, lower beds include coarse fossiliferous lenses 45 cm long, and small rounded lithiclasts, beds average 18 cm, continuous exposure in cliffs 13.7

Unit 14: Dolostone, light bluish gray (5 B 7/1), medium and coarsely crystalline, in 3 bedsets; upper includes faint burrows and few fossils, middle has thin cryptalgalaminae, lower has cross- and even parallel laminae, fossils, and few rounded lithiclasts, beds average 16 cm, exposed in 1.5-to-3-m cliffs 7.9

Unit 13: Dolostone, white (N9) and moderate pink (5 R 7/4) in upper part, weathers grayish orange pink (5 YR 7/2), lower part light and very light gray (N7 and N8), weathers yellowish gray (5 Y 8/1), very coarsely crystalline, no structures in upper part, cross-laminae and few elongate lithiclasts in lower part, beds average 35 cm, continuous exposure in cliffs 13.2

Unit 12: Quartzite, grayish pink (5 R 8/2), weathers grayish orange pink (5 YR 7/2), cross-laminae in some beds, faint rounded lithiclasts, beds average 24 cm, poorly exposed in ledges 7.9

Unit 11: Sandstone, white (N9) and very light gray (N8), weathers pinkish gray (5 YR 8/1), medium grained, dolomitic throughout except basal 2 m of feldspathic quartzite, dolomite near 50 percent of some beds, cross-laminae, few thin cryptalgalaminae in 50-percent-dolomite beds, beds average 28 cm, 2 m cliff of quartzite with ledges above 12.2

Unit 10: Dolostone, medium light gray (N6), coarsely crystalline, sandy throughout, cross- and even parallel laminae, few cryptalgalaminae, beds average 9 cm, exposed in 1.5-m ledges 12.5

Unit 9: Dolostone, very light gray (N8), medium crystalline, few burrows and fossils, beds average 60 cm, continuous cliff 6.0

Unit 8: Dolostone, very light gray (N8) to white (N9), medium crystalline, thin cryptalgalaminae and columnar
Unit 7: Dolostone, medium light gray (N6), coarsely crystalline, alternating fossiliferous beds with oolitic beds, cross-laminae in oolites, beds average 27 cm, continuous cliff exposure

Part 1

Unit 6: Dolostone, light bluish gray (5 B 7/1), medium crystalline, sandy throughout, cross-laminae, beds average 16 cm, 25 percent exposed in ledges

Unit 5: Dolostone, medium gray (N5), medium and coarsely crystalline, thin sandy cryptalgalaminae throughout, contorted and in lithiclasts (some SS-1) in upper part, burrows, cross- and even parallel laminae locally, beds average 26 cm, two outcrops 1 m thick in unit

Unit 4: Dolostone, medium light gray (N6), weathers yellowish gray (5 Y 8/1), medium crystalline, thin cryptalgalaminae, faint rounded lithiclasts and burrows throughout, cross- and even parallel laminae in lower part, few fossils in upper 10 m, beds average 19 cm, exposed in few 35-cm ledges

Unit 3: Limestone and dolostone, medium dark gray (N4) and medium gray (N5), finely crystalline, thin interbeds of both rock types with thin cryptalgalaminae, epi-stratal traces, few small lithiclasts, interbeds average 12 cm, exposed in discontinuous 30-cm ledges

Unit 2: Limestone, medium dark gray (N4), medium crystalline, thick cryptalgalaminae separated by fossiliferous and lithiclast beds, burrows, beds average 9 cm, 50 percent exposed

Unit 1: Limestone, pale red (5 R 6/2) and grayish orange (10 YR 7/4), medium to coarsely crystalline, sandy throughout, cross-laminae, fossils, and epistratal traces locally, beds average 5 cm, 50 percent exposed in ledge

Subtotal 184.5
Total 279.9

Sharp, planar contact

Middle member, Nounan Formation