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The Middle Cambrian Wheeler Formation: Sequence Stratigraphy and Geochemistry Across a Ramp-to-Basin Transition

Elizabeth S. Langenburg
Utah State University

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THE MIDDLE CAMBRIAN WHEELER FORMATION: SEQUENCE
STRATIGRAPHY AND GEOCHEMISTRY ACROSS
A RAMP-TO-BASIN TRANSITION

by

Elizabeth S. Langenburg

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Geology

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2003
ABSTRACT

The Middle Cambrian Wheeler Formation: Sequence Stratigraphy and Geochemistry Across a Ramp-to-Basin Transition

by

Elizabeth S. Langenburg, Master of Science
Utah State University, 2003

Major Professor: Dr. W. David Liddell
Department: Geology

The Middle Cambrian Wheeler Formation is interpreted as having been deposited in the shallow ramp and deeper basin environments of the House Range embayment (HRE), presumably, during a single third-order sequence. In the Drum Mountains, the Wheeler Formation (295 m thick) is dominated by proximal and distal ramp deposits; at Marjum Pass, the Wheeler Formation (190 m thick) is dominated by basinal shale deposits. The Wheeler Formation contains only one biozone marker; the first appearance of Ptychagnostus atatus. Lack of other chronostratigraphic markers and distinctive stratal patterns in the basinal facies makes correlation along this ramp-to-basin transect difficult. Therefore, carbon-isotope stratigraphy and total organic carbon analysis were tested for their utility as intrabasinal correlation tools.

$\delta^{13}$C_{carbonate} isotope values range from -1.7‰ to 0.07‰ (PDB) at Marjum Pass and -1.1‰ to 1.4‰ (PDB) in the Drum Mountains; previously reported $\delta^{13}$C_{carbonate} values in the
Great Basin for this time interval range between -2‰ to 2‰ (PDB). Both localities show small-scale isotope variability; however, this variability is thought to be the result of local isotopic effects and was not used for correlation. TOC values obtained from both sections increase upsection, define a distinct peak, then decrease upsection. These peaks are associated with shale facies and occur near the maximum flooding surface in both sections, indicating that the TOC results could be used for correlation between sections.

The lithologic cyclicity recognized in the shallow-water deposits at the Drum Mountains locality have also been recognized in the deeper-water deposits at Marjum Pass. At each locality the meter-scale cycles shallow upward and display similar stacking patterns. Because cyclicity is preserved in both sections and the total stratigraphic thickness and cycle thickness decrease toward the embayment-controlling fault, it is probable that the cyclicity was the result of small-scale eustatic changes in sea level rather than episodic tectonism.

This ramp-to-basin correlation also supports the validity of *P. atatus* as a global biostratigraphic marker. The first appearance of *Pyhagnostus atatus* has been found below the interpreted maximum flooding surface and was coeval with transgression in both localities, indicating that its appearance was likely synchronous.
ACKNOWLEDGMENTS

This project was funded by grants from the American Association of Petroleum Geologists, the Geological Society of America, the Colorado Scientific Society and the Department of Geology at Utah State University.

I would like to thank my advisor, Dr. David Liddell, and committee members, Drs. Peter Kolesar and Carol Dehler, for support and patience throughout my time at Utah State University. Thanks are also extended to the many people who allowed me to use their labs: Dr. Steven Nelson and Katie Anderson at Brigham Young University, for use of the stable isotope lab and many enlightening emails; Dr. Viorel Autorodari, at the University of New Mexico for use of the elemental analyzer and his help and advice while doing so; also Dr. Dan Jarvie and Humble Geochemical Laboratories, for running the TOC analyses.

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Many thanks to my field assistants who gave up free time to measure and sample Middle Cambrian rocks in the desert: Maya Elrick, Carol Dehler, Dave Liddell, Matt Anders, Stefanie Anders, Dick Heermance, Danette McKinney, Cam Snow and Robert Petrie.

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Elizabeth Langenburg
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INTRODUCTION

Sequence stratigraphy can be used as a tool to better understand the stratigraphic relationships of an area and the paleogeographic setting(s) they represent. However, in sedimentary successions with rapid lateral lithologic changes and limited outcrop, understanding facies associations and correlation between sections becomes difficult. This study evaluates the use of the geochemical composition of marine carbonate rocks as correlation tools across a proximal ramp-to-basin transition.

The Wheeler Formation is a fossil-rich Middle Cambrian sedimentary succession that was deposited across the proximal ramp to basinal environments of the House Range embayment (Grannis 1982; Rees 1986; Vorwald 1984; Schneider 2000). The Wheeler Formation is dominated by carbonate ramp deposits in the Drum Mountains (295 m thick) and basinal calcareous shale deposits at Marjum Pass (190 m thick), in the central House Range (Fig. 1). Because the strata of the Wheeler Formation are highly varied laterally, lack any chronostratigraphic markers and the temporal scale at which the strata were deposited does not correlate with any known biostratigraphic range zone, it provides an excellent opportunity to use geochemistry to attempt intrabasinal correlation and understand lithofacies associations across this proximal ramp-to-basin transition.

C-isotope geochemistry and total organic carbon analyses were combined with traditional sedimentologic techniques to create a high-resolution intrabasinal correlation of the Wheeler Formation. In general, isotopic studies of marine carbonate rocks for this time period have focused on relatively shallow-water deposits and have not investigated the use of deeper-water isotope values for chemostatigraphic correlation (Braiser 1992). This study provides isotope curves for both shallow-water deposits and correlative deep-water deposits, allowing a test of its validity as an intrabasinal correlation tool.
Figure 1. Index map of study locality. Adapted from the recreational map of Utah (GTR maps 1993).
It is the purpose of this research to evaluate the use of chemostratigraphic analysis as a correlation tool for stratigraphic sections of diverse lithofacies and thereby test the use of chemostratigraphy as a correlation tool for the Middle Cambrian Wheeler Formation. This sequence stratigraphic framework can then be used to: understand the paleogeography of the House Range embayment during deposition of the Wheeler Formation, better evaluate the driving force(s) behind meter-scale cyclicity and better understand the paleoecologic response of Cambrian organisms to changes in sea level.
GEOLOGIC HISTORY AND PREVIOUS WORK

Geologic Setting

Paleozoic strata of the western United States are dominantly a record of deposition on a passive continental margin. Neoproterozoic rifting led to thermal subsidence on the newly formed western edge of North America (Stewart and Suczek 1977; Taylor 1989). Post-rifting siliciclastic sediments blanketed the area and created a broad ramp upon which Middle and Late Cambrian carbonate sediments were deposited (Rees 1986). Three belts of deposition existed on the passive margin. An inner detrital belt, to the west of which was a shallow-water carbonate platform and farther west was an outer shelf which faced the open ocean and also received fine-grained detrital sediment (Hintze 1988; Stokes 1988).

Locally, movement on the House Range fault and the initiation of the House Range embayment (HRE) affected deposition on the shallow-water carbonate platform (Rees 1986). The HRE was a half-graben that widened as it extended westward and formed a broad depression in the Eureka-House Range region that terminated just east of the House Range (Palmer 1971; Rees 1986) (Fig. 2). Differing subsidence rates on each side of the embayment resulted in the formation of a northern carbonate platform, which sloped southward toward the more rapidly subsiding trough where deeper-water sediments were being deposited (Rees 1986) (Fig. 2). The northern margin of the HRE maintained a ramp geometry throughout the life of the embayment, the southern margin is not well constrained due to lack of exposed Middle Cambrian strata, but is interpreted as a steep margin (Rees 1986; Elrick and Snider 2002) (Fig. 2). Deposition of the Wheeler Formation occurred during the Middle Cambrian (Bolaspidella Zone) on the northern margin of the HRE (Fig. 3).
Figure 2. A: Map view of House Range Embayment (adapted from Rees, 1986). This non-palispspastic reconstruction shows that the southern embayment boundary is interpreted as a normal fault. B: Cross-section view of HRE. FS = Fish Springs Range, DM = Drum Mountains, MP = Marjum Pass, Central House Range sHR = southern House Range, W = northern Wah Wah Range, S = Snake Range, sSC = southern Schell Creek Range, sE = southern Egan Range.
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Figure 3. Middle Cambrian fossil ranges and formations in west-central Utah. Adapted from Elrick and Snider (2002). See figure 2 for map showing locations of Utah mountain ranges.
Stratigraphy

The Middle and Late Cambrian deposits of west-central Utah are dominated by limestone with interbedded subordinate shale (Hintze 1988). The Whirlwind Formation (37 m thick) overlies the Dome Limestone and is identified by two slope-forming shale beds (upper and basal) separated by a reddish-weathering, mottled dolomitic limestone (Dommer 1980). The overlying Swasey Limestone (56 m thick) is similar to its character at other localities in Utah (Dommer 1980; Rees 1986). The basal Swasey Limestone is a thin-bedded, fossil-poor, argillaceous limestone and is overlain by 30 m of ledge-forming fossil-poor, coarse-grained, carbonate packstone/grainstone (Schneider 2000). In both the Drum Mountains and at Marjum Pass, the contact between the Swasey Limestone and the Wheeler Formation (190-300 m thick) is located at the sharp contact between the light gray, ledge-forming limestone of the Swasey Limestone and the pale red-purple, slope-forming shale of the Wheeler Formation (White 1973; Rowell et al. 1982; Schneider 2000).

The Wheeler Formation at the Drum Mountains locality is dominated by finely-laminated platy shale and thickly-bedded limestone (Hintze 1988; Schneider 2000). The shale ranges in color from pale red-purple at the base to medium-dark gray above (Schneider 2000). Dommer (1980) and Schneider (2000) split the Wheeler Formation at this locality into three informal members based on weathering profile. The lower member (109 m thick) is thin-bedded, fossil-rich argillaceous limestone. The middle member (73 m thick) is a very dark to medium gray medium-bedded rhythmite. The upper member (133 m thick) is medium gray limestone and calcareous shale at the base capped by buff colored calcareous shale and carbonate boundstone at the top (Dommer 1980; Schneider 2000; this study). Four trilobite zones have been identified in the Wheeler Formation (Fig. 3). The transition from
the *Oryctocephalus* to the *Belaspiddella* open-shelf polymeroid-trilobite zones and the transition between the *P. gibbus* and the *Psycheagnostus atatus* open-shelf agnostoid trilobite zones occur in the lower Wheeler Formation (Robison 1976) (Fig. 3).

The Pierson Cove Formation (240 m thick), which overlies the Wheeler Formation in the Drum Mountains, is correlative to the Marjum Formation in the House Range (Fig. 3). This formation is composed of thinly-bedded, pisolithic and oncolitic limestone and dolomite interbedded with calcareous shale (Dommer 1980); the uppermost limestone grades into dolomite (Hintze 1988). The Trippe Limestone overlies the Pierson Cove Formation and caps the Middle Cambrian stratigraphy in the Drum Mountains. This unit (130 m thick) is split into two members; the lower member (108 m thick), is composed of alternating boundstone and dark gray mottled limestone and the upper member, the Fish Springs Member (22 m thick) is a thin-bedded silty intraformational conglomerate (Dommer 1980; Schneider 2000).

The upper boundary of the Wheeler Formation has been a subject of debate and has been changed several times. Dommer (1980) based his placement of the upper contact with the overlying Pierson Cove Formation strictly on a lithologic change, placing the contact in the uppermost transitional beds of the Wheeler Formation, at the base of the lowest limestone and dolomite cliff (Dommer 1980). Vorwald (1984) later re-defined the upper contact; he included the lowermost Pierson Cove Formation of Dommer (1980) in the Wheeler Formation because of its fossil content. These units contain Wheeler-type fauna and are fossil rich (Vorwald 1984), while the Pierson Cove Formation is characterized by unfossiliferous limestone and lime mudstone (Vorwald 1984). The North American Stratigraphic Code (Hedberg 1983) requires that if a formation is to be identified by its lithological characteristics and stratigraphic position, it must be mappable at the surface and
subsurface and cannot be defined by age (isotopic or biostratigraphic). Schneider (2000) placed the upper boundary at the base of the southeast thickening, fissile shale, because this surface is a likely transgressive surface separating a highstand systems tract (HST) from a transgressive systems tract (TST). This study will use the boundary as defined by Schneider (2000).

Lithologic and thickness changes occur laterally in the Wheeler Formation; the lithology previously described is based on exposures of the Wheeler Formation in the Drum Mountains. At the Marjum Pass locality in the central House Range, the Wheeler Formation is fossiliferous and is dominated by dark gray to black shale (Robison 1962; Hintze 1988). This area likely represents deposition at the deepest parts of the HRE; other deep-water HRE deposits are preserved in the Schell Creek, Egan and Snake Ranges of eastern Nevada (Fig. 2) (Rees 1986). The upper contact between the Wheeler Formation and the overlying Marjum Formation at the Marjum Pass locality has historically been placed at the first appearance of a limestone cliff, giving it a thickness of ~150 m (Robison 1962; Rees 1986; Hintze 1988). This boundary has been re-defined in this study and the contact between the Wheeler Formation and Marjum Formation has been moved to 190 m above the Swasey Limestone. The contact, in this study, is placed between a carbonate intraclastic conglomerate and the overlying black fissile shale. This contact is interpreted to represent a marine flooding surface separating the HST from the overlying TST. The Marjum Formation (~330 m thick) conformably overlies the Wheeler Formation and is composed predominantly of rhythmite and subordinate shale that accumulated within the deepest part of the HRE (Elrick and Snider 2002). The Marjum Formation is conformably overlain by the Weeks Formation (365 m thick) (Fig. 3). The overlying Upper Cambrian units are
dominated by limestone and subordinate dolomite; they include the Orr Formation and the Notch Peak Formation (Dommer 1980; Hintze 1988).

Formation of the HRE, which affected deposition in the carbonate belt, may have been coincident with a eustatic transgression (Rowell et al. 1982; Rees 1986). Fossil evidence was used by Rowell et al. (1982) to propose a global sea-level change at the Swasey Limestone/Wheeler Formation boundary. The agnostoid trilobite, *Ptychagnostus gibbus*, appears in stratigraphic sections globally and is found above either shallow-water rocks lacking agnostoids or in strata that are unconformably separated from older strata (Rowell et al. 1982). In Utah, *P. gibbus* is found in the basal beds of the Wheeler Formation, which are characterized by intervals of interbedded shale and carbonate mudstone and, locally, carbonate agnostoid concretions. These beds overlie the Swasey Limestone, which accumulated on a shallow carbonate shelf (Rowell et al. 1982).

Hintze and Robison (1975), Kepper (1976) and McGee (1978) suggested that a diastem marks the boundary between the Swasey Limestone and Wheeler Formation and this surface is thought to represent a submarine hardground (Grannis 1982; this study). Rees (1986) points out that the Swasey Limestone is characterized throughout Utah as a burrowed packstone, which in the HRE localities is overlain by deeper water deposits, such as the Wheeler Formation, thus recording a drowning event. However, on the southern platform (Wah Wah and Cricket Ranges) the drowning event is not recorded. In these ranges, the Eye of the Needle Limestone, a peritidal, fenestral limestone (Hintze and Robison 1975; Kepper 1976) overlies the Swasey Limestone. This difference in lithofacies overlying the Swasey Limestone may indicate the onset of down-dropping on the House Range fault, coincident with transgression.
The transgression recorded in the HRE has been interpreted, in the Drum Mountains, as a single 3rd order cycle upon which several higher-frequency (4th and 5th order) cycles were superimposed (Schneider 2000). The Drum Mountains locality represents the shallowest water deposits of the Wheeler Formation found in the hanging wall of the House Range fault and are correlative with the deeper-water deposits preserved in the central House Range, at Marjum Pass (Fig. 2). Previous work in the Wheeler Formation suggested that episodic movement on the House Range fault controlled the meter-scale cyclicity (Schneider 2000). This interpretation contradicts findings of other workers studying similar age deposits in the Great Basin area. These workers have suggested Milankovitch orbital forcing as a control for meter-scale cyclicity (Grotzinger 1986; Goldhammer et al. 1987; Koerschner and Read 1989; Osleger 1991; Montañez and Osleger 1993; Elrick and Hinnov 1996).
METHODS

Location of Study Area

The Wheeler Formation is well exposed in west central Utah (Fig. 1). Stratigraphic sections were measured and samples were taken at two localities. The Drum Mountains locality is northwest of Delta, UT, Millard County, T 15 S, R 10 W (Fig. 4). The Marjum Pass locality is located in the central House Range west of Delta, UT, Millard County, T 18 S, R 13 W and T 18 S, R 14 W (Fig. 5).

Field Methods

Composite stratigraphic sections were measured at both localities to encompass the most complete exposure of outcrop (Figs. 4 and 5). The composite sections were measured by following marker beds and using a 1.5 m Jacob's staff and Brunton compass to shoot along strike when covered intervals were encountered. Offset by faults was carefully accounted for in order to obtain accurate lithologic thickness. Spray paint was used to mark each 1.5 m increment; lithologic descriptions and sample collections were done based on this 1.5 m spacing. Lithotypes were described at the centimeter scale using a 10 m fiberglass tape and ruler. Color changes were noted using the GSA rock color chart (1991). Grain-size, grain-type, sedimentary structures, bed-thickness, resistance to weathering, fossil content and presence of bioturbation were also noted. Paleocurrent and paleoslope data were obtained (when available) from ripple cross-laminae, soft-sediment folds and carbonate boundstone. The paleocurrent data were rotated to horizontal using the Stereonett 2.46 (2000) software program.

Samples for petrographic and geochemical analysis were collected, regardless of
Figure 4. Topographic map of Drum Mountains study area with locations and thickness of measured sections. From Drum Mountains Wells UT 7.5’ quadrangle 1971. The sections are located in Sec. 17 T15S R10W.
Figure 5. Topographic map of Marjum Pass study area with locations and thickness of measured sections. From the Marjum Pass and Notch Peak, UT 7.5' quadrangle 1972. The sections are located in T18S R13W and T18S R1.
lithology, at 5-10 m interval depending on outcrop availability (Appendix D). These hand samples were used to augment field descriptions of lithofacies and for geochemical analyses. Fresh samples at covered intervals were obtained whenever possible by digging to uncover fresh outcrop.

Labaratory Methods

Geochemical Analyses.---The whole rock analyses of this study were done using samples taken at 5-10 m intervals of calcareous and non-calcareous shale, calcisiltite, wackestone, packstone and grainstone. The 10 m interval was chosen to best encompass stratigraphic changes in $^{13}$C values and show the changes in weight percent total organic carbon (wt. % TOC). However, sample intervals varied in thickness due to the heterogeneity of the depositional environments, which are reflected in the outcrop pattern and wide range of lithologies and cyclicity found in the Wheeler Formation.

For geochemical analyses, the samples were trimmed to avoid calcite veins and weathering rinds and 10 gm of each sample was crushed to 60 mesh (250 micron). The powdered samples were split and analyzed for isotopic composition ($\delta^{13}$C$_{carbonate}$ and $\delta^{13}$C$_{organic}$), TOC, weight percent CaCO$_3$ and a pilot study of trace element analysis. Because diagenesis is a concern when dealing with marine carbonate rocks, the geochemical data (i.e., $\delta^{13}$C$_{carbonate}$, $\delta^{13}$C$_{organic}$, $\delta^{18}$O$_{carbonate}$ and trace element analysis) were evaluated and compared against the work of other authors who have done chemostratigraphic studies (Kaufman and Knoll 1995; Kah et al. 1999; Saltzman et al. 1998). $\delta^{18}$O$_{carbonate}$ and $\Delta\delta$ ($\Delta\delta = \delta^{13}$C$_{carbonate} - \delta^{13}$C$_{organic}$) values were used to identify suspect samples (i.e. diagenetically altered) based on the criteria given by Kaufman and Knoll (1995). A pilot study of the trace element composition
of both suspect and non-suspect samples was done in the Geology Department at Utah State University. Pressed powders were made by combining 7 gm of powdered sample with 5 drops polyvinyl alcohol (the binding agent). To make pressed powders the homogenous mixture of sample and binding agent was pressed in a hydraulic press. The pressed powders were then analyzed in the X-ray fluorescence laboratory for their trace element composition.

\( \delta^{13}C_{\text{carbonate}} \) isotopes were analyzed at Brigham Young University, Department of Geology. A 10 mg split of sample was reacted with 100% phosphoric acid for at least 8 hours at 25° C. The \( \text{CO}_2 \) gas was then extracted on a vacuum line and the gases were analyzed on a Finnigan Delta Plus mass spectrometer. Fractionation of O-isotopes was corrected by using the fractionation factor of 1.01025, \( \delta^{18}O = (\text{raw} \delta^{18}O \text{ value} + 100/1.01025)-1000. \)

Weight percent \( \text{CaCO}_3 \) data were obtained by reacting 5 gm of powdered sample with 10% HCl until all \( \text{CaCO}_3 \) was removed (usually 8 hours). To verify that all \( \text{CaCO}_3 \) was removed, the 10% HCl was drained after 8 hours and fresh 10% HCl was added to the sample. When no reaction occurred between fresh acid and sample, all \( \text{CaCO}_3 \) had been removed. The insoluble residues were then rinsed with de-ionized water, dried in a single wall transite oven at 110° C, allowed to cool in a desiccator and then re-weighed. The equation \((i-f/i) \times 100\), where \(i=\) initial weight and \(f=\) final weight, was used to find weight percent \( \text{CaCO}_3 \) lost during the reaction.

The insoluble residues left from the \( \text{CaCO}_3 \) analyses were analyzed at the University of New Mexico, Department of Earth and Planetary Sciences for \( \delta^{13}C_{\text{organic}} \) isotope composition using the DeltaPlus XL mass spectrometer and elemental analyzer. A 0.5 mg
split of the insoluble residue was loaded into the Delta\textsuperscript{plus} XL, which determined the $\delta^{13}$C\textsubscript{organic} composition of the insoluble residue sample via combustion.

Whole rock TOC analysis was done on the samples by Rock-Eval TOC at Humble Geochemical Laboratory in Houston, TX. 100 mg of sample was loaded into pyrolysis crucibles and samples were pyrolyzed under helium at 300°C for 3-4 minutes followed by heating at 25°C/min. until a temperature of 600°C was reached. During heating carbon is released from organic matter as carbon dioxide, this carbon release is measured through time. Humble Geochemical TOC and Rock-Eval Methodologies require that instrument calibration be done using a rock standard. The standard is analyzed every tenth sample as an unknown, if the standard does not meet specified requirements all nine samples are discarded and the instrument is recalibrated and the samples are analyzed again (Humble Geochemical pers. comm.). Humble Geochemical TOC and Rock-Eval Methodologies also require that analytical data be checked randomly and selectively, these checks are completed on approximately 10% of the samples (Humble Geochemical pers. comm.).

**Petrographic Analysis.**---Both polished sections (5) and thin sections (30) were prepared at Utah State University using hand samples from both localities. All thin sections were stained using Alizarin red S to differentiate between calcite and dolomite. Petrographic analysis of these samples was used to describe each facies by obtaining grain-size, sedimentary structure, grain-type, and grain-abundance data. Petrographic analysis and point counts of the thin sections were done using an Olympus BH-2 polarizing microscope with a mechanical stage. A rarefaction method was used to determine how many points to count (Zar 1999). All rarefaction analyses showed that 150 or fewer counts were needed per sample. All carbonate lithologies were named using the Dunham classification, with the
exception of calcisiltite and shale (Carozzi 1989). Calcisiltite is the term for carbonate rocks with up to 10% sand-size component (Carozzi 1989). Shale facies were differentiated based on carbonate content (i.e., calcareous or non-calcareous); calcareous shale are more resistant while non-calcareous shale are extremely fissile and weather more easily.

**Data Analysis.---**Due to the cyclic nature of the Wheeler Formation and the fact that geochemical samples were taken systematically without regard to cycle position, there was a possibility of “within-cycle” effects (i.e., cycle position) on the geochemical results. To verify that the data do not reflect merely cycle position or lithology, cross plots, correlation coefficients and the Mann-Whitney U test were used to evaluate these possibilities using the graphing tools in the Excel (1997) software program and Mann-Whitney U formulas and critical U tables provided in Zar (1999) (Table C-1).

All paleocurrent data were rotated to horizontal using Stereonett 2.46 (2000) to account for tectonic dip.
RESULTS

Data from the Drum Mountains locality will be presented first, followed by data from the Marjum pass locality.

Drum Mountains

Lithofacies.---The Wheeler Formation in the Drum Mountains is dominated by fine-grained carbonate facies of calcareous shale, calcisiltite, argillaceous limestone and rhythmite with subordinate bioclastic wackestone, packstone, grainstone and boundstone (Figs. 6-11). In general, grain abundance and bed thickness increase up-section. Table 1 provides the rock names and descriptions of each facies described at the Drum Mountains locality; these names will be used throughout this thesis.

Stratigraphy and Cyclostratigraphy.---Previous work in the Drum Mountains suggested that it was deposited during a single 3rd order cycle with 20 smaller-scale cycles (4th and 5th order) superimposed upon the 3rd order cycle (Schneider 2000). This study has identified 19 cycles superimposed on the larger, 295 m thick cycle (Fig. 12). Cycles are dominated by basal fine-grained, thinly-bedded shale or argillaceous limestone overlain by a calcisiltite, wackestone, packstone or grainstone (Fig. 13 and Table A-1). These cycles have distinctive weathering patterns; more resistant carbonate beds overlie less resistant shale and argillaceous limestone beds. Cycle thickness at the Drum Mountains locality ranges between 0.5 m and 94 m and the mean cycle thickness is 15.5 m.

The base of the Wheeler Formation overlies the oolitic bioclastic packstone of the Swasey Limestone. In the uppermost 20 m of the Swasey Limestone, there are 0.25 m-0.35 m thick tangential cross-strata and an undulose surface with wavelengths of 1.0 m and
Figure 6. Outcrop photo of calcareous and non-calcareous shale interbeds. Taken at Marjum Pass, 55 m above the Swasey Limestone.
Figure 7. Calcisiltite facies. Outcrop photo shows asymmetric ripple marks found in lower Drum Mountains locality, 0.5 m above the Swasey Limestone (field book for scale). Photomicrograph of calcisiltite, at 100x magnification, plane polarized light.
Figure 8. Outcrop photo of argillaceous limestone facies. Note cm-scale interbeds of clay-rich calcisiltite and shale. Drum Mountains locality, 45 m above the Swasey Limestone.
Figure 9. Outcrop photo of rhythmite facies. Drum Mountains, 110 m above Swasey Limestone.
Figure 10. Photomicrograph of bioclastic oolitic/oncolitic packstone. Brachiopod is 1.75 mm across. 40x magnification, plane polarized light.
Figure 11. Carbonate boundstone facies, note bioclastic grainstone infilling between boundstone, asymmetric elongate morphology suggesting current action. Photo taken at Drum Mountains locality, 290 m above the Swasey Limestone.
Table 1. Lithofacies descriptions of the Drum Mountains locality.

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Shale</td>
<td>Medium dark gray to black, weathers to various shades of gray, tan and often pale-red purple, fissile, silt and clay-sized grains, dominantly clay-sized particles, not well indurated, often very fissile (papery), slightly effervescent, often associated with calcisiltite (Fig. 6).</td>
</tr>
<tr>
<td>Calcareous Shale</td>
<td>Medium dark gray to dark gray, fissile, silt and clay-sized grains, weathers to various shades of gray and tan, well indurated and extremely effervescent, often fossiliferous, may contain whole and disarticulated sponge spicules, agnostoid and polymeroid trilobites and brachiopods, often associated with calcisiltite (Fig. 6).</td>
</tr>
<tr>
<td>Calcisiltite</td>
<td>Light, medium and medium dark gray carbonate siltstone, very finely to finely crystalline, dominate grain size ranges from very fine silt to coarse silt, generally laminated, locally massive, thin to medium bedded, ledge forming when thick (&gt;0.5m) or recessive when interbedded with shale, local ripple foresets (E) and local asymmetric megaripples (trend 170-175°) often fossiliferous containing whole and disarticulated agnostoid and polymeroid trilobites (Fig. 7).</td>
</tr>
<tr>
<td>Argillaceous Limestone</td>
<td>Light, medium and medium dark gray calcisiltite or carbonate mudstone, laminated or massive, very thinly bedded, cm scale interbeds with calcareous shale, generally recessive (Fig. 8).</td>
</tr>
<tr>
<td>Rhythmite</td>
<td>Thin interbeds of medium-gray calcisiltite with very thin tan-orange dolosiltite interbeds and laminations, or light-gray calcisiltite, cliff forming, dominantly laminated and graded. Individual beds show scoured bases, boudins, cross-strata, intraclasts, graded bedding and rare burrows. Some intervals are nodular and locally contorted (Fig. 9).</td>
</tr>
<tr>
<td>Wackestone and Packstone</td>
<td>Medium light gray to medium dark gray, &gt;10% grains with carbonate mud, finely to coarsely crystalline, often bioturbated, grain size ranges from fine silt to pebble. Grains types include ooids, oncoids, hexactinellid sponge spicules, inarticulate brachiopods, eocrinoids, agnostoid and polymeroid trilobites. Bioclasts can be whole or disarticulated (Fig. 10).</td>
</tr>
<tr>
<td>Grainstone</td>
<td>Light to medium gray, grain supported bioclastic limestone. Medium to thinly bedded generally massive, coarsely to very coarsely crystalline, grain size ranges from fine silt to pebble, some ripple cross-strata, often bioturbated. Often fills between carbonate boundstone. Grain types are trilobite fragments (agnostoid and polymeroid), inarticulate brachiopods, eocrinoids, ooids, oncoids and peloidal mud clasts (Fig. 11).</td>
</tr>
<tr>
<td>Carbonate Boundstone</td>
<td>Light to medium gray, domal, elongate and branching stromatolites. Morphology varies along strike; internal laminations and stromatolite size increase along strike toward the SE. Associated with bioclastic grainstone (Fig. 11).</td>
</tr>
</tbody>
</table>

amplitudes of 0.5 m. The top of the Swasey Limestone shows small-scale surface relief (1-5 mm) and is mineralized with hematite after pyrite crystals. Although no evidence of boring has been found, this surface is considered to represent a submarine hardground.

There are four cycle types recognized in the Drum Mountains. The cycle types have been divided based on the lithology of their cycle caps. The calcisiltite-capped cycles are
generally composed of shale (both calcareous and non-calcareous) overlain by thinly-laminated or rarely massive, thinly-bedded calcisiltite (Fig. 13a). In the Drum Mountains, these cycles are found only in the basal 72 m of the Wheeler Formation and range in thickness from 0.5-7 m; with a mean thickness of 4 m.

The rhythmite-capped cycles are characterized by an argillaceous limestone base overlain by a calcisiltite/dolosiltite rhythmite (Fig. 13b). The rhythmite-capped cycles are generally laminated, contain scours, boudins and graded bedding. These cycles can be found from 10 to 136 m above the Swasey Limestone; they range in thickness from 6-25 m with a mean thickness of 19 m. These cycles dominate the middle Wheeler Formation, giving it its characteristic resistant weathering profile.

The third cycle type is capped by bioclastic, oolitic/oncolitic wacke-packstone (Fig. 13c). This cycle type comprises the upper 132.5 m of the Wheeler Formation at the Drum Mountains locality and is found only once in the lower Wheeler Formation at 57 m. The base of these cycles can be either shale or argillaceous limestone overlain by wacke-packstone or boundstone. The cycle caps can be nodular or laminated and often show ripple cross-stratification. These cycles range from 2 to 94 m in thickness with a mean cycle thickness of 20 m.

The fourth cycle type recognized at this locality is capped by argillaceous limestone (Fig. 13d). These cycles have calcareous shale bases that grade upward into a very thinly-bedded, laminated, resistant argillaceous limestone. This cycle type only appears twice in the Drum Mountains section at 33 m and again at 72 m; the cycle thicknesses are 19.5 m and 17 m, respectively.

In this study, the top of the Wheeler Formation is considered to be at 295 m above the base. The boundary is placed between the carbonate boundstone bed of cycle 19 and
Figure 12. Measured stratigraphic column from the Drum Mountains locality with interpreted cycle tops.
Figure 13. A, B, C: generalized cycle types at the Drum Mountains locality. A: shale overlain by calcisiltite, B: argillaceous limestone overlain by rhythmite, C: shale or argillaceous limestone overlain by wacke-pack-grainstone cap. D: common cycle type found at each locality, calcareous shale base with an argillaceous limestone cap. E, F, G: generalized cycle types at the Marjum Pass locality. E: shale overlain by laminated calcisiltite, F: fissile shale overlain by calcareous shale, G: argillaceous limestone overlain by bioclastic packstone or rhythmite.
the overlying light gray non-calcareous shale, which defines the base of the Pierson Cove Formation (Fig 12) (Schneider 2000).

**Weight Percent CaCO₃ Analysis.** The wt. % CaCO₃ analysis was used to find samples suitable for δ¹³C_carbonate analysis as well as document CaCO₃ changes through the stratigraphic section. The Wheeler Formation in the Drum Mountains is characterized by CaCO₃ values between 76-99 wt. %, with a mean value of 83.8 (std. error ± 4) wt. % (Table C-1). These data show that there are two distinct drops in wt. % CaCO₃ (Fig. 14a). The first decrease occurs at 76 m, in the base of cycle 8, where CaCO₃ is 42 wt. %. The second decrease occurs between 214-224 m. This is in the base of cycle 19 in the upper Wheeler Formation; here CaCO₃ values range between 48-59 wt. % (Fig. 14a).

**Total Organic Carbon Analysis.** Total organic carbon analysis was done on the same samples as those used in the wt. % CaCO₃ analysis. The whole rock TOC values in the Drum Mountains range between 0.04 and 0.13 with a mean TOC value of 0.06 ± 0.005 (std. error) (Fig. 14b and Table C-1). These data show a significant increase in total organic carbon (TOC) between 50 and 76 m, with values ranging between 0.1-0.13 and a second peak at 112 m with a TOC value of 0.11 wt. %.

δ¹³C_carbonate Analysis. δ¹³C_carbonate analysis of the Drum Mountains section provided isotopic values that range between -1.1 ‰ and +1.3 ‰. These values do not appear to be facies dependent (Fig. 15b). Cross-plots of δ¹³C_carbonate vs TOC and δ¹³C_carbonate vs CaCO₃ shows that δ¹³C_carbonate does not vary with changes in TOC or CaCO₃ (Figs. C-1 and C-2). There is an overall negative shift up section from 112 m, where the most positive isotopic value is +1.3 ‰. From this point isotopic values become more negative up section,
ranging between -1.13‰ to 0.85‰ (Fig. 15b). The standard error of each analysis is ± 0.007‰.

$^{13}$C$_{\text{organic}}$ and $\Delta\delta$ Analysis.--- $^{13}$C$_{\text{organic}}$ values range between -29.5‰ and -23.8‰ with a mean value of -27.6‰ (Fig. 15a). The $^{13}$C$_{\text{organic}}$ and $^{13}$C$_{\text{carbonate}}$ values are used to calculate $\Delta\delta$ (Table B-1). $\Delta\delta = {^{13}}C_{\text{carbonate}} - {^{13}}C_{\text{organic}}$. This $\Delta\delta$ value is used to evaluate samples for possible diagenetic effects. Workers have shown that $\Delta\delta$ values provide information about diagenesis and exchange between the carbon reservoirs (Kaufman and Knoll 1995; Kah et al. 1999). $\Delta\delta$ values should be $>25$ and the $^{13}$C$_{\text{carbonate}}$ values and $^{13}$C$_{\text{organic}}$ values should track each other throughout the stratigraphic section (Kaufman and Knoll 1995; Kah et al. 1999). The $^{13}$C$_{\text{organic}}$ data do not show any negative shift in values updosection like the $^{13}$C$_{\text{carbonate}}$. The organic carbon isotope values generally co-vary with the inorganic carbon isotope values (Fig. 15b). $\Delta\delta$ values for the Drum Mountains locality range between 23.8 and 29.4, with a mean value of 27.7.

Compiled Palontology.---The first appearance of Ptychagnostus atmus at the Drum Mountains locality is being considered as a global stratotype section and point for the Middle Cambrian (Rowell et al. 1982; Babcock et al. in prep). Figure 16 shows the observed stratigraphic distribution of trilobites, these data were compiled from Robison (1962), White (1973) and Babcock et al. (in prep). These data show that P. atmus first appears at 62 m at the Drum Mountain locality. This graph also shows that the first polymeroid species are found in the Drum Mountains section 45 m above the base and that the polymeroid trilobites do not show an increase in diversity until ~60 m above the base (Fig. 16).
Figure 14. Geochemical data from the Drum Mountains locality.
A: wt. % CaCO$_3$
B: wt. % TOC whole rock
Figure 15. Carbon isotope data from the Drum Mountains locality.
A: organic carbon isotope values
B: carbonate carbon isotope values
Figure 16. Stratigraphic occurrence of echinoderms at the Drum Mountains locality.

Data compiled from Robinson (1962), White (1977), and Badcock et al. (in prep).

- Trymataspis depressa
- Ptychagnostus ptychagnostus
- Peronopsis sp.
- Trymataspis atavus
- Elrathia cf. E. parallela
- Peronopsis segmenta
- Peronopsis sp.
- Peronopsis intermedia
- P. gilbus
- P. integrata
- Brachyaspidion sucatum
- Glenoides sp.
- Semisphaerocephalus sp.
- Bathyuriscus sp.
- Zacanthoides sp.
- Solenopleura sp.
- Modocia sp.
- Peronopsis sp.
- Peronopsis sp.
- Peronopsis sp.
- Peronopsis sp.
- Peronopsis sp.
- Peronopsis sp.
- Peronopsis sp.
- Peronopsis sp.
- Trymataspis depressa
- Ptychagnostus ptychagnostus
- Peronopsis sp.
- Trymataspis atavus
- Elrathia cf. E. parallela
- Peronopsis segmenta
- Peronopsis intermedia
- P. gilbus
- P. integrata
- Brachyaspidion sucatum
- Glenoides sp.
- Semisphaerocephalus sp.
- Bathyuriscus sp.
- Zacanthoides sp.
- Solenopleura sp.
- Modocia sp.
- Peronopsis sp.
- Peronopsis sp.
Marjum Pass

Lithofacies.—Fine-grained deposits of shale, calcareous shale and subordinate calcisiltite facies dominate the Wheeler Formation at Marjum Pass. Calcareous and non-calcareous shale and subordinate calcisiltite beds grade upward into bioturbated calcisiltite, rhythmite and oolitic wackestone facies with interbedded bioclastic wackestone and shale (Fig. 17). Table 2 lists the rock names and descriptions for each facies found in the Wheeler Formation at Marjum Pass.

Table 2. Lithofacies descriptions of the Marjum Pass locality.

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale</td>
<td>Black and pale-red purple, fissile, silt and clay-sized grains dominantly clay-sized particles, often very fissile (papery), slightly effervescent, associated with calcareous shale (Fig. 6).</td>
</tr>
<tr>
<td>Calcareous shale</td>
<td>Medium gray to dark gray, fissile, silt and clay-sized particles, well indurated and extremely effervescent, often-fossiliferous containing whole and disarticulated sponge spicules, agnostoid and polymeroid trilobites and brachiopods, also contains horizontal burrows. (Fig. 6).</td>
</tr>
<tr>
<td>Calcisiltite</td>
<td>Light, medium and medium dark gray carbonate siltstone, often weathers orange, very finely to finely crystalline, dominate grain size ranges from very fine silt to coarse silt, generally laminated, very thinly to thinly bedded, concretionary and nodular bed forms, often fossiliferous. Fossil fragments include agnostoid and polymeroid trilobites and sponge spicules (Fig. 7).</td>
</tr>
<tr>
<td>Argillaceous Limestone</td>
<td>Medium dark gray calcisiltite or carbonate mudstone, laminated or massive, very thinly bedded, cm scale interbeds with calcareous shale, recessive. (Fig. 8)</td>
</tr>
<tr>
<td>Rhythmite</td>
<td>Thin interbeds of medium-gray calcisiltite with very thin tan-orange dolosiltite interbeds and laminations, cliff forming, dominantly finely laminated some scours, boudins and graded bedding. Some intervals are highly bioturbated (Fig. 9).</td>
</tr>
<tr>
<td>Wackestone-packstone</td>
<td>Finely to coarsely crystalline, grain size ranges from fine silt to coarse silt. Grain types include ooids, agnostoid and polymeroid trilobites. Usually laminated or massive with some irregular bedding contacts (Fig. 10).</td>
</tr>
</tbody>
</table>

Stratigraphy and Cyclostratigraphy.—Previous work in the Wheeler Formation by Schneider (2000) reported that the meter-scale cyclicity observed in the Drum Mountains section was not observed at the Marjum Pass locality and interpreted the lack of cycles at the Marjum Pass locality to represent “missed-beats.” Although it is difficult to recognize the cyclicity at the Marjum Pass locality due to the fine-grained nature of the outcrops, the
current study has defined 16 cycles superimposed on the larger scale 190 m thick section (Fig. 17). Similar to the Drum Mountain locality, the cycles at the Marjum Pass locality are defined by finer-grained, less-calcareous deposits overlain by relatively more resistant, more calcareous deposits (Table A-2).

The contact between the Swasey Limestone and Wheeler Formation at the Marjum Pass locality is similar to that at the Drum Mountains. The top of the Swasey Limestone shows small-scale surface relief is mineralized with hematite staining and hematite replaced pyrite crystals and is overlain by pale red-purple fissile shale. This surface is interpreted to represent a marine hardground and transgressive surface separating the LST from the overlying TST of the Marjum Formation. Cycle thicknesses at Marjum Pass range between 3 m and 25 m, with a mean cycle thickness of 12 m (Table A-2). Compared to the Drum Mountains locality, the Marjum Pass cycles can be recognized by changes in weathering patterns due to finer-grained, more thinly-bedded facies overlain by more resistant, relatively more calcareous, often coarser-grained beds (Fig. 13, d-g).

There are four cycle types at Marjum Pass (Fig. 13, d-g), also defined by the characteristics of the cycle caps. The first cycle type is characterized by a basal shale unit that grades upward and is capped by thinly-bedded laminated calcisiltite (Fig. 13e). These cycles are found throughout the Wheeler Formation at Marjum Pass, they range in thickness from 3-24 m and have a mean cycle thickness of 9.5 m.

The second cycle type (Fig 13f), the calcareous shale-capped cycles, is recognized by a fissile shale base overlain by a well indurated, calcareous shale cap. Shale partings thicken upward as the cycle grades into the resistant, thinly-laminated, calcareous shale cycle cap. These cycle types are found from 33.5-153.5 m at the Marjum Pass locality and range in
Figure 17. Stratigraphic section from the Marjum Pass locality with interpreted cycle tops.
thickness between 5.5-25 m, with a mean thickness of 12 m.

The third cycle type is capped by resistant bioclastic-oolitic packstone or peloidal calcisiltite-dolosiltite rhythmite. These cycles have argillaceous limestone bases (Fig. 13g), which are in sharp contact with the overlying cycle cap. This cycle type is only observed in the upper 40 m of the Wheeler Formation (152-190 m), it ranges in thickness from 7-14.5 m and has a mean cycle thickness of 11 m.

The fourth cycle type is characterized by a very well indurated, thinly-bedded, laminated, argillaceous limestone-cap; the base of this cycle is calcareous shale (Fig. 13d). This cycle type is the least common at Marjum Pass and was only observed twice throughout the Wheeler Formation at this locality, once at 27 m and again at 61.5 m; the cycle thicknesses are 6.5 and 25 m, respectively.

The top of the Wheeler Formation is placed at the contact between the intraclast-bearing calcisiltite at 185 meters and the overlying black fissile shale. This contact, considered to be the base of the Marjum Formation, differs from previous workers who placed the contact at the first appearance of “substantial” limestone (Robison 1962; Rees 1986). This re-defined contact increases the thickness of the Wheeler Formation from ~150 m to ~190 m and was chosen because it likely represents a marine flooding surface separating a HST from the overlying TST.

**Weight Percent CaCO₃ Analysis.**---Results from this analysis show two intervals of decreased wt. % CaCO₃ (Fig. 18a and Table B-2). Weight percent CaCO₃ ranges between 40 and 98 percent with a mean of 69 (± 4 std. error) wt. % CaCO₃. Weight percent CaCO₃ data show a decrease in CaCO₃ at 50 m, with a value of 41 wt. %, and a second decrease occurs at 154 m, with a value of 42 wt. % CaCO₃ (Fig. 18a).
Total Organic Carbon Analysis.— Weight percent (wt. %) TOC values are higher at the Marjum Pass locality than those obtained from the Drum Mountains locality. There are several peaks in TOC throughout the Marjum Pass section. TOC values range from 0.02-0.30 wt. % TOC, with a mean value of 0.08 (± 0.01) wt. % TOC (Fig. 18b and Table B-2). The first peak in TOC values occurs at 50 m with a value of 0.3 wt. %; this peak TOC value is preceded by a gradual increase in TOC values from 27 m (Fig. 18b). The next TOC peak occurs at 128.5 m and shows 0.14 wt. % TOC. A third peak in TOC occurs at 167 m with a value of 0.09 wt. % TOC (Fig. 13b).

$\delta^{13}C_{carbonate}$ Analysis.— The Marjum Pass locality has $\delta^{13}C_{carbonate}$ values that range between -1.76‰ and 0.14‰, with a standard error for each analysis of ±0.007‰ (Fig. 19b and Table B-2). The isotopic values from Marjum Pass do not appear to be facies controlled because $\delta^{13}C_{carbonate}$ values vary within the same facies (Fig. 19b). A cross-plot of $\delta^{13}C_{carbonate}$ vs TOC and $\delta^{13}C_{carbonate}$ vs CaCO₃ shows that $\delta^{13}C_{carbonate}$ does not vary with changes in TOC or CaCO₃ (Fig. C-1). The Marjum Pass isotope data do not show a negative shift upsection like those of the Drum Mountains.

$\delta^{13}C_{organic}$ and Δδ Analysis.— The $\delta^{13}C_{organic}$ curve at Marjum Pass shows that the values compliment the $\delta^{13}C_{carbonate}$ data (Fig. 19a and b). The $\delta^{13}C_{organic}$ data range between -27.9‰ and -24.4‰ with a mean value of -26.9‰. The Δδ values range between 24.5‰ and 27.1‰, with a mean value of 24.9‰ (Table B-2).

Compiled Paleontology.— Paleontologic data were compiled from Robison (1962), White (1973) and Babcock et al. (in prep.) (Fig. 20). Babcock et al. (2002) show that Ptychagnostus atavus first appears at 25.5 m at Marjum Pass (Fig. 20). Figure 20 also shows that polymeroid species appear in the Marjum Pass section at 95 m, but do not become
Figure 18. Geochemical data from the Marjum Pass locality.
A: weight percent CaCO₃
B: weight percent TOC whole rock
Figure 19. Carbon isotope data from the Marjum Pass locality.
A: organic carbon isotope values
B: carbonate carbon isotope values
Figure 20. Stratigraphic occurrence of trilobites at the Marjum Pass locality. Data compiled from Robison (1962), White (1973) and Bahco et al. (in prep).
diverse until 120 m. *Ebrathia kingii* is the most widely distributed of the polymeroid trilobites and first appears at 96 m.

*Statistical Analysis of Wheeler Formation Geochemical Data*

Crossplots and the Mann-Whitney U test were used to test for significant lithologic or within-cycle effects on the geochemical data (Figs. C-1, C-2, C-3 and Table C-1). The cross plot of $\delta^{13}$C$_{carbonate}$ vs. wt. % TOC shows $\delta^{13}$C$_{carbonate}$ values ranging between -1‰ to 1‰ over a wide range of wt. % TOC (0.01 to 0.3 wt. %) (Fig. C-1). Similarly, the $\delta^{13}$C$_{carbonate}$ vs wt. % CaCO$_3$ cross-plot shows $\delta^{13}$C$_{carbonate}$ values of -1‰ to 1‰ spread over a wide range of wt. % CaCO$_3$ values (40 to 95 wt. %) (Fig. C-2). These crossplots suggest that the $\delta^{13}$C isotope values are free from lithologic effects; that is to say that, the $\delta^{13}$C$_{carbonate}$ values have a narrow range, generally staying between -1‰ to 1‰ no matter what the CaCO$_3$ or TOC content of the sample may be. However, the cross-plot of wt. % TOC vs wt. % CaCO$_3$ shows that the cycle bases and cycle caps appear to group together (Fig. C-3). The Mann-Whitney U test was used to test for within cycle effect on wt. % CaCO$_3$ and wt. % TOC.

Data from each locality were separated for position in cycle (cap or base) and U values were calculated for wt. % TOC and wt. % CaCO$_3$. The null hypothesis: there is no significant difference in TOC or CaCO$_3$ between samples taken from cycle bases and cycle caps, could be rejected if either of the two calculated U values were greater than or equal to the U critical value given in a table for $\alpha = 0.05$ (Table C-1) (Zar 1999). Results from the Mann-Whitney U tests were not able to reject the null hypothesis for the Marjum Pass data.
The results from the Mann-Whitney U tests performed on the Drum Mountains data were able to reject the null hypothesis for the wt. % CaCO3 but not for the wt. % TOC.

The field and petrographic observations of the meter-scale cycles in the Wheeler Formation show finer-grained bases overlain by coarser-grained caps, this relationship has been interpreted to represent upward shallowing. The results from the Mann-Whitney U tests performed on the geochemical data from the Wheeler Formation show that there is no significant difference in wt. % TOC between cycle caps and bases at both localities. However, the tests do suggest that there is a significant difference between wt. % CaCO3 at the Drum Mountains locality but not at the Marjum Pass locality. This may be due to the paleogeographic location of each site. The Drum Mountains locality was more proximal to the subtidal carbonate factory and likely received increased amounts of CaCO3 and coarser grained material during shallow periods, while at the Marjum Pass locality, the upward shallowing cycles appear to be reflected as a grain size change but not necessarily a change in wt. % CaCO3.
INTERPRETATION

Stratigraphy and Depositional Environments

As defined herein, the total stratigraphic thickness of the Wheeler Formation in the Drum Mountains locality is 295 m (Fig. 12). Based on stratigraphic associations, sedimentary structures, grain size and sorting, the lithofacies have been interpreted as being deposited in three environments: proximal ramp, distal ramp and basin. The Drum Mountains section records cyclic deposition, shoals upward from distal to proximal ramp facies and is composed of 19 recognized cycles (Fig. 12 and Table A-1). As defined herein, the total stratigraphic thickness at Marjum Pass is 190 m. The Marjum Pass section records deposits of basinal carbonate shale that shoal upward to rhythmite facies of the distal ramp environment; channels and rip-up storm deposits; and is composed of sixteen meter-scale cycles (Fig. 17 and Table A-2).

Rocks of the Wheeler Formation have been grouped into seven lithofacies (Tables 1 and 2). Their environments of deposition have been interpreted and are described below.

Bioclastic, Oolitic Packestone, Calcareous Shale and Carbonate Boundstone Facies.—In the bioclastic, oolitic packstone facies grain sizes range between fine and coarse silt, ripple cross-laminae have also been identified. The fossil composition within this facies includes an open marine fauna of polymeroid trilobites, brachiopods, eocrinoids and sponge spicules. U-tube and horizontal burrows are common (Fig. 21).

Burrowed calcareous shale is found in the upper Wheeler Formation at the Drum Mountains locality. This is light gray in color, weathers tan and is well exposed. This calcareous shale contains a very sparse faunal assemblage; Schneider (2000) shows that fauna within the shale range in density between 1/ m² to 5/ m². The fauna found includes articulate
brachiopods, eocrinoids and agnostoid trilobites, the shale is heavily burrowed, contains both horizontal and vertical burrows and bioturbation increases upward.

The burrowed shale grades upward into a burrow mottled bioclastic packstone, which is overlain by the carbonate boundstone facies. The carbonate boundstone facies is the cliff former found at the top of the Drum Mountains section. This facies is light gray in color and is composed of stromatolites with bioclastic/oolitic grainstone infilling between the stromatolites. The stromatolites can be asymmetrically elongate (Fig. 11) and along strike (to the SE) the stromatolites show a change in morphology.

Figure 21. Basal bedding plane exposure of burrows, Drum Mountains locality, 170 m above the Swasey Limestone, DM cycle 15.
These facies are interpreted to have been deposited in subtidal depths at or below fair-weather wave base, an environment that is found on the proximal ramp (Emery and Meyers 1996). U-tube and horizontal burrows suggest the sediment-water interface was oxygenated and the elongate morphology of the stromatolites and the cross-laminae of the bioclastic, oolitic packstone show the effect of currents. The well-preserved stromatolites and the sparse fauna found in the calcareous shale suggest a quite possibly restricted lagoonal setting and its protective barrier. Other workers (e.g., Grannis 1982; Vorwald 1984; Schneider 2000) support the lagoon interpretation.

Rhythmite Facies.---Dominant grain type of the proximal ramp is fine to medium silt sized peloids. This facies is well sorted and show evidence of intermittent current. The change between calcisiltite and dolosiltite is due to a grain size change with the dolosiltite layers being coarser grained. The contacts between the calcisiltite and dolosiltite are often gradational and previous workers have interpreted incomplete Bouma sequences Tace and Tce (Grannis 1982; Vorwald 1984; Rees 1986; Schneider 2000). The rhythmites are locally contorted showing upright to recumbent folds and often contain boudins, scours and intraclasts (Fig. 22).

Deposition was likely due to suspension settling of fine-grained peloids in the distal ramp environment. These deposits were likely brought in by turbidity currents and were subject to current re-working during storm events. The locally contorted bedding is interpreted by this study and other studies to have been produced by submarine gravity slides (Rogers 1984; Rees 1986).

Argillaceous Limestone and Calcisiltite Facies.---The argillaceous limestone facies is generally recessive and is composed of cm-scale interbeds of non-calcareous shale and clay-rich calcisiltite. The calcisiltite facies is often resistant, can be laminated or massive
Figure 22. Soft-sediment deformation in rhythmite cap of DM cycle 10, 95 m above Swasey Limestone.

and preserves ripple cross-lamination, hummocky cross-strata and ripple marks. The grain type of both facies is peloids with rare fossils. Soft sediment deformation is observed in some of the calcisiltite facies.

Sedimentation is characterized by suspension settling of clay and silt-sized peloid grains, in the quiet water setting of the distal ramp. The ripple marks, ripple cross-laminae and hummocky cross-stratification suggest that this facies has been affected by intermittent current or intermittent storm events. The soft sediment deformation seen in some of the calcisiltite (for example cycle DM 8) suggests distal down-slope movement of sediment flows (Grannis 1982; Compton 1985).
Calcareous and Non-calcareous Shale Facies.---The calcareous and non-calcareous shale are generally recessive and outcrop poorly at the Drum Mountains locality but are well exposed at the Marjum Pass locality. This lithofacies is light medium gray to black in color. These deposits are fissile to very thinly bedded (1-2 cm thick) and the calcareous shale can contain continuous parallel, thin laminae (1-3 mm). Horizontal burrows in these organic-rich deposits are common, grain size ranges from clay to fine silt. The fossil composition of this facies is dominated by agnostoid trilobites and blue-green algae with subordinate sponge spicules. Locally at Marjum Pass, there are agnostoid concretions found in the non-calcareous shale, these concretions are thought to have formed by early cementation of fossil lags. These facies are found throughout the Marjum Pass locality and are found in the basal portion of the Drum Mountains locality (0-95 m). In the Drum Mountains the shale facies are associated with interbedded calcisiltite and argillaceous limestone.

The fine grained nature of these deposits and continuous parallel laminae suggest deposition in a quiet water setting. The abundance of agnostoid trilobites and blue-green algae suggest deposition of planktonic organisms and fine detritus occurred via suspension settling, with sponge spicules being brought in from more proximal localities. These lithofacies are interpreted to represent the deep-water basinal deposits of the Wheeler Formation.

Cycle Interpretations

The meter-scale cycles identified in the Wheeler Formation are all characterized by a more resistant (more calcareous) coarser grained cycle cap overlying a recessive (less
calcareous) cycle base. This change from finer-grained, less-resistant base to coarser-grained, more-resistant cap indicates that the cycles shallow upward.

**Drum Mountains.**---DM cycles 1-8 are dominated by calcisiltite (n=5) capped cycles with subordinate rhythmite (n=1), pack-grainstone (n=1) and argillaceous limestone (n=1) capped cycles (Fig. 13 a, b, c, d). The subordinate rhythmite-, argillaceous limestone- and pack-grainstone capped cycles show evidence of deposition via turbidity currents or show soft sediment deformation, suggesting that, due to rapid sedimentation, aggradation occurred, resulting in over-steepening and sediment gravity flows.

The top of cycle 8 is a mineralized hard ground, as sea level reached the highest point of rise, sedimentation rates slowed and a hardground developed. This surface shows 1-3 cm of surface relief, is stained with hematite and contains hematite-replaced pyrite crystals. DM cycle 9 and the base of DM cycle 10 are dominated by shale and record high wt. % TOC values (Figs. 12 and 14b). Cycle 9 has a 15 m-thick base of shale that is overlain by a 2 m thick, massive, very thinly bedded calcisiltite cycle cap, overlain by the black shale base of DM cycle 10. The combined lithologic and TOC data suggest deposition in a quiet, anoxic, deep-water environment.

The basal 3 m of DM cycle cap 10 is contorted and deformation varies along strike. These deformed beds are interpreted to represent soft-sediment deformation resulting from down-slope movement of partially-lithified sediment on an oversteepened slope (Grannis 1982; Rees 1986). DM cycles 11 and 12 are rhythmite cycle caps with argillaceous limestone bases. The amount of bioturbation and grain size increase upward in DM cycle 12; this cycle cap grades upward to a bioturbated oolitic wackestone. This is the first sign of severe bioturbation in the Drum Mountains and may indicate increased oxygenation at the sediment-water interface.
Bioclastic oncolitic/oolitic packstone-capped cycles are found in the upper Wheeler Formation (164 m - 200 m) and represent shoaling to the proximal ramp environment. These cycle caps overlie argillaceous limestone cycle bases; they are in sharp basal contact with their underlying cycle bases and are in sharp contact with the overlying cycles. These cycles are thought to record a continued shallowing of sea level, increased grain size, increased burrowing and a higher-energy environment. The diversity of fauna increases noticeably in DM cycles 13-18 and includes inarticulate and articulate brachiopods, eocrinoids, polymeroid trilobites, agnostoid trilobites and sponge spicules (Schneider 2000). The overlying calcareous shale of DM cycle 19 is interpreted to have been deposited in a lagoon, protected by the overlying carbonate boundstone reef and underlying bioclastic, oncolitic/oolitic packstone shoals (Grannis 1982; Vorwald 1984; Schneider 2000). Overall, the DM cycles shallow upward, from distal ramp to proximal ramp facies.

**Marjum Pass.---**MP cycles 1-5 are composed of non-calcareous cycle bases with thin calcisiltite cycle caps. These fine-grained lithologies shallow from non-calcareous shale to calcisiltite caps indicating a change in the amount of detrital carbonate being deposited. The fine-grained nature and continuous parallel laminae suggest deposition in a quiet water setting via suspension settling of fine detrital carbonate grains. The top of MP cycle 5 is mineralized with hematite staining and hematite replaced pyrite crystals, shows small-scale relief, is associated with agnostoid concretions and is interpreted to represent a submarine hardground.

Overlying MP cycle 5 is a calcareous shale-capped cycle (MP 6) a calcisiltite capped cycle (MP 7) and an argillaceous limestone-capped cycle (MP 8). MP cycle 6 and the basal portion of MP cycle 7 record high wt. % TOC values, have preserved blue-green algae as carbon films and represent the thickest shale units of the Wheeler Formation at Marjum
Pass. The fine-grained nature and high wt. % TOC suggests quiet, anoxic, relatively deep-water deposition of these cycles.

Overlying the second argillaceous limestone-capped cycle (MP 8) is the second cluster of calcisiltite-capped cycles, MP 9-11 (Fig. 17). The cycle caps of these second (stratigraphically higher) calcisiltite-capped cycles are thicker and weather a distinctive orange color that is recognizable immediately in outcrop; these distinctive orange beds are laterally continuous and lenticular, possibly due to disruption by a bottom current (Fig. 23a). It is important to note that the basal portion of the second cluster of calcisiltite-capped cycles is calcareous shale while the basal portion of the first (stratigraphically lower) calcisiltite-capped cycles was black non-calcareous shale. The differences in lithologic associations and sedimentary structures observed between the two groups of calcisiltite-capped cycles may indicate a higher sediment supply and an overall shallower water depth during deposition of the second cluster.

Overlying the second cluster of calcisiltite-capped cycles are two calcareous-shale capped cycles (MP 12 and 13), which are overlain by the rhythmite- and packstone-capped cycles (MP 14-16). MP cycles 12 and 13 are distinctive from the calcareous shale-capped cycles below them in that they contain abraded fossil fragments of polymeroid trilobites, suggesting an influx of coarser grained sediment to the basin.

The rhythmite- and packstone-capped cycles (MP 14-16) represent a basinward shift in facies and the shallowest water depths reached at the Marjum Pass locality. The rhythmite-capped cycle is burrowed and contains scours and graded bedding. Overlying this burrowed rhythmite-capped cycle is an oolitic packstone, which has ripple cross-laminae and is associated laterally with a cross-stratified channel bed form (Fig. 23b). MP cycle cap 16 is a
Figure 23. A: orange marker beds at Marjum Pass locality, view is looking east 105 m above the Swasey Limestone. B: cross-stratified channel at Marjum Pass, 180 m above the Swasey Limestone.
burrowed rhythmite, which contains scours and graded bedding; the top of the rhythmite bed is an intraclastic conglomerate.

Although harder to recognize, the stacking patterns at Marjum Pass are similar to those seen at the Drum Mountains locality and show a clear upward shallowing sequence overprinted by small-scale cyclicity.

**Sea-level Curves**

Interpreted depositional environments have been combined with the meter-scale cycles observed in each stratigraphic section to create sea-level curves for the Wheeler Formation at each locality (Figs. 24 and 25). The sea-level curves at both localities show an overall upward shallowing and all of the smaller-scale cycles superimposed on these curves also shallow upward. Combining the interpreted depositional environments with the inferred sea-level curves allows a definition of the systems tracts and third-order sequence stratigraphic correlation.

**Systems Tracts**

To apply sequence stratigraphic concepts that were originally defined using seismic profiles of siliciclastic systems to cyclic carbonates deposited on passive margins and exposed in noncontinuous outcrop, Montañez and Osleger (1993) point out that a de-emphasis of stratal geometry and an increased awareness of correlative vertical changes in stacking patterns of meter-scale cycles is needed. This study has combined the interpreted depositional environments, the stacking patterns of the meter-scale cycles and the interpreted marine flooding surfaces observed at each locality to define systems tracts.
Figure 24. Drum Mountains cyclicity, interpreted sea-level curve and system tracts. SB = sequence boundary, TS = transgressive surface, TST = transgressive systems tract, HST = highstand systems tract. Compiled from Schneider (2000) and this study.
Figure 25. Marjum Pass cyclicity, interpreted sea-level curve and system tracts. SB = sequence boundary, TS = transgressive surface, TST = transgressive systems tract, HST = highstand systems tract, LST = lowstand systems tract.
Drum Mountains.---The transgressive systems tract (TST), as defined by Van Wagoner et al. (1981) is characterized by retrogradational parasequence sets common during transgression as sea-level rises and marine sediments build landward. In the Drum Mountains, cycles DM 1-8 have been interpreted to represent the TST. The transgressive surface (TS) is located at the contact between the bioclastic packstone of the Swasey Limestone and the pale red-purple shale of the Wheeler Formation; this boundary marks a marine flooding surface. DM cycles 1-8 are characterized by argillaceous limestone and shale bases overlain by calcisiltite tops. These fine-grained lithofacies were deposited as sea-level rose and drowned the platform margin.

Changes in faunal density were used by Schneider (2000) to support the TST interpretation. Schneider (2000) showed that in the basal-most Wheeler Formation there was an up-section change in faunal density and diversity patterns, which may have been linked to a change in sediment influx during initial flooding of the platform. Upsection to 66.5 m there was an increase in sponge spicule and trilobite density and diversity. After DM cycle 2, sponge spicule density increased, ranging between 15/m²-100/m² (Schneider 2000). The agnostoid trilobite density was shown by Schneider (2000) to range between 1/m²-5/m² from 0-30 m and 15/m²-50/m² through 60 m. The initial increased density may reflect condensation caused by decreasing sedimentation rates, due to a rapid increase in relative sea level (Schneider 2000). The density change in agnostoid trilobites may also reflect changing paleoecologic conditions associated with transgression. Robison (1972; 1976) showed that agnostoid trilobites are associated with open marine settings and avoid netiric environments having excessive runoff. The distribution of the agnostoid trilobites in the lower 60 m of the Wheeler Formation suggests that, after ~30 m, the Wheeler Formation was less turbid, which allowed the presence of agnostoid trilobites.
The top of DM cycle 8 is a hardground and is closely associated with an agnostoid condensed zone. This hardground is interpreted to be the maximum flooding surface. The maximum flooding surface separates the TST from the overlying highstand systems tract (HST).

The HST should be characterized by one or more aggradational parasequence sets followed by one or more progradational parasequence sets deposited during the late part of eustatic rise, a eustatic stillstand and the early part of a eustatic fall (Van Wagoner et al. 1988). Given this definition, we expect to observe progradation of sediment basinward in the stratigraphic record. This would suggest that sediments that were impounded during transgression were then transported to the basin. In the Drum Mountains the HST has been subdivided into the early and late highstand systems tracts (eHST and lHST). This division is based on the character of the cycle caps. The eHST cycles are interpreted as having been deposited during the late part of sea-level rise (shale dominated cycle 9) and during early sea-level fall by turbidity currents (rhythmite-capped cycles 10-12). The rhythmites were produced via initial release of fine-grained sediment to the basin as sea level started dropping. In contrast to the finer-grained rocks associated with eHST, the lHST (cycle caps DM 13-19) are bioclastic oncotic/oolitic wacke-grainstone and carbonate boundstone. These lHST cycles show evidence of deposition in relatively higher-energy, shallower water; the cycle caps are cross-stratified, burrowed and show an increase in faunal diversity relative to eHST cycles. The contact between the carbonate boundstone (cycle cap DM 19) and the overlying non-calcareous shale of the Pierson Cove Formation is a marine flooding surface interpreted to represent the sequence boundary (SB) separating the HST from the overlying TST.
Marjum Pass.—The TS at Marjum Pass is represented by contact between the oolitic packstone of the Swasey Limestone and the overlying pale red-purple shale of the Wheeler Formation. The TST is represented by the fine-grained facies of cycles 1-5, which were deposited as sea-level rose and flooded the platform. The top of cycle 5 has been interpreted as the MFS at the Marjum Pass locality. It is a hardground that is associated with agnostoid concretions.

The stratigraphic position (above the MFS) and depositional environments interpreted for MP cycles 6-16 suggests that they likely represent the distal equivalent of HST at the Drum Mountains. MP cycles 6-9 are interpreted to be the distal equivalent of the eHST while MP cycles 10-16 are interpreted as the likely equivalent to the lHST deposits at the Drum Mountains. MP cycles 6-9 show an increase in carbonate content linked to the influx of detrital carbonate during the eHST. MP cycles 10-16 contain abraded fossil fragments and coarser-grained sediment, which were likely transported from shallower water, possibly during the lHST. The distinctive orange beds, which cap cycles MP 9-11 have a lenticular bed form, suggesting that they were affected by bottom currents and deposited at a shallower water depth than the calcisiltite cycle caps in the lower portion of the section.

The top of MP cycle 16 is an intraclastic conglomerate and its contact with the overlying black paper shale is a marine flooding surface interpreted to be the SB between the underlying HST and overlying TST of the Marjum Formation.

Sequence Boundaries

Because exposures of the Wheeler Formation are limited between the two study localities, following significant surfaces laterally is difficult (Fig. 1). Outcrop patterns do not show unconformities and onlap or downlap characteristics like those seen on seismic
profiles. Similar to other carbonate deposits in the Paleozoic record (see Montañez and Osleger 1993), the water depths and depositional environments of the Wheeler Formation preserved sequence boundaries that do not fit into the Type 1 or Type 2 categories as defined by Van Wagner et al. (1988). In this study, sequence boundaries were placed between significant facies changes or at marine-flooding surfaces, across which there is evidence of an abrupt increase in water depth (Van Wagoner et al. 1988), although these boundaries do not show evidence of prolonged subaerial exposure.

The base of the Wheeler Formation, at both localities, is defined by a marine flooding surface between the oolitic packstone of the Swasey Limestone and the pale red-purple fissile shale of the overlying Wheeler Formation. This contact is a hardground and represents a significant increase in water depth. In the Drum Mountains, 20 m below this transgressive surface (TS1) is an undulose surface that has irregular relief with amplitudes of 1-5 cm and wavelengths of 5-10 cm. This surface is thought to represent a sequence boundary and the undulose surface is interpreted to be the result of erosion. Above this surface the Swasey Limestone is coarse grained, contains ooids, skeletal fragments and 0.25-0.35 m ripple cross-strata; the uppermost 0.5 m of the Swasey Limestone is a massive bioclastic oolitic packstone. This transition upward is thought to be the lowstand systems tract (LST), representing the re-working of sediment during a time of relatively low sea level (Schneider 2000). The SB and LST have not been identified at the Marjum Pass locality but TS1 has been identified between the Swasey Limestone and the overlying Wheeler Formation. Therefore TS1 is used at the datum for correlation between the two sections (Fig. 26).

The maximum flooding surface (MFS) has been interpreted in both sections to be located at a significant hardground, this hardground is associated with deep-water shale
facies in both localities. In the Drum Mountains locality this hardground is 72.5 m above the base, it is represented by a mineralized surface (hematite staining and hematite-replaced pyrite crystals) with small-scale surface relief and is closely associated with an agnostoid condensed zone. The MFS is marked by a similar hardground at the Marjum Pass locality, 33.5 m above the Swasey Limestone. As is the case in the Drum Mountains, the MFS at Marjum Pass is mineralized, shows small-scale surface relief and is associated with agnostoid concretions. In both stratigraphic sections the MFS is associated with shale facies and high wt. % TOC. The fine-grained lithofacies and preservation of high wt. % TOC suggests that quiet, anoxic, deep-water conditions existed in both localities at this time.

The upper sequence boundary (SB2) is at the top of each section, again between two facies representing a significant change in water depth (marine flooding surface). At the Drum Mountains locality this surface is located at 295 m, between the carbonate boundstone beds of the upper Wheeler Formation and the overlying non-calcareous shale of the Pierson Cove Formation. At the Marjum Pass locality the boundary is located between the intraclast conglomerate (190 m) and the overlying black non-calcareous shale of the Marjum Formation. SB2 separates the HST from the overlying TST (Fig. 26).

Controls on Cyclicity

The development of cyclicity in stratigraphic sections can be due to autocyclic or allocyclic mechanisms. Autocyclic models include: 1) prograding tidal-flat facies over the subtidal carbonate factory (Ginsberg 1971) and 2) lateral migration of depositional environments (Cloyd et al. 1990). Allocyclic controls include; 1) episodic tectonism and intraplate stress mechanisms (Cisne 1986; Cloetingh 1986; Schneider 2000) and 2) eustatic oscillation of sea level due to Milankovitch orbital-forcing (Grotzinger 1986; Goldhammer et
Figure 26. Combined stratigraphic correlation of the Wheeler Formation, with systems tracts. TS1 = transgressive surface 1, TST = transgressive systems tract, MFS = maximum flooding surface, eHST = early highstand systems tract, IHST = late highstand systems tract, SB2 = sequence boundary 2.
Ginsberg's (1971) model suggested that regressive cycles are produced from a seaward progradation of a sedimentary wedge, which would decrease the size of the subtidal carbonate factory. Subsidence alone would then create a relative rise in sea level and carbonate sediment generation would resume. The model proposed by Cloyd et al. (1990) suggested that there is no effective change in water depth, Cloyd cited evidence that the cyclicity observed in the Waterfowl Formation (Upper-Middle Cambrian; Canada) represented re-distribution of sediment due to lateral shifts in tidal facies (channels, levees and crevasse-splay). Osleger (1991) has disputed both these models. The autecyclic model of Ginsberg (1971) required progradation of tidal-flats over the subtidal carbonate factory, but, by definition, subtidal cycles, for example the Orr Formation and Notch Peak (Osleger 1991) and Wheeler Formation (this study), lack a tidal-flat cap. A re-distribution of sediment is likely to occur in subtidal settings and may control internal cycle variability, but the lateral continuity of the cycles and the repetitive nature of their lithologies, suggest that their formation was controlled by an external mechanism (e.g., Osleger 1990, 1991).

Osleger (1991) also dismissed an episodic tectonic control, citing evidence that modern examples of tectonic subsidence are in regions of extreme tectonic instability (e.g. New Zealand, southern California) and the relative oscillations of sea level caused by intraplate stress mechanisms are too slow to produce high-frequency carbonate cycles. Osleger also suggested that the cyclicity of the Upper Cambrian Orr and Notch Peak Formations was not controlled by episodic tectonism because the House Range embayment was infilled after early Late Cambrian time (Rees 1986). Episodic tectonism is a likely mechanism to produce laterally discontinuous cycles adjacent to the fault but is not a likely
mechanism to produce laterally continuous cyclicity. Therefore, if episodic tectonism were
the cause of most of the meter-scale cyclicity observed in the Wheeler Formation we would
not expect to observe similar cycles at both localities.

Workers have observed meter-scale cyclicity in Middle Cambrian deposits of the
Great Basin region; for example, in the Wah Wah Range, the Middle Cambrian (*Bcdaspisdel**a
Zone) deposits are characterized by stacked, meter-scale, upward-shallowing cycles. Detailed
studies of these deposits (Kepper 1972, 1976; Bond et al. 1991) have shown that the meter-
scale cycles are characterized by a repetition of facies and that the temporal scale at which
they were deposited corresponds to orbital eccentricity and precession. Elrick and Snider
(2002), who have observed meter-scale cycles in the Marjum Formation, which overlies the
Wheeler Formation, proposed a eustatic control. Many workers have suggested
Milankovitch orbital forcing as the driving force of high-frequency sea-level fluctuations
necessary to create the meter-scale cyclicity observed (Grotzinger 1986; Goldhammer et al.
1987; Koerschner and Read 1989; Osleger 1990, 1991; Montañéz and Osleger 1993; Elrick
and Hinnov 1996). However, given the lack of evidence supporting glaciation during the
Cambrian, the location and timing of deposition of the Wheeler Formation in the HRE (a
newly formed half-graben) and the previous work by Schneider (2000), who suggested
episodic tectonism as a mechanism for 5th-order cycle formation within the Wheeler
Formation, the present study investigated the possibility of both episodic tectonism and
Milankovitch orbital forcing as possible driving mechanisms for meter-scale cyclicity within
the Wheeler Formation.

The House Range fault (Fig. 2) had a NE-SW trend, was located south of the Drum
Mountains and defined the trough-axis of the basin near the Marjum Pass locality. As
proposed by Schneider (2000), the meter-scale cycles observed in the Drum Mountains may
have formed when movement on this fault resulted in exposure and weathering of the carbonate platform, which would deliver coarser-grained debris to the Drum Mountains locality. The lack of cyclicity, observed by Schneider (2000), at the Marjum Pass locality lends support to this model.

In contrast this study has identified meter-scale cycles at the Marjum Pass locality and has interpreted this cyclicity to be laterally equivalent to the cyclicity observed at the Drum Mountains locality. Because meter-scale cyclicity is found throughout the sedimentary record, including times before and after infilling of the House Range embayment (Osleger 1991; Elrick and Snider 2002; this study), a common mechanism to produce such cyclicity is desired. These cycles display a similar stacking pattern to those at the Drum Mountains locality and fit the sequence stratigraphic framework and interpreted systems tracts (Fig. 27). The Drum Mountains section contains more cycles than the Marjum Pass section, which may be due to the proximity of the Drum Mountains section to the sub-tidal carbonate factory. Some of the Drum Mountains cycles may be represented in the Marjum Pass section by sub-tidal “missed beats.” It is likely that high-frequency changes in sea level affected the amount of detrital carbonate sediment able to reach the depositional environments because changes in sea level affects the location (proximity) of the sub-tidal carbonate factory (Rees 1986; Elrick and Snider 2002).

Given the support of past research on similar age rocks, both in and outside of the HRE, and the lateral continuity of cyclicity within the Wheeler Formation; we propose that the cyclicity observed was derived from a single driving mechanism, Milankovitch orbital forcing, not episodic tectonism.
Figure 27. Cyclicity and systems tracts of the Wheeler Formation. TS1 = transgressive surface, TST = transgressive systems tract, MFS = maximum flooding surface, eHST = early highstand systems tract, IHST = late highstand systems tract, SB2 = sequence boundary 2.
Total Organic Carbon.—Weight percent TOC within the Wheeler Formation is relatively low with mean values of 0.06 wt. % in the Drum Mountain locality and 0.08 wt. % at the Marjum Pass locality. As might be predicted, the Marjum Pass locality has an overall higher mean wt. % TOC, likely due to its depositional location in deeper water. Similarities in the wt. % TOC curves have been observed between the two sections: both sections show peak wt. % TOC values in the lower third of each section, after which TOC values reflect mean wt. % TOC values. The peak wt. % TOC values are found from 50-76 m at the Drum Mountains locality and from 27-50 m at the Marjum Pass locality, these values occur near the MFS in both sections and likely reflect the time of deepest water deposition.

Because the MFS separates the end of the TST and beginning of the HST it marks the beginning of sea-level fall and is interpreted to be associated with the maximum water depth reached in the stratigraphic sequence (Van Wagoner et al. 1988). The peak TOC data from the Wheeler Formation are associated with the rocks surrounding the MFS, this high TOC may therefore be linked to the time of maximum water depth.

There are several means of creating high TOC preservation, they include: 1) deep water and associated low oxygen levels, which would prevent scavenging of organics and/or oxidation, 2) increased sedimentation and rapid burial of organic matter, removing it from possible oxidation and/or scavenging and 3) upwelling and increased production, which would contribute more organic matter to the system (Broecker and Peng 1982). Deep water is often associated with low energy deposits, such as shale, and can result in low oxygen levels. The deposits associated with high TOC preservation in the Wheeler Formation are fine-grained shales and contain hematite-replaced pyrite crystals, suggesting anoxic
conditions. Also, after the maximum flooding surface is reached, rates of clastic sedimentation typically increase as sediments impounded in coastal settings are redistributed across the shelf. Because of the stratigraphic position and lithologic characteristics associated with the peak TOC values, this study considers TOC a viable tool for correlation.

It should be noted that the values obtained in the present study differ significantly from other TOC data obtained in previous studies in the Wheeler Formation in the Drum Mountains (Schneider 2000) and the Marjum Pass area (Liddell personal communication). Although overall trends through the Wheeler Formation section are similar between the present study and previous studies, weight percent TOC values from the present study are typically much lower than those found in the other studies. For example Schneider (2000) found TOC values ranging from 0.6 to 4.4 wt. % TOC in the Drum Mountains with many, but not all, of the highest values occurring at 60-80 m above the Swasey Limestone. At Marjum Pass Liddell (personal communication) found TOC values ranging from 0.64 to 4 wt. % TOC. It should be noted that these TOC values were obtained from rocks that ranged between 3.5 and 56.4% CaCO₃ and only 4 of the 20 samples were greater than 50 % CaCO₃ (Liddell personal communication).

The reason for these differences in TOC values may lie in the methodologies used for TOC analysis. The present study employed Humble Geochemical Laboratories in Houston, Texas for analyses. The results from Humble Geochemical Laboratories are based on whole rock pyrolysis. The previous studies by Schneider (2000) and Liddell (personal communication) were done via ashing of the insoluble residue portion of samples in the laboratory at Utah State University. These discrepancies need to be investigated further to better understand the significant difference found between the three data sets.
Diagenesis.—Because this study used whole rock analyses of marine carbonates, diagenesis was a concern. Verification of primary carbon isotope values had to be done before chemostratigraphic correlation could be attempted. Kaufman and Knoll (1995) have suggested several criteria for testing the effects of diagenesis on marine carbonate values (Fig. 28).

The carbon isotope values from the Wheeler Formation are close to the range of modern marine carbonates and dolomites (Hudson 1977; Tucker and Wright 1990) and show little covariance with δ¹⁸O, suggesting that meteoritic diagenesis has been minimal (Fig. 29a). Figure 29b is provided for comparison of the Wheeler Formation isotopic data with those of other Cambrian carbonates; data in figure 29b were compiled from Saltzman et al. (1998). Saltzman et al. (1998) suggested that the δ¹⁸O values from Shingle Pass, Nevada generally do not co-vary with δ¹³C values and show no obvious stratigraphic trend, which argues for preservation of primary carbonate isotope values. A similar pattern is seen in the C isotopes from the carbonates in this study. Several investigators have found that the majority of Proterozoic carbonates do not show evidence for alteration significant enough to greatly change the original δ¹³C values (Kaufman et al. 1991; Narbonne et al. 1994; Pelechaty et al. 1996; Saltzman et al. 1998). Therefore, this study used the combination of δ¹⁸O values and Δδ values to identify suspect samples (Table 3). If the samples failed to meet both Δδ > 25 or did not have δ¹⁸O values between -5 ‰ and -10 ‰, they were considered suspect (see Kaufman and Knoll 1995 for details). A trace element pilot study using X-ray fluorescence (XRF) of the “suspect” and several “non-suspect” samples was used to investigate the trace element composition of the pilot study samples. None of the samples, “suspect” or “non-suspect”, failed the trace
Figure 28. Flow chart for geochemical analysis, adapted from Kaufman and Knoll (1995).
Figure 29. $\delta^{13}C_{\text{carbonate}}$ vs $\delta^{18}O_{\text{carbonate}}$ cross plots. A: Wheeler Formation data, diamonds are data from the Drum Mountain locality, squares are data from the Marjum Pass locality. B: compiled data from Saltzman et al. (1998), Shingle Pass Nevada.
Petrographic analysis of the "suspect" and "non-suspect" samples showed equal amounts of neomorphism, supporting the findings of Margitz (1983) and Banner and Hanson (1990), who have shown that extremely high water:rock ratios are necessary to significantly alter $\delta^{13}C$ values. Scholle and Arthur (1980) have shown that secular variations exist in $\delta^{13}C$ values despite differing degrees of alteration. Therefore, all of the $\delta^{13}C_{\text{carbonate}}$ values obtained from Wheeler Formation samples were used to create a $\delta^{13}C_{\text{carbonate}}$ curve.

Table 3. XRF pilot study for diagenesis. Values marked with * indicate suspect samples, note that these fail the $\delta^{18}O$ and $\Delta\delta$ criteria.

<table>
<thead>
<tr>
<th>(desired value, from Kaufman and Knoll 1995)</th>
<th>Mg/Ca</th>
<th>Mn/Sr</th>
<th>$\delta^{18}O$</th>
<th>$\Delta\delta$</th>
</tr>
</thead>
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<tr>
<td>DRUM MOUNTAINS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.01</td>
<td>0.15</td>
<td>-9.16</td>
<td>27.67</td>
</tr>
<tr>
<td>43</td>
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<td>0.10</td>
<td>-8.22</td>
<td>29.38</td>
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<td>0.24</td>
<td>3.21</td>
<td>-9.23</td>
<td>27.63</td>
</tr>
<tr>
<td>129</td>
<td>0.10</td>
<td>0.05</td>
<td>-8.78</td>
<td>27.54</td>
</tr>
<tr>
<td>296*</td>
<td>0.42</td>
<td>1.70</td>
<td>-10.08</td>
<td>23.15</td>
</tr>
<tr>
<td>243*</td>
<td>0.36</td>
<td>1.56</td>
<td>-10.03</td>
<td>23.77</td>
</tr>
<tr>
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</tr>
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<td>0.00</td>
<td>2.83</td>
<td>-9.34</td>
<td>26.57</td>
</tr>
<tr>
<td>MARJUM PASS</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0*</td>
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<tr>
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<td>0.01</td>
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<td>-10.26</td>
<td>26.48</td>
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</table>

Because the suspect values identified via $\delta^{18}O$ and $\Delta\delta$ values passed the trace element analysis pilot study, $\delta^{13}C_{\text{organic}}$ and $\delta^{13}C_{\text{carbonate}}$ values were plotted with stratigraphy to further investigate areas of diagenesis or exchange between the C-reservoirs. Kaufman and Knoll (1995) and Kah et al. (1999) showed that if biological fractionation does not change through the stratigraphic section $\delta^{13}C_{\text{carbonate}}$ and $\delta^{13}C_{\text{organic}}$ should track together. Kaufman and Knoll (1995) also suggested that although diagenesis can alter the isotopic composition of either
no diagenetic process is known that will alter both signals with the same magnitude in the same direction.  

Figures 15 and 19 show that, in general, the C-isotope curves track one another. In the Drum Mountains section $\Delta \delta$ values are $\geq 27.4$ until 214 m upsection. At 214 m and above $\Delta \delta$ values begin to drop and range between 23.2 and 29.2. Although the samples from throughout the Drum Mountain section pass the diagenetic tests this shift in $\Delta \delta$ values may represent diagenesis (likely in the carbonate values) and may be coincident with the increased grain size in the upper Wheeler Formation at the Drum Mountains locality.

The Marjum Pass data show that the isotope values track each other and maintain $\Delta \delta$ values $\geq 25$, except in the samples taken at 0 and 27 m, these samples have a $\Delta \delta$ value of 24.7 and 24.5, respectively. Although both samples pass the trace element analysis criteria, they may represent altered values (Table 3). Figure 19 shows that the isotope values from the sample taken at 0 m appear to come together while the isotope values from the sample taken at 27 m shift in the same direction. This sample is considered primary, but a tighter sampling interval is desired to verify the curve shape. Because there is excellent co-variance and $\Delta \delta$ values obtained from Marjum Pass suggest primary isotopic values, the Marjum Pass section is considered a more reliable indicator of sea-water chemistry within the HRE.

**Shallow-to-Deep Isotopic Gradient.**---As shown by the data from the Wheeler Formation, an isotopic gradient exists between the shallow and relatively deeper-water deposits. The Drum Mountains isotopic values range between -1.1%o to 1.3%o with a mean value of 0.02%o. The isotopic values from Marjum Pass range between -1.76%o to 0.14%o with a mean value of -0.67%o. For example if we consider samples surrounding the MFS in both sections (using the MFS for stratigraphic control) we see that the isotope values in the
Drum Mountains locality range between 0.93 \%o to 1.72 \%o (40 to 70 m). Conversely the isotope values obtained from the Marjum Pass locality range between -1.1 \%o to -0.94 \%o (50 to 76 m), indicating that an isotopic gradient exists.

The inorganic carbon flux to the deep ocean includes both dissolved inorganic carbon (DIC) and the carbonate sediments that are dissolved as they settle through the water column (Kump 1991). The $^{13}\text{C}/^{12}\text{C}$ ratio in the DIC in the ocean varies from place to place because photosynthetic organisms fractionate $^{12}\text{C}$ preferentially (Broecker and Peng 1982). Because photosynthesis occurs only in the mixed layer and because some of this material is oxidized after its deposition in deeper ocean layers, the isotopic ratio in the surface water is higher (more positive) than the ratio in deep water (more negative) (Broecker and Peng 1982; Kaufman and Knoll 1995). This difference in isotopic ratios may be reflected between the two depositional environments of the Wheeler Formation.

$\delta^{13}\text{C}$ Isotope Composition of the Wheeler Formation

Overall the $\delta^{13}\text{C}_{\text{carbonate}}$ curves generated from both localities of the Wheeler Formation reflect near zero values and are consistent with C-isotope values obtained by other workers for this time period in western North America (Braiser and Sukhov 1998; Montañez and Banner 2000) (Figs. 15, 19 and 30). Reported Middle Cambrian C-isotope values range between -4 \%o and 1 \%o and Montañez and Banner (2000) presented compiled C-isotope data and a 5-point averaged C-isotope curve for the middle Middle Cambrian in western North America; their data show a shift of ~2 \%o in the lower Belaspickella Zone (Fig. 30). The Wheeler Formation was deposited in the Belaspickella Zone and the isotope data
from the Wheeler Formation are consistent with those shown by Montañez and Banner (2000).

![Graph showing Middle Cambrian isotope data](image)

**Figure 30.** Compiled Middle Cambrian C-isotope data (Montañez and Banner 2000). Wheeler Formation data fit curve within yellow circle in inset.

The C-isotope values reported for this time period also show small-scale variability at the scale of 0.5 %‰ to 1 %‰, similar to the small-scale shifts found in the Wheeler Formation. However, this small-scale variability is generally considered by other workers to represent background noise and chemostratigraphic correlations are made using shifts >2 %‰ (Braiser and Sukhov 1998; Saltzman et al. 1998; Montañez and Banner 2000). Because
the small-scale variability within the Wheeler Formation ranges between magnitude 0.4 % to 1 %, is not consistent between the two sections and is generally represented by one point peaks, it is not used as an intrabasinal correlation tool. Although the data from the Wheeler Formation cannot be used for intrabasinal correlation they are consistent with and can be used to support other data from western North America for this time.

*Lithostratigraphic and Chemostratigraphic Correlation*

Using the flooding surfaces and systems tracts previously interpreted along with the first appearance of *P. atatus*, a proposed global biostratigraphic marker (Rowell et al. 1982 and Babcock et al. in prep) stratigraphic correlations of the Wheeler Formation have been made (Fig. 26). The basal correlation is at TS1 between the Swasey Limestone and the overlying Wheeler Formation in both localities. The second correlation is defined by the first appearance of *P. atatus* in both sections. The third correlation is placed at the interpreted MFS in each locality; 32 m above the Swasey Limestone at the Marjum Pass locality and 72 m above the Swasey Limestone at the Drum Mountains locality. SB2 marks the top of each section, separating the HST from the overlying TST. Because of the small-scale variability seen within the Wheeler Formation $\delta^{13}C_{\text{carbonate}}$ isotopes and because the isotopic values are not consistent between the two stratigraphic sections it is not used for correlation. However, when peak TOC values were plotted with stratigraphy it was observed that the high wt. % TOC values straddle the MFS and the first appearance of *P. atatus* (Fig. 26). The peak TOC values are found in both sections during the latest TST and earliest HST. This, along with the facies associated with this stratigraphic interval, suggests that organic carbon preservation was coincident with the deepest water depth and was therefore used for correlation.
The basal portions of each stratigraphic section are dominated by fine-grained carbonate facies with relatively thinner, subordinate coarser-grained beds. The transgressive systems tract is characterized by fine-grained lithofacies deposited on the distal ramp in the Drum Mountains that pass basinward to basin facies at Marjum Pass with no detectable break in slope (a homoclinal ramp, Fig. 30a) (Read 1982). This is followed by the early highstand systems tract (eHST); which is interpreted to be a time of early highstand shedding. The basal beds of the eHST, in the Drum Mountains locality, are locally contorted. Previous work by Grannis (1982) showed the paleoslope was directed to the southeast and that this soft-sediment deformation represents a break in slope (steepened ramp, Fig. 31b). This study has found that the deformed beds of DM cycle 10 are stratigraphically above other cycles that show evidence of soft-sediment deformation (DM-7 and DM-8); suggesting that, during the eHST, in the Drum Mountains, as carbonate production caught up to sea level, the ramp steepened as it prograded basinward. This steepened ramp may have been unstable, resulting in the production of soft-sediment deformation preserved in outcrop (Fig. 23).

**Ramp Morphology.**---Carbonate ramps are gently-sloping platforms on which shallow, wave-agitated facies of the nearshore zone pass downslope into deeper water without a marked break in slope (Ahr 1973). Read (1982) further divided Ahr’s definition of carbonate ramps into homoclinal ramps and distally-steepened ramps. Homoclinal ramps have relatively uniform slopes into the basin and generally lack significant sediment gravity flow deposits and slumps in deep-water facies (Read 1982). The distally-steepened ramps as described by Read (1982) share characteristics of ramps and shelves; however, they differ
from shelves because the major break in slope occurs seaward of the transition from wave-agitated lime sand to subwave-base muds.

Subtidal meter-scale cycles as defined by Osleger (1991) are distinguished by an upward increase in grain size, bed thickness and cross-bedding and other high-energy sedimentary structures. Both stratigraphic sections of this study are dominated by subtidal cycles that never shallow to intertidal depths. Osleger (1991) suggested that the fact that these cycle morphologies do not shallow to intertidal depths implies flat ramp morphology and a relatively high-energy regime. Osleger (1991) pointed out that open, deeply-submerged ramps would be vulnerable to strong storm-current activity generated in response to swells that originate in the open ocean; these storm currents would travel unimpeded, up the ramp losing little energy until they impinged on the ramp bottom. These storm-currents would then rework and redistribute sediment, inhibiting aggradation above the zone of active-storm reworking (Osleger 1991). In contrast, reef-rimmed platforms may be dominated by a low energy regime, as swells would rapidly lose energy during contact with the protective reef and the platform would maintain a fully-agraded, low-energy, flat-capped profile, enhancing the development of peritidal lithofacies and associated evidence of episodic subaerial exposure (Osleger 1991).

Based on the facies, cycle types and the stratal patterns observed at the Drum Mountains locality deposition likely occurred below wave base on the distal ramp during the TST and eHST, sea level subsequently shallowed upward and deposition continued on the proximal ramp (Fig. 31a-c). Similarly, at the Marjum Pass locality, sedimentation occurred below wave base and shoaled from basinal depths to the proximal ramp depositional environment (Fig. 31a-c). The dominance of subtidal cycles within the Wheeler Formation
Figure 31. Depositional model for the Wheeler Formation.
suggests a flat ramp geometry; however, the contorted units associated with the eHST indicate that the ramp may have become locally steepened (Fig. 31b).

The internal deformation of the contorted units of DM cycle-cap 10 suggests that deformation occurred during a submarine gravity slide. Rees (1986) pointed out that, because these contorted units are comprised of the same lithofacies as the beds that surround them, the slides were locally initiated. The eHST position of these deposits suggests that the change in ramp morphology was coincident with progradation during the eHST and falling sea level. The progradation as sea level fell allowed the steepened part of the ramp to move basinward, as the HRE filled (Fig. 31b). This observation is supported by Rees (1986) who observed several resedimented deposits associated with the deep ramp. Rees (1986) observed a greater abundance of submarine mass-movement deposits (i.e., contorted limestone and limestone breccia facies) at Marjum Pass in the House Range and the Steptoe section in the northern Egan Range than in other sedimentary successions associated with the HRE. Resedimented deposits can also be found in the Snake, south Egan and southern Schell Creek Ranges. All resedimented deposits occur in strata that are stratigraphically above the Wheeler Formation (i.e., Marjum Formation, Lincoln Peak Formation, Patterson Pass Shale and Emigrant Springs Formation) and paleogeographically closer to the axis of the HRE. The stratigraphically younger resedimented deposits suggest a progradation of the steepened ramp toward the axis of the embayment as it infilled.

During the initial flooding of the platform (TST), deposition was dominated by fine-grained detrital carbonate peloids and transported fossil fragments as the carbonate factory moved shoreward to shallower depths. During the time of maximum water depths, both localities were dominated by shale facies, high TOC values and low wt. % CaCO₃, due to the reduced amount of detrital carbonate reaching the basin. During eHST, as sea level began to
fall, a pulse of carbonate sediment was able to reach the basin and was deposited (Fig. 31a). This sediment was likely impounded during the TST (Schneider 2000); as sea level began to fall it was released. This large amount of sediment influx prograded rapidly, changed the ramp morphology, caused an oversteepening and resulted in slope failure and production of the contorted units at the Drum Mountains locality (Fig. 31b). During and after this local change in ramp morphology, deposition at Marjum Pass was dominated by distal turbidites and suspension settling while deposition at the Drum Mountains section shows evidence of continued shallowing to the proximal ramp environment (Fig. 31c).

**Paleoecologic Implications.**--- The polymeroid trilobite species become abundant during the end of the TST at the Drum Mountains locality (60 m) and during the HST at the Marjum Pass locality (120 m). This suggests that the water depth required for polymeroid habitation was obtained first in the initially shallower-water environments of the Drum Mountains section and then at the deeper-water environment at Marjum Pass as sea level continued to fall. This supports observations made by Robison (1976), who showed that polymeroid trilobites are most common in shallow, open-marine environments.

The first appearance datum (FAD) of *P. atatus* at the Drum Mountains locality is currently being considered as a candidate for a global stratotype section and point (GSSP) for the Middle Cambrian. *P. atatus* is one of the most clearly recognizable horizons on an intercontinental scale in the Cambrian System (Babcock et al. in prep). This research shows that, in both stratigraphic sections, the first appearance of *P. atatus* occurs at similar times in the Wheeler Formation. *P. atatus* is coincident with transgression and appears in each section just below the MFS supporting its use as a GSSP for the Middle Cambrian (Fig. 26).
SUMMARY

1) The Middle Cambrian Wheeler Formation is a record of deposition during a single 3rd-order sequence. The cyclicity preserved and recognized in the proximal through distal ramp deposits at the Drum Mountains locality are also recognized in the relatively deeper-water deposits at the Marjum Pass locality and is likely the result of small-scale eustatic changes in sea level. The meter-scale cycles observed in both localities are of the same character; both shallow upward and both localities display similar stacking patterns within the sequence stratigraphic framework.

2) Although an isotopic gradient exists between the shallow water and correlative deep water deposits, both localities reflect near zero C-isotope values. These values are consistent with those found by other workers in western North America. Based on the excellent co-variance of $\delta^{13}$C$_{organic}$ and $\delta^{13}$C$_{carbonate}$ and the $\Delta\delta$ values obtained for the Marjum Pass locality this study finds that the deeper-water setting is more reliable for C-isotope analysis than the shallower-water setting.

3) The ramp upon which the Wheeler Formation was being deposited likely experienced a change in morphology. Late in Wheeler Formation time this change resulted in a steepened ramp morphology at the Drum Mountains locality while deposition at the Marjum Pass locality continued unaffected for some time.

4) Paleontologic data suggest that there is a possible migration of polymeroid trilobite organisms due to environmental changes during the 3rd order sea-level fluctuation. This migration is most notably evident in the polymeroid trilobite species, which inhabit the open marine shelf environments and whose appearance occurs at the Drum Mountains locality during the eHST and at the Marjum Pass locality during the lHST. This
difference in the time of appearance of polymeroid trilobites at each locality may suggest that they were not able to inhabit the deeper water environment until sea level had dropped and environmental conditions became favorable.

5) The FAD of *P. atatus* is a likely candidate for a global stratotype section and point (GSSP) in the Middle Cambrian. *P. atatus* has one of the broadest distributions of Cambrian trilobite and has been identified in Australia, China, Vietnam, North Korea, Russia, Kazakhstan, Sweden, Denmark, Norway, the United Kingdom, Greenland, Canada and the United States (Babcock et al. in prep). In the Wheeler Formation the first appearance of *P. atatus* occurs in each section below the interpreted maximum flooding surface. These data support the use of *P. atatus* as a biostratigraphic marker for the Middle Cambrian.
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APPENDICES
Appendix A: Cycle Morphology of the Wheeler Formation
Table A-1. Cycle morphology of the Drum Mountains locality.

<table>
<thead>
<tr>
<th>Cycle #</th>
<th>Cycle Thickness (m)</th>
<th>Cumulative thickness to cycle cap (m)</th>
<th>Cycle Morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM-1</td>
<td>0.5</td>
<td>0.5</td>
<td><strong>BASE</strong>: recessive, 0.1 m pale-red purple, fissile shale, contains sponge spicules and is in sharp contact with underlying and overlying cycle cap.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>CAP</strong>: resistant, 0.4 m dark gray, calcisiltite, massive, thinly bedded, undulose bedding contacts and is in sharp contact with overlying cycle base. Rotated paleocurrent data show ripple crests trend 170°-175° plunge 3°, crests are asymmetric toward 260°-265°. (Fig. 7).</td>
</tr>
<tr>
<td>DM-2</td>
<td>2.5</td>
<td>3</td>
<td><strong>BASE</strong>: recessive, 1 m of pale-red purple, fissile shale, contains sparse sponge spicule and agnostoid fragments, gradational contact with overlying cap.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>CAP</strong>: resistant, 1.5 m medium-dark gray, calcisiltite, thinly bedded, undulose bedding contacts and ripple cross-stratification and is in sharp contact with overlying cycle base.</td>
</tr>
<tr>
<td>DM-3</td>
<td>8</td>
<td>11</td>
<td><strong>BASE</strong>: recessive 3 m pale-red purple, fissile shale, grades into 3 m thick, medium light gray, argillaceous limestone with very thin wavy-parallel laminae. Contains agnostoid trilobites and sponge spicules throughout.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>CAP</strong>: argillaceous limestone grades upward to resistant, 2 m, medium-gray calcisiltite, thinly, wavy parallel laminae, thinly bedded with sparse tan dolomitic burrows and undulose bedding contacts is in sharp contact with overlying cycle base. Contains agnostoid trilobites and sponge spicules throughout.</td>
</tr>
<tr>
<td>DM-4</td>
<td>22</td>
<td>33</td>
<td><strong>BASE</strong>: recessive, 19 m, medium gray argillaceous limestone, thinly-, even parallel, laminated which is in sharp contact with cycle cap. Contains sponge spicules and agnostoid trilobites throughout.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>CAP</strong>: resistant, 3 m thick, medium-gray rhythmite, thinly-, even parallel laminated, thinly bedded and in sharp contact with overlying cycle base. Contains agnostoid trilobites and sponge spicules throughout.</td>
</tr>
<tr>
<td>DM-5</td>
<td>19.5</td>
<td>52.5</td>
<td><strong>BASE</strong>: recessive, 18 m thick, medium gray to pale red, argillaceous limestone, thinly wavy and flat parallel laminae, thinly bedded, grades through 3 m of degraded calcareous shale to cycle cap. Contains agnostoid trilobites and sponge spicules throughout.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>CAP</strong>: resistant, 1.5 m, medium gray argillaceous limestone thinly-, even parallel laminae, thinly bedded, in sharp contact with overlying cycle base.</td>
</tr>
<tr>
<td>DM-6</td>
<td>6</td>
<td>58.5</td>
<td><strong>BASE</strong>: recessive, 5 m, medium gray, fissile calcareous shale becomes more resistant upward as partings thicken, contains agnostoid trilobites, in gradational contact with cycle cap.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>CAP</strong>: resistant, 1 m, medium dark gray, calcisiltite, massive, very thinly bedded, in sharp contact with overlying cycle base. Cap contains agnostoid and polymeroid trilobites, inarticulate and articulate brachiopods and rare hematite replaced pyrite crystals.</td>
</tr>
</tbody>
</table>
| DM-7 | 8  | 66.5 | **BASE**: recessive, 3.5 m of pale-red purple, fissile calcareous shale, shale partings thicken upward. Shale contains agnostoid trilobites and is in erosive contact with overlying cycle cap.  
**CAP**: resistant, 4.5 m thick, medium-dark gray, bioclastic pack-grainstone, massive, thin to medium bedded with wavy parallel bedding contacts, large nodules (5-15 cm on long axis) (Fig. A-1), interbedded with 0.5-1 m thick, pale-red, fissile calcareous shale. Fossils in cycle cap include agnostoid and polymeroid trilobite fragments, inarticulate and articulate brachiopods and sponge spicules. |
| DM-8 | 5.5 | 72  | **BASE**: recessive, 4.5 m, light gray calcareous shale becomes more resistant upward as partings thicken, contains sponge spicules. Calcareous shale is in gradational contact with overlying cycle cap.  
**CAP**: resistant, 1 m thick, light-medium gray, calcisiltite, thinly bedded, nodular, ripple cross-stratified, (apparent E-directed) (Fig. A-2) and is in sharp contact with overlying cycle base. Top of DM-8 is mineralized with hematite staining, hematite replaced pyrite crystals and has up to 1 cm surface relief; this surface is overlain by 10 cm thick agnostoid coquina. |
| DM-9 | 18 | 90  | **BASE**: recessive, 17 m thick, medium dark gray calcareous shale, contains articulated sponge spicules and agnostoid trilobites, shale becomes more resistant upward as partings thicken, in gradational contact with overlying cycle cap.  
**CAP**: resistant, 1 m of, medium gray argillaceous limestone, thinly-, even parallel laminae, very thinly bedded, contains sponge spicules and agnostoid trilobites and is in sharp contact with overlying cycle base. |
| DM-10 | 25 | 116 | **BASE**: recessive, 2 m, black, fissile shale in sharp contact with overlying cycle cap.  
**CAP**: resistant, cliff forming 23 m, medium-dark gray, rhythmite, thinly-, even parallel laminae, very thinly bedded, with sparse boudins, scours and intraclasts throughout. Basal 3 m of rhythmite is contorted. Undistorted rhythmite beds overlie in sharp contact with basal contorted beds of cycle cap. Cycle cap contains sparse polymeroid trilobites and sponge spicules and is in sharp contact with overlying cycle base. |
| DM-11 | 23.5 | 138.5 | **BASE**: 11.5 m of recessive, medium gray, argillaceous limestone, massive and thinly bedded in sharp contact with overlying cycle cap.  
**CAP**: resistant, cliff forming 12 m, medium gray, rhythmite, thin, even, parallel laminae, thinly bedded, contains burrows in upper 8 m, polymeroid trilobites and inarticulate brachiopods found throughout cycle cap. Cycle cap is in sharp contact with overlying cycle base. |
<table>
<thead>
<tr>
<th>Site</th>
<th>Top Bed</th>
<th>Bottom Bed</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM-12</td>
<td>24</td>
<td>162</td>
<td>BASE: recessive, 8.5 m of light to medium gray, argillaceous limestone, thin, even parallel laminae, thinly bedded and in sharp contact with overlying cycle cap. CAP: resistant, cliff forming 15.5 m of medium gray, rhythmite, even parallel and wavy parallel laminae, thinly bedded, contains graded bedding, scours intraclasts and polymeroid trilobites. Bioturbation increases upward, lenses of oolitic wackestone throughout, grades to upper 3 m of bioturbated bioclastic oolitic wackestone, fossil fragments include polymeroid trilobites, sponge spicules and agnostoid trilobites.</td>
</tr>
<tr>
<td>DM-13</td>
<td>2</td>
<td>164.5</td>
<td>BASE: recessive, 1.5 m medium gray, argillaceous limestone, massive to even parallel laminated, grades upward to cycle cap. Contains agnostoid and polymeroid trilobites and inarticulate brachiopods throughout. CAP: resistant, 0.5 m of thin bedded, medium gray bioclastic oolitic-wackestone, burrow-mottled with poorly preserved lamination and undulose bedding contacts in sharp contact with overlying cycle base. Contains agnostoid and polymeroid trilobites and inarticulate brachiopods.</td>
</tr>
<tr>
<td>DM-14</td>
<td>8</td>
<td>172</td>
<td>BASE: recessive, 5 m of medium gray, argillaceous limestone thinly-, even parallel laminae, thinly bedded, in sharp contact with overlying cycle cap. CAP: resistant, 3 m, light gray, oolitic bioclastic packstone, thinly-, even parallel laminae, thin bedded, contains scours and boudins in sharp contact with overlying cycle cap. Contains agnostoid and polymeroid trilobites and inarticulate brachiopods throughout.</td>
</tr>
<tr>
<td>DM-15</td>
<td>5.5</td>
<td>177.5</td>
<td>BASE: recessive, 3 m of medium dark gray calcareous shale in sharp contact with overlying cycle cap. Contains agnostoid and polymeroid trilobites, sponge spicules and inarticulate brachiopods. CAP: resistant, 2.5 m thick, light gray bioclastic-oolitic packstone, bioturbated, massive, thin to medium bedded with wavy parallel bedding contacts. Contains agnostoid and polymeroid trilobites, sponge spicules and inarticulate brachiopods.</td>
</tr>
<tr>
<td>DM-16</td>
<td>7</td>
<td>184.5</td>
<td>BASE: recessive, 5.5 m of pale red, calcareous shale in grades upward to cycle cap. Contains agnostoid and polymeroid trilobites and inarticulate brachiopods. CAP: resistant, 1.5 m bioturbated, massive, thin bedded oolitic/oncolitic wackestone with wavy nonparallel bedding contacts.</td>
</tr>
<tr>
<td>DM-17</td>
<td>12.5</td>
<td>197</td>
<td>BASE: recessive, 9.5 m of thinly-, medium gray argillaceous limestone, thinly-, even parallel laminae in sharp contact with overlying cycle cap. Contains polymeroid trilobites, sponge spicules and inarticulate brachiopods.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>CAP</strong>: resistant, 3 m thick, medium dark gray, cross-stratified, oolitic/oncolitic bioclastic packstone, thin bedded with sharp bedding contacts and is in sharp contact with overlying cycle cap.</td>
</tr>
<tr>
<td>----------</td>
<td>--------</td>
<td>--------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>DM-18</td>
<td>4</td>
<td>201</td>
<td><strong>BASE</strong>: recessive, 2 m medium gray argillaceous limestone, thinly-, even parallel laminae, thinly bedded, contains polymeroid trilobites and is in sharp contact with overlying cycle cap.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>CAP</strong>: resistant, 2 m thick, medium dark gray oolitic bioclastic packstone, massive to thinly-, even parallel laminae, thinly bedded, bioturbated. Cycle cap contains eocrinoids and polymeroid trilobites and is in sharp contact with overlying cycle base.</td>
</tr>
<tr>
<td>DM-19</td>
<td>94</td>
<td>295</td>
<td><strong>BASE</strong>: recessive, 59.5 m of medium gray, calcareous shale, alternates at meter scale (1-3 m) between recessive (lower carbonate content; 75-80 wt %) and non-recessive shale (higher carbonate content; 86-88 wt %), horizontal burrows, articulate brachiopods and eocrinoids. Bioturbation increases upward becomes nodular and grades into overlying cycle cap.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>CAP</strong>: resistant, cliff forming, basal 2 m of burrow mottled wackestone grades into 32.5 m of light gray, wacke-grainstone and boundstone, thin to medium bedded, massive cliff former. Basal cliff is heavily bioturbated wackestone grades upward to carbonate boundstone with skeletal grainstone in-filling. Cycle cap is in sharp contact with overlying medium gray non-calcareous shale.</td>
</tr>
</tbody>
</table>
Figure A-1. Bioclastic pack-grainstone, cap of DM cycle 7, 77 m above the Swasey Limestone. Note the erosional basal contact and large nodules (5-15 cm on long axis).
Figure A-2. Ripple-laminated calcisiltite in DM cycle 8 cap. Drum Mountains, 66 m above the Swasey Limestone.
Table A-2. Cycle morphology at the Marium Pass locality.

<table>
<thead>
<tr>
<th>Cycle #</th>
<th>Cycle Thickness (m)</th>
<th>Cumulative thickness to cycle cap (m)</th>
<th>Cycle Morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP-1</td>
<td>6</td>
<td>6</td>
<td>BASE: recessive, 0.5 m of pale-red purple, fissile shale with interbedded agnostoid grainstone concretions (10-15 cm on long axis) that directly overlie and are in sharp contact with Swasey Limestone. 2 m of pale-red purple, fissile shale with rare laminated calcisiltite concretion interbeds, grades upward to cycle cap. CAP: resistant, 3.5 m thick, medium gray, thinly-, even parallel laminated calcisiltite concretions and thinly-, even parallel laminated, thinly bedded argillaceous limestone. Contains agnostoid trilobites throughout and is in sharp contact with overlying cycle base.</td>
</tr>
<tr>
<td>MP-2</td>
<td>3</td>
<td>9</td>
<td>BASE: recessive, 2.5 m of pale-red purple, fissile shale is in sharp contact with overlying cycle cap. CAP: resistant, 0.5 m of medium dark gray calcisiltite, thinly-, even parallel laminated, very thinly bedded in sharp contact with overlying cycle base.</td>
</tr>
<tr>
<td>MP-3</td>
<td>11.5</td>
<td>20.5</td>
<td>BASE: recessive, 5 m of black, fissile shale grades upward to 5.5 m thick, medium gray, lisingan banded, calcareous shale, which grades upward to cycle cap. Cycle base contains agnostoid trilobites throughout. CAP: resistant, 1 m, medium-gray calcisiltite, massive, very thinly bedded. Cycle cap contains agnostoid trilobites.</td>
</tr>
<tr>
<td>MP-4</td>
<td>6.5</td>
<td>27</td>
<td>BASE: recessive, 1.5 m thick black fissile shale, grades upward to 5 m thick calcareous shale with well preserved blue-green algae. Calcareous shale partings thicken upward grading into the cycle cap. CAP: resistant, 5 cm, medium gray calcisiltite, massive, thinly bedded, with replaced pyrite crystals, in sharp contact with overlying cycle base. Cycle cap contains agnostoid trilobites.</td>
</tr>
<tr>
<td>MP-5</td>
<td>6.5</td>
<td>33.5</td>
<td>BASE: recessive, 1.5 m, black fissile shale contains well preserved algae and grades into recessive, 1.5 m, medium gray, calcareous shale with very thinly-, even parallel laminae. Grades upward to cycle cap. Cycle base contains agnostoid trilobites throughout. CAP: resistant, 4 m of medium gray argillaceous limestone, thinly laminated, very thinly bedded, contains interbeds of thinly laminated calcisiltite concretions. Cycle cap contains agnostoid trilobites. Top of MP-5 is mineralized with hematite staining, hematite replaced pyrite crystals, has 2-3 cm surface relief and is in sharp contact with overlying cycle base.</td>
</tr>
<tr>
<td>MP-6</td>
<td>13.5</td>
<td>47</td>
<td>BASE: recessive, 7.5 m of interbedded (5 mm-20 cm scale interbeds) of black fissile non-calcareous and fissile calcareous shale, grades upward losing non-calcareous shale to 4.5 m, medium gray calcareous shale. Shale partings thicken upward as shale grades to cycle cap.</td>
</tr>
<tr>
<td>MP</td>
<td>Thickness</td>
<td>Depth</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>-----------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>14.5</td>
<td>61.5</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>25</td>
<td>86.5</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>17</td>
<td>103.5</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>110.5</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>24</td>
<td>134.5</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>5.5</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>13.5</td>
<td>153.5</td>
<td></td>
</tr>
</tbody>
</table>

**CAP**: resistant, 1.5 m, medium gray calcareous shale very well indurated, thinly, even parallel laminated, with horizontal burrows and agnostoid and polymeroid trilobites. Cycle cap is in sharp contact with overlying cycle base.

**BASE**: recessive, 3.5 m, black fissile shale, grades upward through 7 m thick interbedded black, non-calcareous shale and calcareous shale (1-25 cm thick interbeds), grades upward to 2.5 m thick, medium dark gray calcareous shale with horizontal burrows. Cycle base is in sharp contact with cycle cap.

**CAP**: resistant, 0.5 m thick, medium gray calcisiltite, thinly, even parallel laminated, sharp internal bedding contacts and sharp contact with overlying cycle base.

**BASE**: recessive, 15 m thick, medium gray calcareous shale, shale partings thicken upward as shale grades into cycle cap.

**CAP**: resistant, 10 m, medium gray argillaceous limestone, thinly, even parallel laminae, thinly bedded, sharp internal contacts and is in sharp contact with overlying cycle base.

**BASE**: recessive, 14 m, medium gray calcareous shale in sharp contact with cycle cap.

**CAP**: resistant, 3 m, orange weathering dark gray calcisiltite, thinly, even parallel laminae, lenticular bed form, in sharp contact with overlying cycle base.

**BASE**: recessive, 4 m, dark gray to black calcareous shale overlain by 2.5 m thick, black fissile shale. In sharp contact with overlying cycle cap.

**CAP**: resistant, 0.5 m thick orange weathering dark gray calcisiltite, thinly, even parallel laminated, lenticular bed form, in sharp contact with overlying cycle base.

**BASE**: recessive, 11 m, black fissile shale grades upward to calcareous shale with subordinate interbeds of black fissile shale. Calcareous shale contains trilobite fragments and horizontal burrows. In sharp contact with overlying cycle cap.

**CAP**: resistant, 1.5 m, orange weathering dark gray calcisiltite contains thinly, even parallel laminae, lenticular bed form, in sharp contact with overlying cycle base.

**BASE**: recessive, 2 m thick, black fissile shale in sharp contact with overlying cycle cap.

**CAP**: resistant, 3.5 m thick, calcarceous shale with abundant horizontal burrows, algae and whole polymeroid trilobites, in sharp contact with overlying cycle base.

**BASE**: recessive, 5 m thick, black fissile shale grades upward to 7 m thick, dark gray calcareous shale which contains horizontal burrows and trilobite fragments. Calcareous shale is in sharp contact with overlying cycle cap.
<table>
<thead>
<tr>
<th>MP-14</th>
<th>14.5</th>
<th>168</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CAP:</strong> resistant, 0.5 m orange weathering, dark gray calcareous shale, well indurated, in sharp contact with overlying cycle base.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>BASE:</strong> recessive, 7 m, dark gray to black calcareous shale with subordinate black fissile shale interbeds. Cycle base is in sharp contact with overlying cycle cap.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CAP:</strong> resistant, cliff forming, 7.5 m, dark gray rhythmite, thinly-parallel laminae, thin bedded and burrow mottled, sharp internal bedding contacts. Rhythmite is in sharp contact with overlying cycle base.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MP-15</th>
<th>11</th>
<th>182</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BASE:</strong> recessive, 7.5 m thick, medium dark gray argillaceous limestone, thinly-parallel laminae, thin bedded, in gradational contact with overlying cycle cap.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CAP:</strong> resistant, cliff-forming, 3.5 m thick, rhythmite, overlain by 3 m thick medium dark gray oolitic bioclastic packstone, massive and thinly bedded. Packstone contains scours, undulating bed contacts, boudins and mineralized bedding surfaces. Laterally the packstone bed is a 1.5 m thick oolitic bioclastic packstone with cross-beds and lenticular bed form.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MP-16</th>
<th>7</th>
<th>189</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BASE:</strong> recessive, 2.5 m, dark gray, intensely burrowed calcisiltite. Burrowed interval is in sharp contact with overlying, resistant 1.5 m thick, dark gray to black argillaceous limestone, thinly-parallel laminae, thin bedded, in gradational contact with overlying cycle cap.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CAP:</strong> resistant, 2 m, dark gray rhythmite, contains thinly-parallel laminae, graded bedding, scours. The top of the rhythmite is a 1 m thick, medium dark gray calcisiltite intraclast conglomerate (clast size ranges from 1.5-10 cm).</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix B: Geochemical Data of the Wheeler Formation
<table>
<thead>
<tr>
<th>Systems tract</th>
<th>cycle # / cycle position</th>
<th>Height above</th>
<th>TOC</th>
<th>CaCO₃</th>
<th>δ¹⁸O_carb</th>
<th>δ¹³C_carb</th>
<th>δ¹⁸O_carb</th>
<th>Δδ</th>
</tr>
</thead>
<tbody>
<tr>
<td>top of Swasey</td>
<td>top of Swasey</td>
<td>0</td>
<td>0.04</td>
<td>98.0</td>
<td>-27.94</td>
<td>0.318</td>
<td>-9.162</td>
<td>27.67</td>
</tr>
<tr>
<td>TST 3/cap</td>
<td></td>
<td>10.5</td>
<td>0.08</td>
<td>95.6</td>
<td>-28.03</td>
<td>0.272</td>
<td>-9.154</td>
<td>28.15</td>
</tr>
<tr>
<td>TST 4/base</td>
<td></td>
<td>21</td>
<td>0.09</td>
<td>99.8</td>
<td>-27.87</td>
<td>0.448</td>
<td>-8.369</td>
<td>28.71</td>
</tr>
<tr>
<td>TST 5/cap</td>
<td></td>
<td>30</td>
<td>0.04</td>
<td>95.9</td>
<td>-28.26</td>
<td>0.445</td>
<td>-8.215</td>
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<td>-27.23</td>
<td>-0.653</td>
<td>-9.341</td>
<td>26.57</td>
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| MEAN          | 0.06 | 86.06 | -27.64 | 0.02 | -9.45 | 27.66 |
| STD ERROR     | 0.005 | 3.680 | 0.558 | 0.007 | 0.258 | 66 |
Table B-2. Geochemical data from the Marjum Pass locality.

<table>
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<tr>
<th>Systems</th>
<th>cycle #</th>
<th>Meters above</th>
<th>CAO&lt;sub&gt;13&lt;/sub&gt;</th>
<th>C&lt;sup&gt;13&lt;/sup&gt;C&lt;sub&gt;org&lt;/sub&gt;</th>
<th>C&lt;sup&gt;13&lt;/sup&gt;C&lt;sub&gt;carb&lt;/sub&gt;</th>
<th>O&lt;sup&gt;18&lt;/sup&gt;C&lt;sub&gt;carb&lt;/sub&gt;</th>
<th>Δδ</th>
</tr>
</thead>
<tbody>
<tr>
<td>top of Swasey</td>
<td>top of Swasey</td>
<td>base (wt. %)</td>
<td>(wt. %)</td>
<td>(vs PDB)</td>
<td>(vs PDB)</td>
<td>(vs PDB)</td>
<td></td>
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<td>-0.984</td>
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<td>0.08</td>
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<td>-0.900</td>
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<td>94.3</td>
<td>-28.66</td>
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<td>-27.70</td>
<td>-0.967</td>
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<tr>
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<td>-26.97</td>
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<td>0.04</td>
<td>58.3</td>
<td>-27.73</td>
<td>-0.958</td>
<td>-10.365</td>
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<tr>
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<td>0.04</td>
<td>78.5</td>
<td>-26.36</td>
<td>-0.191</td>
<td>-7.703</td>
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<td>0.08</td>
<td>42.3</td>
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<td>-28.08</td>
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**MEAN** | 0.08 | 69.88 | -27.28 | -0.73 | -9.85 | 26.51 |

**STD** | 0.013 | 3.513 | 0.287 | 0.007 | 0.258 | ----- |
Appendix C. Statistical Analysis of Geochemical Data
Table C-1. Statistical analysis of geochemical data from the Wheeler Formation.

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<th>Marjum Pass</th>
<th>Cannot Reject or Reject Null</th>
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<td>N1 = 12</td>
<td>U1 = 93.75</td>
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<td>U2 = 171</td>
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<td><strong>CaCO3</strong></td>
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<td>U1 = 46.5</td>
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<td>U2 = 109.5</td>
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<td><strong>U critical</strong></td>
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<td>Ucrit. = 115</td>
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Figure C-1. $\delta^{13}$C$_{carbonate}$ vs. weight percent TOC (whole rock), data are compiled from the Drum Mountain and Marjum Pass localities.

- □ cycle base
- ◆ cycle cap
Figure C.2. $\delta^{13}$C$_{\text{carbonate}}$ vs. weight percent CaCO$_3$, data are compiled from the Drum Mountains and Marjum Pass localities.

- cycle base
- cycle cap
Figure C-3. Weight percent TOC (whole rock) vs. weight percent CaCO₃, data are compiled from the Drum Mountains and Marjum Pass localities.

- □ cycle base
- ♦ cycle cap
Appendix D. Detailed Stratigraphic Columns
Ripple cross-stratification
Graded bedding
Scour
Intraclasts
Parallel wavy laminae
Contorted bedding
Concretion
Algae
Ooids/oncoids
Stromatolite
Sponge spicule
Polymeriod trilobite
Agnostoid trilobite
Articulate brachiopod
Inarticulate brachiopod
Skeletal fragments
Vertical burrows
Horizontal burrows
Eocrinoid

Rhythmite
Limestone
Calcareous shale
Non-calcareous shale
Undulose bedding contact
Sample location
Marks cycle top

KEY
Drum Mountains
Marjum Pass