Stratigraphy of the Middle Cambrian Lincoln Peak Formation and Evolution of the House Range Embayment, eastern Nevada

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STRATIGRAPHY OF THE MIDDLE CAMBRIAN LINCOLN PEAK FORMATION AND EVOLUTION OF THE HOUSE RANGE EMBAYMENT, EASTERN NEVADA

by

Ibrahim Zallum

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

MASTER OF SCIENCE in

Applied Environmental Geoscience

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2017
Stratigraphy of the Middle Cambrian Lincoln Peak Formation and Evolution of the House Range Embayment, eastern Nevada

By Ibrahim Zallum, Master of Science
Utah State University, 2017

Abstract

The Middle Cambrian Lower Shale and Middle Limestone Members of the Lincoln Peak Formation of the Schell Creek Range in eastern Nevada represents the sediment-starved, distal, deeper-marine equivalent of the coeval Wheeler and Marjum Formations in the House Range in western Utah. These two members of the Lincoln Peak Formation were deposited in a deep basin setting and comprise at least three, 3rd-order sequences. These sequences and the 6th-order cycles contained within them mirror the sequences in the Wheeler Formation and Marjum Formation, but at a lower “resolution”, due to the greater water depth and lower sediment supply in the present Schell Creek Range compared to the present House Range. Small-scale cycles in the Lincoln Peak Formation are attributed to small-scale changes in sea level and/or in sediment supply.

The greater depth at the present Schell Creek Range compared to the House Range and Drum Mountains, coupled with the initial rapid subsidence of the House Range Embayment, results in the modification of current models of the House Range Embayment, with a normal listric fault as the source of the creation of the House Range Embayment’s accommodation space. The size of the House Range Embayment is also constrained to a ~400 km long NE-SW
margin, which ends in western Nevada, and is bounded there by a carbonate platform and shallow subtidal and terrestrial deposits, associated with a possible island arc. Previous inclusions of units from eastern California as part of the House Range Embayment were due to faulty lithostratigraphic correlation, which ignored fossil evidence from these units. (108 pages)
Public Abstract

This study examined the Middle Cambrian (c. 500 MA) Lincoln Peak Formation and Patterson Pass Shale. The initial goal was to create a stratigraphic model for these units. This model was then compared to those from already studied units in western Utah, which combined with the Nevada units form the rock record of an ancient feature known as the House Range Embayment, which was an area of greater water depth superimposed on the continental shelf. This study found that the Nevada units exhibit a series of depositional sequences similar to those in western Utah, but at a lower resolution. This reflects the greater water depth and distance from sediment supply in Nevada, compared to Utah during the Cambrian. In addition, the size of the House Range Embayment was better constrained, and was shown to be part of a larger extensional basin, which confirms and expands on earlier studies of the embayment.
Acknowledgements

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Finally, I’d like to thank the faculty members who opposed the promotion of this study from a Plan B to a Plan A once the scope of the study was greatly expanded. That removed any chance for full funding, and made my progress more difficult, but it served to make my success all the sweeter.

-Ibrahim Zallum
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1. Introduction

1.1. General Statement

The Middle Cambrian Lincoln Peak Formation and Patterson Pass Shale of eastern Nevada represent the distal, deeper-marine extension of the coeval Wheeler and Marjum Formations in western Utah (Rees, 1986). These units comprise the sedimentary record of the House Range Embayment, an important geologic feature in the Middle Cambrian of the Western United States (Rees, 1986; Langenberg, 2003). To date, neither Nevadan formation is well understood, nor have known sequence stratigraphic models been created for either of them. A study of the sequence-stratigraphy will improve current understanding of factors which controlled deposition of the Lincoln Peak Formation and Patterson Pass Shale, such as water depth, sediment supply, current flow, and biota. An understanding of the sequence stratigraphy of the Lincoln Peak Formation and Patterson Pass Shale will also provide an opportunity to compare the effects of sea-level change in marine environments with different structural settings in the same basin, both in terms of lithology and biota. While the effects of sea level change on proximal shallow marine settings are generally well understood, the same cannot be said for distal, deeper-marine settings. This research can therefore show the exchange between shallow- and deep-marine settings. Finally, this research will result in a better understanding of the tectonic evolution of the House Range Embayment.
1.2. Purposes of Investigation

The aims of this project are: (1) To collect and summarize previous research conducted on the Lincoln Peak Formation and Patterson Pass Shale; (2) To add to and update previous research on the Nevadan units with new data from field and laboratory work; (3) To use these data to better understand the environment of deposition; (4) To gain a better understanding of the biota which existed in the region during the Middle Cambrian; (5) To create a sequence-stratigraphic framework for the units of eastern Nevada; (6) To compare the resulting sequence stratigraphy of eastern Nevada with that reconstructed for Western Utah, to gain a better understanding of the effects of sea-level change on coeval distal- vs. proximal-marine settings; (7) To better understand and reconstruct the geology and geography of the region of House Range Embayment—especially those portions of the embayment in Nevada; (8) To test the hypothesis that the documented sequence-stratigraphic and biota changes in the Wheeler and Marjum Formations will be reflected, in a subdued manner, within the Patterson Pass Shale and Lincoln Peak Formation; (9) To test the hypothesis that the Patterson Pass Shale and the coeval Lower Shale Member of the Lincoln Peak Formation are, in fact, the same formation, and represent the lateral transition from a shallow-water environment of the Wheeler and Marjum Formations in western Utah, to a deeper marine environment in eastern Nevada.

1.3. Location of the Study Area

The region covered by this study is the Basin and Range Province of eastern Nevada, North of Pioche and west of the Nevada-Utah border, and includes parts of Lincoln, White Pine,
and Nye Counties (Fig.1). There, a series of north-trending mountain ranges are separated from one another by a series of plains covered by Quaternary deposits. The specific mountain ranges are, from east to west: 1. Snake Range, 2. Schell Creek Range, 3. Egan Range, 4. Grant and White Pine Ranges. Of these, the Schell Creek Range and Egan Ranges were the focus of this study.
Figure 1. Index map of study area, in eastern Nevada. Field localities are: 1. Patterson Pass, southern Schell Creek Range. 2. Dry Canyon, Egan Range. 3. Connors Pass, northern Schell Creek Range. 4. Cooper Canyon, northern Schell Creek Range.
1.4. Geologic Setting

The Middle Cambrian units which are the scope of this study are surmised to have been deposited in a sedimentary trough—the House Range Embayment (Fig. 2), created along the passive margin of the North American Plate (Rees, 1986; Li and Droser, 1997). This trough was part of a large outer detrital belt (Fig. 3), located west of the carbonate platform that separated the outer detrital belt from an inner detrital belt to the east (Willis, 1909; Robison, 1965; Stewart and Suczek, 1977). The outer detrital belt would have stretched east from what is now western Nevada to present-day central Utah (Palmer and Hazzard, 1956; Stewart and Suczek, 1977; Brett et al, 2009). It would have also stretched north-south from present-day southern Idaho to the area just north of Pioche, southern Nevada (Willis, 1909; Robison, 1965; Stewart and Suczek, 1977).

The outer detrital belt was present in the study area throughout much of the Middle Cambrian (Fig. 3), though a prograding carbonate ramp filled in the outer detrital belt from present-day north and east over the course of the Cambrian (Robison, 1965; Stewart and Suczek, 1977). Outer-detrital-belt deposits are underlain by carbonate-platform deposits similar to those east of the outer detrital belt. Based on the presence of carbonate-platform deposits under and to the east of the House Range Embayment, the sequence is interpreted as evidence of subsidence combined with marine transgression toward present-day east, associated by the worldwide Sauk II supersequence (Willis, 1909; Robison, 1965; Raine and Smith, 2012).
Figure 3. A series of maps which illustrate the transition from carbonate platform to outer detrital belt in the area of the House Range Embayment. This would have occurred over the course of the Middle Cambrian. Toward the end of the Middle Cambrian, the basin was filled in by the progradation of the carbonate platforms from present-day east and north, though the process was slowed by the gradual eustatic sea level rise at the time. Modified from Robison (1965).
The House Range Embayment was formally described by Margaret Rees (1986) and named after the mountain range where the type units are exposed. However, the presence of outer detrital belt deposits in western Utah and eastern Nevada was noted in earlier research (Willis, 1909; Robison, 1965). Units associated with this feature are the Wheeler Formation and overlying Marjum Formation of western Utah (Rees, 1986; Li and Droser, 1997). The presence of this embayment is inferred from the observation that the thickest outer detrital belt shale deposits are close to a line which runs northeast from a point just north of Pioche, Nevada, to central Utah, and that these deposits thin to the north (Rees, 1986). The presence of the embayment is also inferred from the vertical change from carbonate platform to outer detrital belt deposits north of Pioche (Wheeler, 1944; Rees, 1986). The House Range Embayment was initially believed to have formed as a result of the breakup of the supercontinent of Rodinia (Rees, 1986). However, the ages of Rodinia’s formation and breakup were not well constrained at the time, and it is now known that Rodinia broke up ~100 MA before the Cambrian (Unrug, 1997; Scotese, 2009).

Instead, the House Range Embayment coincides with the breakup of the supercontinent Pannotia (Fig. 4), and the associated opening of the Iapetus Ocean 520 million years ago (Unrug, 1997; Sears and Price, 2003; Scotese, 2009). The Breakup of Pannotia rifted Laurentia (present-day North America) away from the rest of Pannotia, and turned Laurentia into an island-continent, which drifted north toward the equator (Fig. 4). All margins of Laurentia were passive margins, which underwent subsidence and extension. These created in western North America a series of normal faults which ran present-day northeast-southwest (Stewart and Suczek, 1977; Rees, 1986; Langenberg, 2003; Sears and Price, 2003; Scotese, 2009; Miller et al., 2012). The passive margins to the present-day west may have been additionally affected by the formation of
a spreading center somewhere west of present-day Nevada and Idaho (Sears and Price, 2003). Volcanism, possibly tied to the spreading center, was also present in the region, with volcanic ash deposits discovered in Schwin Formation of the Shoshone Range in central Nevada (Stewart and Suczek, 1977). Rifting associated with extension of Laurentia is believed to have created a normal fault which ran through Pioche and Clark Counties just before the start of the Drumian stage, ~506 MA (Fig. 5; McCollum and Miller, 1991; ICS, 2017). This fault is believed to have been down on the present-day northwest (Rees, 1986). This would have drowned the carbonate platform north of the fault, and this drowning created the asymmetrical sedimentary trough which became the House Range Embayment (Rees, 1986). This trough was bounded to the present-day north by a carbonate ramp and to the northwest and west by hemipelagic or pelagic settings where chert was deposited (Robison, 1965; Steward and Suczek, 1977; Rees, 1986).

Both the Lincoln Peak Formation and Patterson Pass Shale were deposited within this trough, which subsided at a rate sufficient to exceed the rate of deposition. Over the course of the Middle Cambrian, the House Range Embayment was filled in via progradation of the carbonate ramp from present-day north and east (Robison, 1965). This ended deposition of the Patterson Pass Shale and Lower Shale and Middle Limestone Members of the Lincoln Peak Formation in Nevada, and the Wheeler Formation and Marjum Formation in Utah around 500 MA (Robison, 1965; Rees, 1986; McCollum and Miller, 1991; ICS, 2017). Exposures deposited within the House Range Embayment are found in a series of north-trending mountain ranges, in the central Basin and Range (Rees, 1986; Elrick and Hinov, 1996; Brett et al., 2009). These exposures have become fragmented in Nevada due to the development of the Basin and Range Province (Kellogg, 1963; Crafford, 2007). Formations deposited within the House Range Embayment are the Wheeler Formation, and Marjum and Pierson Cove Formations in Western Utah (Rees,
The Carrara Formation in southwestern Nevada and eastern California is often included as a unit of the House Range Embayment, based on lithostratigraphic correlation (Hunt and Mabey, 1966; Rees, 1986; Brett et al., 2009). However, the biostratigraphy of the unit indicates that the Carrara Formation predates the House Range Embayment by ~15 MA, despite its similar lithology (Palmer and Hazzard, 1956; Osleger et al., 1996). Instead, present eastern California was in the time-period of the study dominated by subtidal to terrestrial settings from the middle Bonanza King Formation (Osleger et al., 1996). The Lincoln Peak Formation and Patterson Pass Shale represent the distal, deeper-marine equivalents of House Range Embayment units in western Utah (Rees, 1986).

**Figure 4.** Paleogeographic map of the Earth c. 510 MA, which displays the breakup of Pannotia. At the time of the deposition of the House Range Embayment, Laurentia (present-day North America) already had drifted away from Siberia and Baltica. The resulting extension led to subsidence along the coastlines of Laurentia. The study area, marked on the map, would have been close to the continental slope, in northwestern Laurentia. Modified with Permission of Scotese (2013, 2014).
**Figure 5.** (A) Location of the House Range Embayment in its later history; north arrow points to paleo-north pole. (B) Model of the down-north normal fault surmised to have created the House Range Embayment. The sites shown are: CP: Connors Pass, Northern Schell Creek Range; DM: Drum Mountains; MP: Marjum Pass; PP: Patterson Pass, Southern Schell Creek Range; S: Snake Range; sHR: southern House Range; W: Wah-Wah Mountains. The North Arrow points to the direction of the paleo-North Pole. Modified from Langenberg, 2003.
**Figure 6.** Generalized stratigraphic columns of the major units of the House Range Embayment, in Utah and Nevada. *Elrathina*, a trilobite associated with the base of the Lincoln Peak Formation (Drewes and Palmer, 1957) falls under the *Ptychagnostus gibbus* biozone. Modified from McCollum and Miller, 1991.
2. Previous Research

2.1. Nevada Overview

Exploration of Middle Cambrian units in Nevada began in the late nineteenth century, and coincided with the “opening of the west” (Willis, 1909). It was observed that the earliest Cambrian deposits were predominantly composed of near-shore ortho quartzite, succeeded first by a series of inner-detrital-belt deposits (e.g., the Pioche Shale), then carbonate-platform deposits (Willis, 1909; Wheeler, 1939, 1940, 1944, 1948; Robison, 1965; Hay, 1982). In areas north of a line through Pioche and Clark Counties the platform deposits are succeeded by outer-detrital-belt deposits associated with the House Range Embayment (Willis, 1909; Wheeler, 1944; Robison, 1965; Rees, 1986). However, modern understanding and classification of the stratigraphic units of eastern Nevada did not come about until the 1950’s and 1960’s (Drewes and Palmer, 1957; Kellogg, 1963; Robison, 1965). These established the Lincoln Peak Formation and Patterson Pass Shale as the main Middle Cambrian units of eastern Nevada.

2.2. Lincoln Peak Formation

The Lincoln Peak Formation was formally described by Drewes and Palmer (1957), based on an exposure 330 m in height, on the southern slope of the southern fork of Lincoln Canyon. This is below the head of Mount Washington/Lincoln Peak, in the Snake Range of White Pine County, Nevada (Drewes and Palmer, 1957). Additional exposures of the Lincoln Peak Formation are present at Connors Pass and Cleve Creek Baldy, in the northern Schell Creek
Range of Nevada (Table 1) (Drewes, 1967; Hintze, 1973; McCollum and Miller, 1991), and in the White Pine and Grant Ranges, respectively in White Pine and Nye Counties, Nevada (Moores et al., 1968). Most research on the Lincoln Peak Formation was carried out in the 1960s and 1970s, with little research afterward (Robison, 1964; Robison, 1965; Drewes, 1967; Moores et al., 1968; Cebull, 1970; Hintze, 1972).

The Lincoln Peak Formation is conformably underlain by the Pole Canyon Limestone (Figs. 6 & 7), with which it forms a contact marked by the appearance of paper shale beds (Drewes and Palmer, 1957; Drewes, 1958). However, the lower contact in all exposures of the Lincoln Peak Formation is disrupted (Fig. 7) and, in some cases, obscured by thrust faulting (Drewes, 1958; Moores et al., 1968). The formation is conformably overlain in the southern Snake Range by the Johns Wash Limestone (Fig. 6), whose base is composed of a relatively uniform, finely crystalline and clastic limestone with coarse cross-bedding (Drewes, 1958). The thickness of the Lincoln Peak is variable, and ranges from 300 m to 1,000 m (Drewes, 1958; Moores, 1968). This variation in thickness is believed to be the result of tectonic activity in the region in the time after initial deposition, which led to structural thinning or thickening of parts of the Lincoln Peak Formation (Drewes, 1958). The Lincoln Peak Formation is metamorphosed, with mica abundant in the shale beds (Drewes, 1958). This metamorphism was pre-Cenozoic, and possibly took place as early as the Ordovician Period (Drewes, 1958).

The lithology and stratigraphy of the Lincoln Peak Formation are varied, with different lithologies and stratigraphies present in exposures from each mountain range (Drewes and Palmer, 1957; Drewes, 1958; Lumsden, 1964). However, all exposures of the Lincoln Peak Formation are predominantly composed of varieties of medium-gray interbedded calcisiltite and shale/calcilutite (Drewes, 1985; Hintze, 1973). In addition, all exposures share the four-fold
division of the faunal zones within the Lincoln Peak Formation (Fig. 6). The lowest faunal horizon of the Lincoln Peak is the *Elrathina* zone (part of *Ptychagnostus gibbus* biozone). This is succeeded by the *Cedaria*, then *Tricrephepalus*, and finally *Aphelaspis* faunal zones (Drewes, 1958). No fossils of the *Bolaspidella* biozone, which is normally between the *Ptychagnostus gibbus* and *Cedaria* biozones, are known (Drewes and Palmer, 1957). This indicates that the lowermost Lincoln Peak is coeval with the Wheeler Formation, whereas the lower-middle to middle part of the Lincoln Peak approximately corresponds to the Marjum Formation. The Upper Shale Member of the Lincoln Peak Formation corresponds to the Weeks Limestone and the lower half of the Orr Formation, which overlie the Marjum Formation in western Utah (Drewes, 1958; McCollum and Miller, 1991). This means that the Lincoln Peak Formation temporally spans the Middle Cambrian to the lower-Upper Cambrian (McCollum and Miller, 1991), or between ~506 and ~495 MA (ICS, 2016).

At the type exposure in the southern Snake Range, the Lincoln Peak Formation is mostly composed of ~5 cm shaly limestones, interbedded with thin siliceous and micaceous laminated shales, with a mean ratio of 60:40, respectively (Drewes, 1958). The shale is medium-gray when fresh, and weathers light olive-gray or pale yellow-brown (Drewes, 1958). The base of the Lincoln Peak Formation is typified by the presence of a relatively thin layer of gray “paper” shale (Drewes and Palmer, 1957). Grayish-red units are present 60 m above the lower contact of the formation (Drewes and Palmer, 1957; Drewes, 1958). There is also a thin Middle Limestone Member about two-thirds of the way up the type section, less than 30 m thick, and a cap of alternating meter-scale beds of limestone and shale, no more than 60 m thick (Drewes and Palmer, 1957). Fossiliferous, limy nodules are common near the top of the formation (Drewes, 1958). The Lincoln Peak Formation bears lithological similarities to the Weeks Limestone of the
House Range, Utah (Drewes, 1958), the Hicks Formation of the Gold Hill district, Utah, and Secret Canyon Shale in the Eureka district, Nevada (Drewes, 1958). However, these units are not entirely coeval with the Lincoln Peak Formation (Drewes, 1958; McCollum and Miller, 1991).

In the Schell Creek Range, the Lincoln Peak Formation is composed of three members, which total ~550 m thick (Drewes, 1967). The three members are the Lower Shale Member, Middle Limestone Member, and Upper Shale Member (Drewes, 1967; Hintze, 1973; McCollum and Miller, 1991). The Lower Shale Member is composed of fissile, silty, olive-gray shale, with inter-beds of calcisiltite (Drewes 1967). In addition, scattered beds of limestone are present, up to 60 cm thick, which account for ~10% of the total thickness of the Lower Shale Member (Drewes, 1967). The Lower Shale Member corresponds to the Wheeler Formation and much of the Marjum Formation (Drewes and Palmer, 1957; McCollum and Miller, 1991).

The overlying Middle Limestone Member is composed of medium to dark-gray limestone beds, which contain *Girvanella*, trilobites, and worm burrows (Drewes, 1967). The member straddles the same period as the transition between the Marjum Formation and Weeks Limestone (McCollum and Miller, 1991). The Middle Limestone Member is not present in all outcrops of the Lincoln Peak Formation, as it thins toward the southwest from a maximum thickness of ~150 m thick (Drewes, 1967).

The Upper Shale Member is composed of a series of 2-20 cm interbeds of fissile to platy, olive-gray to yellow-gray shale and fine-grained, trilobite-hash limestone. This member accounts for a third to three-quarters of the exposure’s total thickness, and correlates to the Weeks Limestone and the lower two members of the Orr Formation (Drewes, 1967; McCollum and Miller, 1991). In the White Pine and Grant Ranges, the Lincoln Peak Formation is ~1000 m
thick, and is composed of a series of alternating yellow- and light-orange-weathering shale and thin-bedded, blue-gray limestone (Moores, 1968).
Figure 7. Stratigraphic column of the Lincoln Peak Formation, as present at the type locality in the Snake Range, Nevada. Note the transition from paper shales at the base, to limestone beds near the Upper Shale Member of the Lincoln Peak Formation. The exact height of the transition from *P. gibbus* to *P. atavus/Bolaspidella* biozones is uncertain. After Drewes and Palmer, 1957.
2.3. **Patterson Pass Shale**

The Patterson Pass Shale was formally described by Kellogg (1963), based on a type exposure on the south side of the western entrance of Patterson Pass, in the southern Schell Creek Range, southeast of Ely, Lincoln County, Nevada. Rapid erosion of the underlying formations, coupled with hard-weathering overlying strata, left what Kellogg (1963) called “excellent exposures” of the upper three-quarters of the approximately 650 m outcrop. Kellogg (1963) also referred to good exposures of Patterson Pass Shale at Dry Canyon, east of Patterson Pass in the Egan Range, White Pine County, Nevada. Early work on the formation focused on the stratigraphy and sedimentology of the formation, and dated it to the Middle Cambrian, based on the fossil assemblages found (Kellogg, 1963). Additional research on the formation was conducted by Rees (1986), as part of her formal description of the House Range Embayment. This research documented the sedimentary structures in the unit, which allowed for a better understanding of the environment of deposition. However, since the 1980’s, little original research has been conducted on the stratigraphy, sedimentology, or paleobiology of the Patterson Pass Shale. Both units of study are underlain by carbonate platform deposits of the Pole Canyon Limestone, and overlain by the Johns Wash Limestone for the Lincoln Peak Formation and the Emigrant Springs Limestone for the Patterson Pass Shale (Kellogg, 1963).

The Patterson Pass Shale is conformably underlain by the Pole Canyon Limestone, as is the Lincoln Peak Formation (Kellogg, 1963). The contact is gradational, but generally faulted (Kellogg, 1963). The Patterson Pass Shale is conformably overlain by the Emigrant Springs Limestone, though the upper contact is often faulted (Kellogg, 1963; Rees, 1986). Only two good exposures of the Patterson Pass Shale were found (Fig. 8). Both are nearly identical in
stratigraphy, and mainly differ in their degree of exposure (Kellogg, 1963; Rees, 1986). The Patterson Pass Shale is described as lithologically identical to the lower 50 m of the Lincoln Peak Formation (Kellogg, 1963). The base of the formation is largely composed of gray paper shale, overlain by interbeds of yellow-gray or light-gray soft, calcareous mudstone and shale. The upper 35% of the formation is composed of olive-gray to medium or dark-gray, laminated and thinly-bedded calcisiltite. Storm deposits and contorted beds have been observed in this unit, particularly in the upper part of the Patterson Pass Shale (Rees, 1986). The Patterson Pass Shale is coeval with the Lower Shale Member of the Lincoln Peak Formation (McCollum and Miller, 1991). The age of the formation is based on the presence of the trilobites Hypagnostus and Marjumia, which belong to the Bolaspidella biozone (Kellogg, 1963). In addition, fossils of the phosphatic brachiopod Paterina have been found (Kellogg, 1963). Fossil preservation is poor and fragmentary (Kellogg, 1963). An exception to this are horizontal burrows from the upper-150 m of the unit, which are well preserved and occasionally abundant (Rees, 1986).

The Emigrant Springs Limestone which overlies the Patterson Pass Shale is also coeval with the Middle Limestone and Upper Shale Members of the Lincoln Peak Formation (McCollum and Miller, 1991). The Emigrant Springs Limestone is divided into members A, B, and C (Kellogg, 1963). Member A, and much of Member B are coeval to the Upper Shale Member of the Lincoln Peak Formation (Fig. 6). Member A is coeval to the Middle Limestone Member of the Lincoln Peak Formation (McCollum and Miller, 1991). The lower part of Member A is composed of calcisiltite beds separated by thin shale beds (Kellogg, 1963). This is overlain by bedded calcisiltite with abundant agnostid trilobite remains. The upper part of Member A is composed of intra-formational limestone breccia and conglomerate interbedded with calcisiltite, the upper part of which is highly contorted and imbricated, with recumbent folds
and wrinkles, of unknown origin (Kellogg, 1963). Member B of the Emigrant Springs Limestone is composed of varicolored mudstone and silty calcisiltite, which give way to calcisiltite and calcilutite. The uppermost 130 m of Member B consist solely of limestone (Kellogg, 1963). Seven species of phosphatic brachiopods, generally well-preserved, have been described from this formation (Streng and Holmer, 2006).

Figure 8. The two main exposures of the Patterson Pass Shale in the Schell Creek and Egan Ranges in Nevada. A: Patterson Pass, southern Schell Creek Range; B: Dry Canyon, Egan Range. Modified from Kellogg, 1963.
2.4. *Wheeler Formation*

The Wheeler Formation and Marjum Formations are the coeval, proximal deposits of the Lincoln Peak Formation and Patterson Pass Shale in the House Range Embayment (Rees, 1986; Li and Droser, 1997; Langenberg, 2003; Brett et al., 2009). These two units will serve as a control, to compare with data obtained from the two units of this study.

The Wheeler Formation represents the first stage in the history of the House Range Embayment in western Utah (Rees, 1986), and is 150-190 m thick at Marjum Pass, in the House Range (Rees, 1986; Langenberg, 2003; Miller et al., 2012). However, the thickness of the formation varies laterally, with exposures in the Drum Mountains to the east twice as thick as those in the House Range (Langenberg, 2003; Miller et al., 2012). In addition, there are multiple definitions for the upper contact of the Wheeler Formation, which can vary the described thickness of the unit from 130 to 190 m at the House Range, and about twice that thickness in the Drum Mountains (Langenberg, 2003). The upper contact is typically indicated by a time-transgressive transition from predominantly shale below to limestone and dolomite above (Howley and Jiang, 2010). This definition places the total thickness of the Wheeler Formation at Marjum Pass at ~150 m, whereas the thickness of the Wheeler Formation at Drum Mountains is ~260 m.

The Wheeler Formation is generally composed of laminated gray, platy calcareous shale and thickly-bedded limestone, which form slopes and lowlands and which weather light-gray (Miller et al., 2012). As with the Lincoln Peak Formation, there are variations in the lithologies of exposures mapped as Wheeler Formation (Langenberg, 2003; Brett et al., 2009). At Marjum Pass (Fig. 9), the base of the Wheeler Formation is composed of a series of fissile paper shale
beds, and platy gray shale, with concretions containing agnostid trilobites (Langenberg, 2003; Brett et al., 2009). These are followed by a series of platy gray calcareous shale deposits, then another series of alternating paper and calcareous shale beds. These are followed by a coarsening-upward sequence of calcareous shale and limestone, often bioturbated, and sometimes oolitic (Langenberg, 2003). At the Drum Mountains (Fig. 10), the lithologic sequence begins with a base composed of argillaceous limestone, succeeded by calcareous shale beds, then a thick layer of alternating limestone and argillaceous limestone. These beds fine upward into calcareous shale beds, capped as at Marjum Pass by bioturbated limestone (Langenberg, 2003). The two sites represent, respectively, distal and proximal ramp environments of deposition, with water-depth decreasing toward the Drum Mountains (Langenberg, 2003). The presence of internal deformation associated with gravity falls and slides indicates that when local sea-level was at its highest, the ramp upon which the Wheeler Formation was deposited regularly over-steepened (Langenberg, 2003). The interpreted depositional setting is a rather shallow, open-water setting, which might have become a lagoon toward the end of the period of deposition (Robison, 1965; Langenberg, 2003), though another interpretation is that it instead underwent a transgression (Brett et al., 2009; Howley, 2010).

The Wheeler Formation is generally believed to represent two, 3rd order sequences which largely preserve Transgressive and Highstand Systems Tract deposits (Howley and Jiang, 2010). The earlier sequence begins below the Lincoln Peak Formation, in the Swasey Limestone, and spans the lower Wheeler Formation (Howley and Jiang, 2010). The second sequence spans much of the upper Wheeler Formation (Howley and Jiang, 2010). An alternative model is that the Wheeler Formation represents a single 3rd order sequence, with a sub-3rd order sequence present in the upper Wheeler Formation (Langenberg, 2003).
The Wheeler Formation biostratigraphically falls within the *Ptychagnostus gibbus* and lower-most *Bolaspidella* biozones, with most of the formation within the *Ptychagnostus atavus* sub-biozone of the Bolaspidella biozone (Fig. 6, McCollum and Miller, 1991; Langenberg, 2003; Brett *et al.*, 2009). The accuracy in dating the Wheeler Formation is aided by its rich fossil record, for which it is considered a Lagerstätte (Brett *et al.*, 2009; Robison and Babcock, 2011). A notable marker associated with the first-appearance datum of *Ptychagnostus atavus* is the Drumian Isotope Carbon Excursion (DICE) (Babcock *et al.*, 2007). The DICE is a worldwide negative $\delta^{13}$C excursion, which has been successfully used in the House Range Embayment, where it appears to coincide with, or is just under the Maximum Flooding Surface (MFS) (Langenberg, 2003; Howley and Jiang, 2010). The DICE biostratigraphically falls on the boundary between the *Ptychagnostus gibbus* biozone and *Ptychagnostus atavus* section of the *Bolaspidella* biozone (Langenberg, 2003; Howley and Jiang, 2010). The exact stratigraphic height above the base is variable, with the DICE at Marjum Pass ~25 m above the lower contact of the Wheeler Formation, but ~72 m above the lower contact of the Wheeler Formation at Drum Mountains (Langenberg, 2003; Brett *et al.*, 2009; Howley and Jiang, 2010).

Finally, the magnetostratigraphic studies of the formation have been conducted, though it has largely been confined to the upper part of the Wheeler Formation (Halgedahl *et al.*, 2009). The limestone beds of the unit have low magnetic susceptibility, whereas shale units have high susceptibility (Halgedahl *et al.*, 2009). A consequence of this is that the formation generally shows a decline in magnetic susceptibility toward the upper contact of the formation. The values associated with each type of bed in the Wheeler Formation can serve as a guideline with which to compare the formations of study. In addition, the values for magnetic susceptibility are correlative with gamma-ray measurements of the Wheeler Formation, so that magnetic
susceptibility can be a possible proxy for gamma-ray measurements, and for carbonate content (Halgedahl et al., 2009).
Figure 9. Stratigraphic column of the Wheeler Formation at Marjum Pass, with inferred relative sea levels and corresponding sequence-stratigraphic framework. Note the generally "coarsening-upwards" sequence of increased carbonate content. TS = Transgressive Surface; TST = Transgressive Systems Tract; HST = Highstand Systems Tract; SB = Sequence Boundary. The drop in relative sea level was caused by progradation of shallower water deposits. Used with permission of Langenberg, 2003.
Figure 10. Stratigraphic column of the Wheeler Formation at the Drum Mountains. The general trend is toward increased carbonate deposition near the middle and again near the top of the unit. The Drum Mountains and Marjum Pass also share similar sequence stratigraphies. However, the lithology here is more carbonate-rich than equivalent Marjum Pass outcrops. TS = Transgressive Surface; TST = Transgressive Systems Tract; HST = Highstand Systems Tract; SB = Sequence Boundary. Used with permission of Langenberg, 2003.
2.5. Marjum Formation

The Marjum Formation conformably overlies the Wheeler Formation, and represents the second stage in the history of the House Range Embayment (Rees, 1986). The Lower contact with the Wheeler Formation is marked by the appearance of thrombolytic or stromatolitic bioherms (Langenberg, 2003; Elrick and Snider, 2003). The Marjum Formation’s total thickness varies, with exposures thinner to the west. However, the Upper Marjum Formation is thicker to the west than to the east (Elrick and Snider, 2002). At 160-430 m, the Marjum Formation is thicker than the Wheeler Formation (Miller et al., 2012). At Marjum Pass, the Marjum Formation is 250-300 m thick (Elrick and Snider, 2002; Brett et al., 2009).

The Marjum Formation generally coarsens upward (Elrick and Snider, 2002; Brett et al., 2009). The lower part of the formation (Fig. 11) is composed of thin, gray, interbedded micritic limestone and argillaceous rhythmite beds, 2-10 cm thick (Elrick and Snider, 2002). The argillaceous limestone is sufficiently rich in clay and sand locally to be classified as calcareous shale (Elrick and Snider, 2002). These interbeds alternate with beds of dark-gray, fissile to platy calcareous clay-to-mud shale, with little bioturbation (Elrick and Snider, 2002). The argillaceous limestone beds become less common up-section (Fig. 11), and give way to rhythmite limestone beds alone (Elrick and Snider, 2002). Farther up the stratigraphic column, beds of carbonate-mud mounds are present, composed of dark-gray mudstone, with fenestrae and stromatactoid structures (Fig. 12) (Elrick and Snider, 2002). There are also increasingly common deposits of cross-bedded and bioturbated limestones near the upper contact (Elrick and Snider, 2002). The Marjum Formation is coeval laterally with the Pierson Cove Formation to the east, and is overlain by the Weeks Limestone (McCollum and Miller, 1991). The interpreted environment of
deposition is a proximal sedimentary trough, which was gradually filled from the north by a carbonate platform, represented by the Weeks Limestone (Elrick and Snider, 2002).

The sequence stratigraphy of the Marjum Formation is composed of at five or six sequences, largely composed of Transgressive Systems Tract and Highstand Systems Tract deposits (Smith, 2007; Brett et al., 2009). The Marjum Formation falls within the following faunal stages of the *Bolaspidella* biozone: upper *Psychagnostus atavus*, *Psychagnostus punctuosus*, *Eldoradia*, and the lower *Lejopyge laevigata* (McCollum and Miller, 1991). As with the Wheeler Formation, the Marjum Formation is considered a Lagerstätte (Brett et al., 2009).
Figure 11. Generalized Stratigraphic Column of the Marjum Formation at Marjum Pass. As with the Wheeler Formation, there is a general trend towards greater carbonate deposition up-section. However, the Marjum Formation is more calcareous compared to the Wheeler Formation, and is on average two to three times thicker than the Wheeler. After Elrick and Snider, 2002.
3. METHODS

3.1. Site Selection

To identify possible sites for study, geographic descriptions or coordinates of known sites were sought for the Lincoln Peak Formation and Patterson Pass Shale (Hintze, 1972). Most important for this were geologic maps of the region compiled in the 1960s (Tschanz and Pampeyan, 1963; Drewes, 1967). Geologic maps and coordinates associated with the sites were superimposed on topographic and satellite maps on Google Earth and ArcMap, to evaluate whether the formation is on a cliff-side or in a valley, the presence or absence of vegetation, and road access. Different lighting angles were also used, in order to reveal any possible large-scale sedimentary structures. The eventual list of sites to consider was narrowed to seven, mainly in the Schell Creek Range, though there was a site each from the Egan and Snake Ranges (Table 1).
Table 1
Basic information on the sites selected for fieldwork: site names and locations, unit at site, and notes on the site (vegetation, topography, bedding, etc.).

<table>
<thead>
<tr>
<th>Site</th>
<th>Location (WGS1984, mountain range)</th>
<th>Formation and exposure thickness</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Canyon</td>
<td>38°39’52.2” N, 115°0’56.45” W (Egan Range)</td>
<td>PPS (~200 m)</td>
<td>Cliff forming; exact location uncertain. Lower contact faulted.</td>
</tr>
<tr>
<td>Connors Pass</td>
<td>39°1’38.65” N, 114°35’53.54” W (Schell Creek Range, by Hwy 6)</td>
<td>Lincoln Peak Formation (~550 m)</td>
<td>Preserves almost the entire Lincoln Peak Formation. Outcrops are on a road cut. Bedding very evident.</td>
</tr>
<tr>
<td>Cooper Canyon</td>
<td>39°6’4” N, 114°35’29.1” W (Schell Creek Range)</td>
<td>Lincoln Peak Formation (unknown thickness)</td>
<td>Potentially preserves upper and lower contacts; little of the middle contact remains.</td>
</tr>
<tr>
<td>Cooper Canyon Valley</td>
<td>39°6’4” N, 114°35’29.1” W (Schell Creek Range)</td>
<td>Lincoln Peak Formation (~50 m)</td>
<td>Valley just south of Cooper Canyon; upper contact preserved. Bedding evident.</td>
</tr>
<tr>
<td>Cleve Creek Baldy</td>
<td>39°14’49.71” N, 114°17’53.22” W (Schell Creek Range)</td>
<td>Lincoln Peak Formation (~550 m)</td>
<td>Little vegetation in satellite maps. Seems to preserve both contacts. Possible bedding present.</td>
</tr>
<tr>
<td>Sacramento Pass</td>
<td>39°10’14.2” N, 114°19’47.13” W (Snake Range)</td>
<td>Lincoln Peak Formation (unknown thickness)</td>
<td>Heavily wooded.</td>
</tr>
</tbody>
</table>
3.2. Field Work

Sites selected (Table 1) were visited in the summer of 2016, to evaluate their quality, and to take preliminary measurements in better sites. Bedding exposure was noted, as were any notable contacts and hard surfaces. Basic stratigraphy was also noted, with emphasis on any bedding structures, fossil content, metamorphism, and color. This initial expedition narrowed down the list of sites from the original seven to three: Patterson Pass, Connors Pass, and Cooper Canyon (Fig. 1). Connors Pass was chosen as the main study site. This was due to the virtually complete exposure of the Lincoln Peak Formation there, which only lacks an intact upper contact. Cooper Canyon was chosen as another site, as it was believed to preserve both the upper and lower contacts of the Lincoln Peak Formation.

Based on the data derived from this initial expedition, a second expedition was made, to focus on the three sites. Stratigraphic measurements were taken of all sites visited, where possible. Bedding orientations and dips were measured with a Brunton compass. Unit thickness was measured with a 1.5 m Jacob’s staff, which was equipped with an Abney level. Notes were taken of any faults, contorted beds, or folds found, to aid in measurement accuracy. Large features which could not be measured with a Jacob’s staff were measured with a measuring tape, and beds too small for the staff were measured either by ruler or a reference item of known size. Detailed bedding structures, signs of bioturbation, or metamorphism were noted. Paleocurrent data were collected wherever ripples and subaqueous dunes were found. Samples were collected every Jacob’s staff length where possible. Particular care in sample collection was given in the lowest 20 m of the Lincoln Peak Formation, as this was where the lower contact and DICE were likely to be found. Samples also were collected from the uppermost 20 m of the Pole Canyon.
Limestone, due to the suspected gradational nature of that contact, and the possible start of the sequence in the uppermost Pole Canyon Limestone, as is the case with the Swasey Limestone below the Wheeler Formation in Utah (Kellogg, 1963).

3.3. Laboratory Work

3.3.1. Magnetostratigraphy

Samples collected from the field were prepared and subjected to magnetostratigraphic analysis. Magnetic susceptibility was measured with a Czech-made, hand-held SM-30 Magnetic susceptibility meter manufactured by ZH Instruments. This meter can detect magnetic susceptibilities as low as $1 \times 10^7$ SI units. This was done to enable comparison to magnetic-susceptibility measurements previously taken for the Wheeler Formation (Halgedahl et al., 2009). Samples were isolated and measured in the lab due to concerns that the magnetic susceptibility of neighboring beds would affect the measurements. Measurements were taken twice per sample with the interpolation method, by holding the meter first 15-20 cm away from the sample, then against each sample, and once again at 15-20 cm from each sample. The results were then averaged and recorded in a table.

3.3.2. Gamma-ray Analysis

All samples tested for magnetic susceptibility were then placed in a lead container, into which was inserted the NaI probe of an InSpector™ 1000 Digital Hand-Held Multichannel Analyzer. This was left to analyze each sample for 12 hours. The use of a lead container eliminated background radiation, and the long period of analysis meant more accurate
measurements of detected constituent nucleotides within each sample. The results were then compared with magnetic susceptibility, to test for a relationship, as predicted in Halgedahl et al. (2009).

3.3.3. Isotope Analysis

Once all samples from the Pole Canyon Limestone and Lincoln Peak Formation were tested for gamma-ray intensity and magnetic susceptibility, samples were then processed for analysis in an Elemental Analyzer to detect organic δ^{13}C. This was to seek evidence of the Drumian Isotope Carbon Excursion (DICE). Due to time and monetary constraints under which this study was conducted, only shale samples were analyzed. These come entirely from the lowermost 20 m of the Lincoln Peak Formation, which correspond to the Wheeler Formation in western Utah (Drewes and Palmer, 1957). In addition to these samples, a control from the Mowry Shales was used, kindly provided by Andrew Lonero at Utah State University.

To prepare samples for the Elemental Analyzer, a modified version of the protocol developed by Katherine Paukert at Utah State University was used. Cuttings from each sample were washed in ethanol, then powdered. Ten grams of the powder of each sample were then loaded into a 200 ml beaker. The contents of each beaker were rinsed once in 20 ml of distilled water, stirred, and left to settle. Each sample was then scanned with a UV flashlight, to detect any hydrocarbons in the resultant solution, and the water drained from the sample. Five ml of distilled water were then added to each sample, followed by 20 ml of hydrochloric acid at 20% concentration, and mixed carefully to ensure complete reaction of the acid with carbonates in the samples. The samples were dried over a heater at 324 K for eight hours, then rinsed with distilled water which filled the beaker five times to neutralize each sample pH. The samples were given a
single run in the centrifuge for a minute and left to dry. Finally, 10-40 mg of each sample was placed into separate tin envelopes, which were fed into the analyzer. The quantity depended on the expected organic content of the samples. All samples were calibrated with 200 μg of Acetanilide.

3.3.4. Petrographic Analysis

Samples from the Pole Canyon Formation (3), Lower Shale Member (5), Middle Limestone Member (1), and Upper Shale Member (2), were made into thin sections to study bedding and find microfossils. The thin sections were made in two thicknesses: ~50 μm, and ~20 μm, at Utah State University’s Thin Section Laboratory. The thicker thin sections were used to study carbonate, and to find fossils and other larger structures in the shale. The thinner thin sections were made only for shale samples to study bedding structures, which are readily visible at 20 μm (Egenhoff and Fishman, 2013). The billets used to create the thin sections were made into polished sections, which were studied under a binocular microscope. The Dunham classification was used to describe the samples, with the exception of calcisiltite and shale (Kellogg, 1963; Langenberg, 2003).
4. Results

4.1. Connors Pass

Connors Pass was the only site visited which preserved the entirety of the Lincoln Peak Formation, except for the upper contact. All laboratory results, and most field data collected, come from this site.

4.1.1. Lithofacies

The Upper Pole Canyon Limestone and Lincoln Peak Formation at Connors Pass can be divided into seven lithofacies (Table 2). The predominant facies, which are found in the Lower Shale Member of the Lincoln Peak Formation at Connors Pass are rhythmites, which can be divided into two subtypes, based on relative quantity of calcisiltite to shale in the interbeds. Rhythmites with a rather even ratio of the two lithologies are Type A Rhythmites, whereas those where calcisiltite predominates comprise the more-common Type B Rhythmites. Type B Rhythmites are more likely to have ribbon limestone, particularly up-section. The next most common lithofacies, found in the Middle Limestone Member of the Lincoln Peak Formation is the Limestone and Shale Facies, which has alternating meter-scale beds of limestone and calcareous phyllitic shale. The base of the Lincoln Peak Formation is dominated by a sequence of Paper Shale Facies, composed of very calcareous, fissile shale, increasingly parted by calcisiltite beds upward. The Pole Canyon Limestone underlies the Lincoln Peak at Connors Pass. It can be divided into three facies: Thick-Bedded Limestone Facies, a Banded Limestone Facies, and a Ribbon Limestone Facies.
Table 2
Classification and description of seven sedimentary lithofacies identified in this study for the Pole Canyon Limestone and Lincoln Peak Formation, particularly the Lower Shale and Middle Limestone Members of the latter, based on field data collected in Nevada.

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Description</th>
<th>Water depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thick-Bedded Limestone (Pole Canyon) (Fig. 13; Fig A1)</td>
<td>Alternating light and medium blue-gray bands of metamorphosed lime mudstone and wackestone in beds greater than 30 cm, with <em>Girvanella</em>. Heavily brecciated. Darker layers are more argillaceous, with trace hematite crystals less than 0.1 mm wide.</td>
<td>&lt;5 m</td>
</tr>
<tr>
<td>Banded Limestone (Fig. 14)</td>
<td>Flaser-bedded medium- to dark-gray metamorphosed lime mudstone, in beds 10-20 cm. Darker laminae have elevated iron content, with rare hematite crystals.</td>
<td>&lt;30 m</td>
</tr>
<tr>
<td>Ribbon Limestone (Pole Canyon) (Fig. 15; Fig. A-2)</td>
<td>Metamorphosed banded, rhythmite-like beds with alternating laminae of pale-orange silty dolomitic grainstone and light-gray lime mudstone. Orange dolomite hematite stained, and contains abundant peloids and ooids 0.1-0.8 mm in diameter. Silt grains metamorphosed into micas.</td>
<td>30-50 m</td>
</tr>
<tr>
<td>Paper Shale (Lincoln Peak) (Fig. 16; Fig. A-3; Fig. A-4; Fig. A-8)</td>
<td>Dark blue to slate-gray, very calcareous mud and clay shales, with a papery texture. Very fissile and soft. Slightly metamorphosed. Local trilobite hash. Shale has increasingly more calcisiltite beds up-section. Upper part grades into Type A rhythmites.</td>
<td>~100 m</td>
</tr>
<tr>
<td>Rhytmites (Type A) (Lincoln Peak) (Fig. 17; A-5)</td>
<td>10-20 cm packets, evenly divisible into calcisiltite and shale beds, each 3-10 cm thick. Calcisiltite is laminated and preserves Bouma sequences, and possible fine cross-laminations. Base of sequence composed of peloid-rich calcisiltite, and fines upward to carbonate mud and laminated shale/calcilutite. Shale is laminated and fissile. Both are medium to dark gray, though the shale weathers a light buff to orange color.</td>
<td>100-50 m</td>
</tr>
<tr>
<td>Rhythmites (Type B) (Lincoln Peak) (Fig. 18; Fig. A-6)</td>
<td>Largely medium- to dark-gray calcisiltite beds 5 to 20 cm thick, separated by 5cm beds of platy phyllitic dark-gray calcareous shale. Both weather green or olive-gray. Calcisiltite often heavily metamorphosed, with the original structure destroyed. Calcisiltite is gradually replaced by ribbon-limestone up-section in the Lower Shale Member of the Lincoln Peak Formation.</td>
<td>30-50 m</td>
</tr>
<tr>
<td>Limestone and Shale (Lincoln Peak) (Fig. 19; Fig. A-7)</td>
<td>Generally composed of parallel-laminated to cross-stratified, medium to dark-gray metamorphosed lime mudstone and calcisiltite in meter-scale beds. These often alternate with platy, phyllitic shale beds, which range from 10 cm to meter-scale. Cross stratification, ripples, and channel forms are present throughout, but become more common up-section.</td>
<td>&lt;30 m</td>
</tr>
</tbody>
</table>
4.1.2. Stratigraphy

The thickness of the Upper Pole Canyon Limestone is 50 m, and that of the Lower Shale and Middle Limestone Members of the Lincoln Peak Formation is 212 m (Fig. 12). The Upper Pole Canyon Limestone’s Thick-Bedded Limestone Facies (Fig. 13) are succeeded by Banded Limestone Facies (Fig. 14). The transition between the two is covered by 3 m of regolith. Banded Limestone beds are overlain by Ribbon Limestone Facies (Fig. 15), though the contact between the two is obscured by a zone of white silicified rock (Fig. 12).

A valley 3 m wide formed along a thrust fault separates the Ribbon Limestone Facies from an overlying 11 m packet of Paper Shale Facies of the Lower Shale Member (Fig. 16), of which the lowermost 3 m are covered in float and regolith. The Paper Shale has a gradational contact 3 m thick with the overlying Type-A Rhythmite Facies (Fig. 16), indicated by increasingly common calcisiltite partings up-section. This is separated from the rest of the Paper Shale Facies below it by a fault 50 cm wide (Figs. 12 and 16). The Type-A Rhythmite Facies (Figs. 16 and 17), which overlie the transitional lithotype, are composed of 10-20 cm packets of shale and calcisiltite beds, the latter of which exhibit Bouma sequences. Near the base, these rhythmite packets are about equally composed of fissile shale and calcisiltite. These become increasingly carbonate-rich up-section. Type-A rhythmite packets are interrupted at a 1.5 m fault gouge, which cuts through a shale lens. This lens transitions upward to another 4.5 m of Type A Rhythmite packets. These are succeeded by increasingly carbonate-dominated rhythmite packets, where the calcisiltite component forms beds 5-25 cm thick, separated by beds of phyllitic shale 3-50 mm thick. This is the first of Type B Rhythmite packet in the Lower Shale Member of the Lincoln Peak Formation. It ends 11 m below a fault mylonite 50 cm wide. The interval between the end of the Type B Rhythmite Facies and the fault is composed of Type A Rhythmite Facies,
which quickly transition back to Type B Rhythmite Facies above the fault. Type B Rhythmite Facies dominate much of the rest of the Lower Shale Member (Fig. 12). The calcisiltite of the Type B Rhythmite lithofacies gradually develops thicker beds and ribbon texture up-section. Contorted bedding is common throughout rocks of this facies, with fold axes which trend between 110° and 130°. Most contorted bed zones are 2-3 m wide in the Lower Shale Member. The Type B Rhythmite packets are succeeded by 38 m of Limestone and Shale Facies of the Middle Limestone Member, which caps the Lower Shale Member. This cap begins with around 3 m of slabby lime mudstone and calcisiltite beds, which alternate with phyllitic shale beds. These are succeeded by meter-scale calcisiltite beds, which possess 2-5 cm lenticular beds, cross stratification, and 10-20 cm channel forms. These are overlain by 8 m of alternating meter-scale laminated calcisiltite and phyllitic shale beds, also with ripple laminae. This sequence is topped by 1.5 m of marble, then around 3 m of rippled limestone from the Limestone and Shale Facies, with burrows and scattered *Girvanella* present. Measurements of the ripples in these beds give a current direction toward ~110°. A thrust fault along a gully separates the top of the Middle Limestone Member from the overlying Upper Shale Member of the Lincoln Peak Formation.

While not part of the time-period of study, the Upper Shale Member of the Lincoln Peak Formation is briefly described. The Upper Shale Member begins with a Paper Shale Facies 8 m thick, of which the upper 2 m form a gradational contact between the Paper Shale and 33 m of Type A Rhythmite packets above. The Type A Rhythmite packets are succeeded by Type B Rhythmite packets (Fig. 18), which are truncated at the top by a 1 m thrust fault. This fault separates the Lincoln Peak Formation from the overlying Johns Wash Limestone. Scattered Ribbon Limestone beds, similar to those of the Middle Limestone Member, are present in this part of the Upper Shale Member, particularly toward the uppermost beds of the unit. The
measured exposed Upper Shale Member has a total thickness of ~780 m. However, most of this is repeated strata, caused by the tight tectonic folding which affected the formation. The true thickness of the Upper Shale Member is likely closer to 300 m, an estimate that corresponds to that arrived at by Drewes (1967). The true thickness of the entire Lincoln Peak Formation at Connors Pass is likely ~550-600 m.

The Upper Shale Member of the Lincoln Peak Formation, while similar in general structure to the Lower Shale Member of the Lincoln Peak Formation, differs from the latter in being more vividly colored, with stronger green and brown-gray weathered colors. Metamorphism is more widespread up-section, with the uppermost rhythmites sufficiently metamorphosed to produce staurolite crystals and meter-scale foliation, which were initially mistaken for meter-scale beds in low-light conditions. Multi-meter zones of contorted bedding are common, with the largest ~14.5 m wide, with a fold axis which trends ~110°.

4.1.3. Magnetostratigraphy

Samples from Connors Pass reveal three distinctive magnetic susceptibility zones in the Lower Shale and Middle Limestone Members, and another two zones in the underlying Pole Canyon Formation (Table 3). Samples from the Thick-Bedded Limestone of the Pole Canyon Limestone have magnetic susceptibilities close to, or just below zero. Similar values were derived for the Banded Limestone. Ribbon Limestone beds in the uppermost Pole Canyon Limestone yielded susceptibilities which range from 1.27 to 1.47x10⁻⁵ SI units. Samples from the Paper Shale packet of the Lower Shale Member show a further increase in magnetic susceptibility to an average of ~1.31x10⁻⁴ SI units. The highest value for magnetic susceptibility in the Paper Shale packet was just below the transition to Type A Rhythmite beds, with the value
as high as $1.8 \times 10^{-4}$ SI units. Magnetic susceptibility remains high throughout the Type A and B Rhytmite Facies, and peaks again toward the top of the Middle Limestone Member, where it reaches $2.24 \times 10^{-4}$ SI units. Up section, magnetic susceptibility declines to around $1.5 \times 10^{-5}$ SI units in the Upper Shale Member of the Lincoln Peak Formation. Beds in the Upper Shale Member are no more than half as magnetically susceptible as similar beds in the Lower Shale Member.

4.1.4. Gamma-Ray Stratigraphy

The Lincoln Peak Formation possesses little radioactivity, even in beds with elevated organic content (Table 3). Values for the Pole Canyon Limestone average 0.1 μCuries, whereas those for the paper shale and interbeds range from 0.17 to 0.216 μCuries. Gamma-ray levels remain slightly elevated throughout the Lower Shale Member, and peak again in the Middle Limestone Member of the Lincoln Peak Formation, before they decline again in the Upper Shale Member of the Lincoln Peak Formation. The source of the limited radioactivity in the Lincoln Peak Formation is possibly $^{40}$K, which was detected by the analyzer. Due to low radioactivity for all of the Lincoln Peak Formation, the detected presence of $^{40}$K is considered unreliable.
Table 3

Magnetic-susceptibility and gamma-ray values of the lithotypes in Pole Canyon Limestone (PC), Lower Shale (LLP), Middle Limestone (MLP) and Upper Shale (ULP) Members of the Lincoln Peak Formation. Measurements of radioactivity levels are so low they could not be converted into API values. All radioactivity measurements in the samples appear to come from $^{40}$K. Samples not measured are indicated with NM.

<table>
<thead>
<tr>
<th>sample</th>
<th>Radioactivity (μCurie)</th>
<th>% radioactivity error</th>
<th>Mag-susceptibility (x10-3 SI units)</th>
<th>Facies source</th>
<th>Unit</th>
<th>Stratigraphic height from base of LLP (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1-1</td>
<td>0.137</td>
<td>2.1</td>
<td>-0.0003</td>
<td>Thick-Bedded</td>
<td>Limestone PC</td>
<td>-45</td>
</tr>
<tr>
<td>H1-2</td>
<td>0.096</td>
<td>3</td>
<td>NA</td>
<td>Thick-Bedded</td>
<td>Limestone PC</td>
<td>-40</td>
</tr>
<tr>
<td>H1-3</td>
<td>0.149</td>
<td>2</td>
<td>NA</td>
<td>Thick-Bedded</td>
<td>Limestone PC</td>
<td>-18</td>
</tr>
<tr>
<td>H1-4</td>
<td>0.116</td>
<td>2.5</td>
<td>-0.0014</td>
<td>Banded Limestone PC</td>
<td>-17</td>
<td></td>
</tr>
<tr>
<td>H1-6</td>
<td>NM</td>
<td>NM</td>
<td>-0.001</td>
<td>Banded Limestone PC</td>
<td>-16</td>
<td></td>
</tr>
<tr>
<td>H1-7</td>
<td>0.112</td>
<td>2.5</td>
<td>-0.0023</td>
<td>Banded Limestone PC</td>
<td>-15</td>
<td></td>
</tr>
<tr>
<td>H1-8</td>
<td>0.119</td>
<td>2.5</td>
<td>0.0043</td>
<td>Banded Limestone PC</td>
<td>-14</td>
<td></td>
</tr>
<tr>
<td>H1-9</td>
<td>0.125</td>
<td>2.4</td>
<td>0.0127</td>
<td>Ribbon Limestone PC</td>
<td>-13</td>
<td></td>
</tr>
<tr>
<td>H1-10</td>
<td>NM</td>
<td>NM</td>
<td>0.0141</td>
<td>Ribbon Limestone PC</td>
<td>-12</td>
<td></td>
</tr>
<tr>
<td>H1-11</td>
<td>0.217</td>
<td>1.5</td>
<td>0.0052</td>
<td>Silicified rock PC</td>
<td>-11</td>
<td></td>
</tr>
<tr>
<td>H1-12</td>
<td>0.107</td>
<td>2.7</td>
<td>0.0147</td>
<td>Ribbon Limestone PC</td>
<td>-1,5</td>
<td></td>
</tr>
<tr>
<td>H2-1</td>
<td>0.216</td>
<td>1.5</td>
<td>0.0931</td>
<td>Paper Shale LLP</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>H2-2</td>
<td>0.173</td>
<td>1.7</td>
<td>0.104</td>
<td>Paper Shale LLP</td>
<td>7,5</td>
<td></td>
</tr>
<tr>
<td>H2-3</td>
<td>0.174</td>
<td>1.8</td>
<td>0.0922</td>
<td>Paper Shale LLP</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>H2-4</td>
<td>0.191</td>
<td>1.6</td>
<td>0.181</td>
<td>Paper Shale LLP</td>
<td>10,5</td>
<td></td>
</tr>
<tr>
<td>H2-5</td>
<td>0.215</td>
<td>1.6</td>
<td>0.0886</td>
<td>Paper Shale LLP</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>H2-6</td>
<td>0.141</td>
<td>2.2</td>
<td>0.103</td>
<td>Paper Shale LLP</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>H2-7</td>
<td>0.134</td>
<td>2.3</td>
<td>0.0947</td>
<td>Type A Rhythmite Limestone and Shale LLP</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>H2-14</td>
<td>0.257</td>
<td>1.4</td>
<td>0.185</td>
<td>Limestone and Shale MLP</td>
<td>230</td>
<td></td>
</tr>
<tr>
<td>H2-15</td>
<td>NM</td>
<td>NM</td>
<td>0.224</td>
<td>Paper Shale MLP</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>H3-3a</td>
<td>0.144</td>
<td>2</td>
<td>0.0141</td>
<td>Paper Shale ULP</td>
<td>267</td>
<td></td>
</tr>
<tr>
<td>H3-4a</td>
<td>0.109</td>
<td>2.7</td>
<td>NA</td>
<td>Paper Shale ULP</td>
<td>269</td>
<td></td>
</tr>
<tr>
<td>H3-5a</td>
<td>0.118</td>
<td>2.5</td>
<td>0.0159</td>
<td>Paper Shale ULP</td>
<td>270</td>
<td></td>
</tr>
<tr>
<td>H3-6a</td>
<td>0.133</td>
<td>2.2</td>
<td>0.0154</td>
<td>Type B Rhythmite ULP</td>
<td>295</td>
<td></td>
</tr>
</tbody>
</table>
4.1.5. Chemostratigraphy

Shale samples from the Lower Shale Member of the Lincoln Peak Formation range in TOC from ~0.2 to 2.1%, with the highest organic content in shale from just before the start of the calcisiltite partings (Table 4). These roughly correspond with the changes in values obtained from magnetometer and Gamma-ray readings for the same samples. As with the Wheeler Formation δ¹³C, most of the values were negative. In addition, two zones can be identified. The boundary coincides with the change from the Paper Shale to Type A Rhythmites. The latter has less negative δ¹³C values.

Table 4
δ¹³C and %TOC of shale samples from the lower 10m of the Lower Shale Member of the Lincoln Peak Formation. The stratigraphic height is from the base of that unit.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Stratigraphic height (m)</th>
<th>δ¹³C</th>
<th>%TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2-1</td>
<td>6</td>
<td>-12.75</td>
<td>1.06</td>
</tr>
<tr>
<td>H2-2</td>
<td>7.5</td>
<td>-12.38</td>
<td>1.161</td>
</tr>
<tr>
<td>H2-3</td>
<td>9</td>
<td>-12.54</td>
<td>2.078</td>
</tr>
<tr>
<td>H2-4</td>
<td>10.5</td>
<td>-10.63</td>
<td>0.534</td>
</tr>
<tr>
<td>H2-5</td>
<td>12</td>
<td>-10.48</td>
<td>0.226</td>
</tr>
<tr>
<td>H2-6</td>
<td>16</td>
<td>-10.32</td>
<td>0.433</td>
</tr>
</tbody>
</table>

4.1.6. Paleontology

Samples from Connors Pass often yielded fragmentary fossils. *Girvanella* is common in Pole Canyon Limestone Thick-Bedded Limestone Facies (Fig. 12), and a thin section of this facies found a possible phosphatic brachiopod, 0.4 mm in diameter.

Macrofossils were not found in Ribbon Limestone Facies of the Pole Canyon Limestone. However, a possible eocrinoid element less than 1 mm in diameter was found in a micrite lamina.
of a thin section of a sample from the upper contact with the Lincoln Peak Formation. In addition, an unidentified, thin-walled, hollow circular fossil 3.5 mm in diameter was found in the same lamina.

No visible fossils were found in the Paper Shale package at the base of the Lower Shale Member of the Lincoln Peak Formation while in the field. However, analysis of thin sections of the Paper Shale Facies which forms the base of the Lincoln Peak Formation found Ptychagnostus sp. remains, 1-3 mm in length. A single stalk of an unknown eocrinoid was also found. Scattered Planolites burrows 1-3 mm long were found. The fossils are in no particular orientation, though they are organized into discrete, irregularly-shaped laminae. Most body fossils are black, which indicates carbonization of the remains.

The calcisiltite of the Type A Rhythmite Facies of the Lower Shale Member contain 0.1-2 mm peloids, which are clustered toward the base of the Bouma sequences. The peloids fine and sparsen upward within each Bouma sequence.

Girvanella is present but rare in the Limestone and Shale Facies of the Lower Shale Member. Scattered horizontal burrows were found in the limestone components of the Limestone and Shale Facies. Fragmentary remains of trilobites are common in the calcisiltite of the interbedded facies, particularly in Type B Rhythmite Facies of the Upper Shale Member of the Lincoln Peak Formation. The quality of trilobite preservation is poor, so field identification was not possible. In addition, a couple of fragments of an unidentified phosphatic brachiopod were found in the Type B Rhythmite Facies of the Lower Shale Member of the Lincoln Peak Formation.

Fossil preservation is limited in the Paper Shale Facies of the Upper Shale Member of the Lincoln Peak Formation, with possible Planolites and fragments of brachiopod shells found.
These are better aligned along the bedding plane than fossils in the Paper Shale Facies of the Lower Shale Member, and the packet possesses clearer bedding structures under the microscope.
Figure 12. Stratigraphic column of the Lincoln Peak Formation, at Connors Pass. The uppermost 50 m of the Pole Canyon Limestone are included to demonstrate the contact between the two units. A carbon curve is provided for the lowermost 20 m of the Lincoln Peak Formation, for which tests for organic $^{13}C$ excursions were conducted.
Figure 13. Thick-Bedded Limestone Facies, which displays alternating dark and light-gray laminated beds accentuated by diagenesis. This image was taken ~40 m below the base of the Lincoln Peak Formation. *Girvanella* fossils can be seen on bottom-left of the image. Calcite veins formed either during diagenesis or metamorphism. Top is up-section.
Figure 14. Banded Limestone Facies, with flaser beds present. This limestone facies is found between the Thick-Bedded Limestone and Ribbon Limestone beds of the Upper Pole Canyon Formation. Top is up-section.
Figure 15. Ribbon Limestone Facies, ~10 m below the base of the Lincoln Peak Formation. This facies becomes more common in the Pole Canyon Limestone near the contact with the Lincoln Peak Formation. The orange bands are the result of weathered, iron-rich dolomite. Top is up-section.
Figure 16. Paper Shale Facies at right, near the base of the Lincoln Peak Formation. This is separated from parted Paper Shale to the left of the image by a fault mylonite. Type A Rhythmite beds are visible in the top-left of the image. Left is up-section.
Figure 17. An example of Type A Rhythmite Facies. The beds in this case are thin, and do not exceed 5 cm. The shale preferentially weathers to create conspicuous furrows, up to 3 cm thick and 5 cm deep. Note the increased thickness of the calcisiltite beds, relative to the shale down-section (base of photo).
Figure 18. Type B Rhythmite Facies, which display contorted bedding common to this facies. The fold in this picture is overturned to the west (left). Left is up-section.
Figure 19. Beds of the Limestone and Shale Facies, which forms the 38 m of the Middle Limestone Member of the Lincoln Peak Formation. Large calcite veins and the marble texture are clearly visible in some of the beds. Alternating light and dark bands of calcisiltite can be seen in some of the less metamorphosed beds. To the left are faint ripples. Image was taken 260 m above the base of the Lincoln Peak Formation. Top is up-section.
4.2. Cooper Canyon

Cooper Canyon was selected as a site based on the possibility that both the upper and lower contacts of the Lincoln Peak Formation would be present there. Fieldwork revealed that the lower contact was buried under alluvium, and only a few scattered and detached blocks of Pole Canyon Limestone of the Thick-bedded Mudstone Facies could be found below it. However, the upper contact was found in the southern valley of Cooper Canyon.

4.2.1. Stratigraphy

Only the upper ~50 m of the Upper Shale Member are exposed at Cooper Canyon (Fig. 20). As at Connors Pass, the Type B Rhythmite Facies is dominant, particularly in the lowermost 22 m of the exposure. The lowermost 10 m of these Rhythmite Facies beds contain 5 cm ripples. These reveal a flow direction toward ~138°. The uppermost 12 m of the Rhythmite Facies packets show an increase in bedding thickness and ripple size, and also include sand-waves. Ripple- and sand-wave flow direction was toward ~230°. Above these rhytmites is a 13.5 m thick faulted and covered interval, likely shale beds. A 3 m faulted calcisiltite bed overlies this covered section. Type B Rhythmite Facies 1.5 m thick overlie the faulted calcisiltite, with 2-5 cm ripples and cross-laminations. The Type B Rhythmite Facies is succeeded by a series of alternating meter-scale beds of Limestone and Shale Facies 4.5 m thick. This sequence is capped by 10-12 m of Ribbon Limestone, similar to Ribbon Limestone found in the Pole Canyon Formation and the uppermost Type B Rhythmite Facies. This outcrop contains one larger scale coarsening-upward cycle, and at least six clearly-defined, smaller-scale coarsening-upward sequences, in the upper 20 m of the outcrop. Three of these, in turn, are in the alternating meter-
scale beds, with the base of each composed of calcareous phyllitic shale, followed by a limestone cap—a pattern similar to Limestone and Shale Facies at Connors Pass, though from farther up-section.
Figure 20. Stratigraphic column of the Upper Shale Member of the Lincoln Peak Formation at Cooper Canyon.
4.3. *Patterson Pass*

4.3.1. *Stratigraphy*

Patterson Pass contains the type exposure of the Patterson Pass Shale, described as a largely complete section with excellent exposures (Kellogg, 1963). A similar characterization was provided by Margaret Rees (1986). Satellite imagery of the area showed promise, with what appeared to be somewhat sparse tree cover. However, in two expeditions to Patterson Pass, only the uppermost 30 m were located, though these were well-exposed. The rest of the formation was covered by a large talus slope or otherwise forested. Exposures which were found are predominantly 20-40 cm Facies of medium to dark slate-gray calcisiltite and subordinate calcareous shale beds (Fig. 21), the latter thinly laminated. As at Connors Pass, the Facies coarsen up-section. These Facies are similar to Type B Rhythmites and the Limestone and Shale Facies, respectively, at Connors Pass. However, they differ in that they do not exhibit evidence of metamorphism, though diagenesis has produced a series of thin calcite veins along bedding planes (Fig. 21). The Limestone and Shale Facies possess thin laminae, which form a series of alternating bands of lighter and darker limestone. Patterson Pass beds weather pale yellow to orange-buff. The laminae of the more argillaceous limestone beds also tend split on weathering (Fig. 21). The calcisiltite often contains horizontal burrows, though no *Girvanella* was found. The lithology and stratigraphy broadly correspond to work by Kellogg (1963) and Rees (1986), and can be classified as a coarsening-upward sequence, where Type B Rhythmites give way to Limestone and Shale Facies beds up-section.
Figure 21. Bedding of the Upper Patterson Pass Shale (Limestone and Shale Facies). More argillaceous beds in this exposure weather pale-buff to orange. Limestone forms alternating light and dark beds, which become platy on weathering. Top is up-section.
5. Interpretation

5.1. Stratigraphy and Environments of Deposition.

Total measured thickness of the Lower Shale and Middle Limestone Members of the Lincoln Peak Formation at Connors Pass is 212 m. This is considerably thinner than the combined thicknesses of the coeval Wheeler Formation and Marjum Formation in western Utah. It is also considerably thinner than the exposure at Patterson Pass, which was measured at ~650 m by Kellogg (1963), though the two units are largely identical lithologically and structurally. Sections of the Lower Shale Member coeval to the Wheeler Formation are more argillaceous than Wheeler Formation outcrops at either Marjum Pass or Drum Mountains, whereas the rest of the Lower Shale Member, coeval to the Marjum Formation, is roughly as carbonate rich as the Marjum Formation, and therefore more calcareous than the Wheeler Formation.

As the Lower Shale Member of the Lincoln Peak Formation and the Patterson Pass Shale are identical lithologically, genetically, and belong to the same geographic area, they are here considered part of the same unit. As the Lincoln Peak Formation was named prior to the Patterson Pass Shale, it assumes seniority, so all exposures of Patterson Pass Shale should be referred to the Lower Shale Member of the Lincoln Peak Formation. Similarly, as Member A of the Emigrant Springs Formation is largely identical to the Middle Limestone Member lithologically and genetically, it should be merged with the Middle Limestone Member of the Lincoln Peak Formation. Member B of the Emigrant Springs Limestone in turn should be merged with the Upper Shale Member of the Lincoln Peak Formation, as the lithology of the two units are largely identical (Kellogg, 1963).
The outcrop at Connors Pass preserves seven facies, successively deposited in a basin, distal carbonate ramp, and proximal carbonate ramp. This three-fold division is similar to that used by Langenberg (2003). The underlying Pole Canyon Limestone is interpreted to be deposited in a fourth environment: a shallow carbonate platform, as in previous work (Robison, 1965).

5.1.1. **Thick-Bedded Limestone Facies (Pole Canyon Limestone)**

The presence of *Girvanella* indicates that the setting was within the photic zone, consistent with earlier work on the carbonate platform which preceded the formation of the House Range Embayment (Robison, 1965). *Girvanella*, which is interpreted as the remains of an algal or cyano-bacterial film, the oncoidal form of which is an indicator of current activity sufficient to roll the fragments back and forth along the sea-floor. Likely depth at deposition was less than a few tens of meters, and more likely $<5$ m (Flügel, 2004).

5.1.2. **Banded and Ribbon Limestone Facies**

These two facies are composed of bands of alternating varicolored carbonate laminae. Beds in the Banded Limestone Facies alternate between light and dark colored, flaser-bedded lime mudstone, whereas beds in the Ribbon Limestone Facies consist of varve-like bands of gray mudstone and orange silty iron-rich (ferroan) dolomite. The environment of deposition for the Banded Limestone is interpreted in this study to be a shallow subtidal or intertidal setting, subjected to storm activity. This is based on the presence of flaser bedding in Banded Limestone. The transition from the Thick-Bedded Limestone to Banded and Ribbon Limestone Facies likely represents transition to a more energetic setting.
The Ribbon Limestone Facies which is more common up-section, bears a passing resemblance to lake varves, with sand replaced with peloids and shale replaced with lime mud. This indicates a similar environment of deposition to the Banded Limestone, though less energetic. This change may have been caused by an increase in water depth to below wave-base, or alternatively a change in climatic conditions. The alternation in grain type in this facies is possibly seasonal in nature. The overall environment during the deposition of the two facies is interpreted to be analogous to a tropical version of the North Sea in the Holocene, where flaser bedding is common. It is therefore considered a representation of the distal portion of the carbonate platform. Likely depth of both Facies is 30-50 m, with the ribbon limestone representative of greater water depth.

5.1.3. Paper Shale Facies

Contrary to Kellogg (1963), this facies does not seem to form a gradual contact with the Ribbon Limestone beds of the Upper Pole Canyon Limestone. This contact is interpreted as evidence for a rapid increase in water depth, which led to a local drowning of the carbonate platform. This facies may account for the thrust-faulting found at the base of all Lincoln Peak Formation outcrops (Drewes and Palmer, 1957), as it creates a structural weakness between the Pole Canyon Limestone and Lincoln Peak Formation (Drewes and Palmer, 1957). The Paper Shale Facies is interpreted to represent deep-basin deposits, from a time when marine depth was at its greatest in eastern Nevada. The dark gray color, elevated organic content in the first 9 m, presence of hematite-after-pyrite nodules, and limited though noticeable bioturbation indicate a stressed environment, with dysoxic conditions. The lack of any cross-laminae in the shale indicates a low-energy setting (Schieber and Southard, 2009; Egenhoff and Fishman, 2013).
However, the presence of fossil fragments which are aligned with bedding in paper shales of the Upper Shale Member of the Lincoln Peak Formation indicates possible current flow from winnowing, and a possibly a more oxygenated environment. This is supported by the lower radioactivity of samples from the Paper Shale packet of the Upper Shale Member compared to the equivalent Lower Shale Member’s packet, and the lower abundance of fossils. The brachiopod shell fragments likely came from the area of Patterson Pass, where equivalent beds have yielded abundant fossilized phosphatic brachiopods (Streng and Holmer, 2006).

There are two possible methods by which shale of the Lincoln Peak Formation could have been deposited. Both would produce similar results at the macroscopic level. The first method is by the suspension settlement of mud as “marine snow”, created by the flocculation of terrigenous mud and clay particles, which entrap within them carbonate and organic fragments, and settle with these to the bottom of the sea-floor (Schieber et al., 2003; Macquaker et al., 2010). The second method for the deposition of paper shale is through turbidity currents (Egenhoff and Fishman, 2013), which can produce similar structures. In this case, the organic matter and carbonate either settle with the terrigenous mud, or are entrained within a turbidity flow. The lack of direct access to shale sources from the east throughout much of the history of the embayment, combined with high relative shale content in sections of the Lincoln Peak Formation coeval to the Wheeler Formation, and absence of carbonate turbidites until farther up-section, point toward deposition via “marine snow”. In this case deposits composed of floccules, trilobite shells, and eocrinoid stalks were draped onto the sea-floor, then disturbed by bioturbation that created Planolites trace fossils. Sediment supply likely came from the inner detrital belt to the present-day east. This belt was separated from the House Range Embayment by a carbonate platform, save in northern Utah, where the inner and outer detrital belts appear to
have briefly merged in the time prior to the First Appearance Datum of *Pychagnostus atavus* (Buterbaugh, 1982; McCollum and Miller, 1991). This would have allowed sufficient quantities of terrigenous mud to reach Nevada, and would also account for the thinning of the shale deposits westwards within the House Range Embayment.

The calcareous content of the Paper Shale Facies indicates that it was unlikely for depth to have reached the Calcite Carbon Compensation Depth during the Cambrian. The lack of signs of major storm activity indicates a minimum water depth of >30 m (Walker and Plint, 1992), which is the maximum storm wave-base depth for present-day continental shelves. The lack of meter-scale bedding indicates that water depth was sufficient to protect the area from the effects of eustatic sea level change. Therefore, it seems likely that water depth at the time this Facies was deposited was greater than 100 m. The presence of turbiditic calcisiltite partings toward the top of the Paper Shale Facies likely marks the beginning sediment input from the growth of the carbonate belt to the east, and the beginning of a decrease in water depth.

### 5.1.4. *Rhythmites (A and B)*

Both Rhythmites are composed of packets of alternating calcisiltite and phyllitic, calcareous shale, with a tendency toward a decrease in shale content up-section. Presence of partial Bouma sequences in many of the calcisiltite beds suggests deposition by settlement of suspended sediments transported by turbidity currents. Deposition of the phyllitic shale was likely through the same means the Paper Shale was deposited, though this was increasingly interrupted by turbidity flows. The up-section decline in shale deposition in Type B Rhythmites, combined with the gradual increase in cross-laminations, ripples, and the appearance of ribbon limestone, indicate a gradual decline in water depth, to a level above storm-wave base, sufficient
to rework the sediments on the seafloor. The source of the calcisiltite is likely the seaward-prograding carbonate belt to the present east and north (Robison, 1965).

The presence of contorted bedding throughout much of the Rhythmite, particularly in Type B Rhythmite packets, suggests that the area was subjected to submarine gravity slides. Due to extension which the area underwent during the Middle Cambrian (Stewart and Suczek, 1977; Rees, 1986; Sears and Price, 2003), it is likely that some of these represent the occurrence of earthquakes that caused multiple failures of loosely consolidated sediments on slopes along the embayment margin. This scenario parallels the upper continental slope found off the east coast of present-day New Zealand, where large-scale slumps have been related to seismic activity (Lewis, 1971). By analogy, the slope of the basin margin in the region may have been about 1°-4°, similar to slopes of some upper continental slopes in the present (Lewis, 1971). Additional evidence for this may come from possible hemi-pelagic and pelagic sediments to the northwest, which would have been deposited even deeper than at the embayment (Stewart and Suczek, 1977). However, a similar effect could be achieved though faulting and lithospheric flexure in the north toward the sedimentary trough of the House Range Embayment. This would depress the southern margin of the embayment, and create a south-facing slope atop the continental shelf north of the embayment margin. This is considered a more likely explanation, as the trend of the fold axes of contorted beds is generally ~110-130°, and their asymmetric shape, overturned to the southwest, favors a ramp sloping southwest (Fig. 18).

A similar interpretation is advanced for the Rhythmites of the Upper Shale Member of the Lincoln Peak Formation, based on the presence of similar structures. Both Rhythmite facies are interpreted to represent a distal ramp setting in the Schell Creek Range, with the ribbon
limestone found in the upper Type B Rhythmite Facies an indication of a transition to mid-ramp settings.

5.1.5. *Limestone and Shale Facies*

These two lithotypes comprise the Middle Limestone Member at Connors Pass and at Cleve Creek Baldy, north of Connors Pass (Table 1) (Drewes, 1967). Due to their intertwined nature, they are treated as one facies, though they can occur independently of each other (Fig. 12). Widespread presence of ripples, cross-lamination, channels, and local cross-bedding indicate a much more energetic environment than for previous facies discussed, perhaps a supra-tidal or intertidal environment similar to that of the Upper Pole Canyon Formation. The alternation of meter-scale packets of limestone and shale indicates cyclical deposition, caused by regular low-magnitude changes in sediment influx, or in energy, or perhaps eustacy. These facies are here interpreted to have been deposited at depths no greater than 20-30 m, perhaps in a proximal carbonate ramp environment. The well-developed Middle Limestone Member at Cleave Creek Baldy suggests that area may have been less subjected to the effects of sea-level change, and therefore possibly shallower than at Connors Pass, though further fieldwork is required to confirm this. Connors Pass, in turn, seems to have been slightly deeper than at Patterson Pass, where Member A of the Emigrant Springs Formation consists entirely of limestone similar to that found at Connors Pass and Cooper Canyon, save at its base, which contains meter-scale alternate packets of shale and limestone (Kellogg, 1963).
5.2. Cyclostratigraphy

In addition to two major 3rd-order cycles that begin within the Upper Pole Canyon Limestone and at the base of the Upper Shale Member of the Lincoln Peak Formation, the Lower Shale Member of the Lincoln Peak Formation at Connors Pass can be divided into two more 3rd-order cycles (Fig. 12). The uppermost cycle of the Lower Shale Member of the Lincoln Peak Formation in turn contains at least eight 5th- or 6th-order cycles, which are entirely displayed in the well-exposed Middle Limestone Member. The Upper Shale Member of the Lincoln Peak Formation at Cooper Canyon possesses a single large-scale 3rd-order cycle, which can be subdivided into three 4th-order cycles. The second of these cycles can be divided into three 5th- or 6th-order cycles, identical to those of the Limestone and Shale Facies beds of the Middles Limestone Member of the Lincoln Peak Formation. All intraformational cycles coarsen upward. In addition, there are packets similar of facies identical to those at Connors Pass that comprise the greater part of the Lincoln Peak Formation, and these individually coarsen upward (Fig. 22)

5.2.1. Connors Pass

The Upper Pole Canyon Limestone exhibits relatively less cyclicity, except for a single 3rd-order cycle, which spans the lowermost 30 m of the formation, and possible seasonal laminae from the Ribbon Limestone of the uppermost Pole Canyon. These both appear to represent a deepening-upward cycle.

The lowermost 16 m of the Lower Shale Member of the Lincoln Peak Formation exhibit a single major shallowing-upward cycle, composed of the Paper Shale Facies that grade upward
to Type A and then Type B Rhythmite packets. The origin of this cycle is interpreted as a
decrease in water depth, caused by infilling of the House Range Embayment. Smaller scale
cycles found only where the Paper Shale grades upward to calcisiltite partings as the Paper Shale
transitions to the Rhythmites (Fig. 22A), as well as within the Rhythmites themselves (Fig. 22B).
In both cases, these minor cycles are no more than 20 cm thick. As with most of the larger scale
cycles, these cycles each shallow upward. Smaller cycles are likely tied to turbidity flows,
caused either by over-steepening (Langenberg, 2003), or seismic activity, or a combination of the
two. They are therefore considered parasequences. Increase of calcisiltite beds up-section is
interpreted as due to the growth of the carbonate ramp to the north and east which allowed
successively more calcisiltite to reach the present Connors Pass area in turbidity flows though
time.

The second major cycle begins at the faulted shale lens 16 m above the base of the
Lincoln Peak Formation, where it rapidly transitions to Type A, then Type B Rhythmite packets,
through 12 m. This is followed by a third, much larger cycle, which begins 28 m above the base
of the Lincoln Peak Formation. Combination of the first and second major cycles of the Lower
Shale Member produces a single, generally shallowing-upward cycle, which begins with a base
of Paper Shale, and terminates with the base of the Type B Rhythmites (Fig. 12).

The third major cycle begins with the deposition of Type A Rhythmite packets, which
continue 6-8 m, where they are replaced by Type B Rhythmite packets. The transition between
Type A and Type B Rhythmite beds is transected at Connors Pass by a fault mylonite (Fig. 12).
Beyond the fault, Type B Rhythmite packets are almost continuous until the Limestone Facies
and Shale Facies of the Middle Limestone Member are encountered (Fig. 22C).
Within the Limestone and Shale Facies, eight sets of alternating meter-scale interbedded Shale and Limestone packets have been identified. Three of these are near the base of the limestone beds (230-236 m above the base of the Lincoln Peak Formation), and another five lie near the top of the limestone beds (250-258 m above the base of the Lincoln Peak Formation). There may have originally been more packages between these two sets of packages, but heavy metamorphism there might have obscured these. The concentration of meter-scale cycles toward the top of the unit is in marked contrast to the Wheeler Formation, where most detectable meter-scale cycles are either evenly spaced out, as at Marjum Pass, or largely concentrated in the lower half of the unit, as at Drum Mountains (Figs. 8 and 9). These cycles are all interpreted to be shallowing-up cycles.

The final major shallowing-up cycle of exposures at Connors Pass is associated with the Upper Shale Member of the Lincoln Peak Formation. Only one large-scale cycle has been found there, as well as the cycles represented by the rhythmites. The abrupt structural changes in the basin which affected the Upper Shale Member of the Lincoln Peak Formation prevented confident identification of additional major cycles.

5.2.2. Cooper Canyon

The upper 50 m of the Lincoln Peak Formation displays one large-scale shallowing-up 3rd-order cycle. In addition, there are two shoaling-up 4th-order cycles. These are, from bottom to top: Type B Rhythmite to Limestone and Shale, then Limestone and Shale to Ribbon Limestone. The combined Limestone Facies and Shale Facies in turn possess three meter-scale 5th- or 6th-order cycles, each shallowing up, of phyllitic shale succeeded by limestone. The cause of these meter-scale cycles are likely small-scale variations in sediment supply, tectonics, or small-scale
eustacy during the time of deposition. Larger scale cycles likely result from a decrease in water depth, perhaps caused by the loss of accommodation space as the embayment was filled in.

**Figure 22.** The three broad types of 4th-order cycles observed at all Lincoln Peak Formation localities. All are coarsening-upward cycles. The meter-scale bedding packages are included in C. A. Paper Shale to Type A Rhythmite facies. B. Type A to Type B Rhythmite Facies. C. Type B Rhythmite Facies to Limestone and Shale Facies.

5.3. *Sequence Boundaries and Systems Tracts*

5.3.1. *Connors Pass*

The Lower Shale Member of the Lincoln Peak Formation at Connors Pass comprises three sequence-stratigraphic entities, which correspond to the three major cycles within it (Fig. 12). The first sequence begins in the Pole Canyon Limestone ~10 m below the base of the Lincoln Peak Formation, with the appearance of Ribbon Limestone. This marks the start of a Transgressive Systems Tract (TST). This encompasses the Ribbon Limestone beds and the overlying Paper Shale beds up to the calcisiltite partings. There the putative DICE marker and an increase in total organic carbon mark the Maximum Flooding Surface (MFS), and the start of the Highstand Systems Tract (HST), which encompasses the remainder of the first cycle, which ends
16 m above the base of Lincoln Peak Formation (Fig. 12). This HST encompasses the uppermost Paper Shale and lowermost Type A Rhythmite packets, which end 16 m above the base of the Lincoln Peak Formation. The base of the 1.5 m shale lens, which overlies the first sequence suggests another flooding surface, and the start of a second sequence. The second Paper Shale Facies represents the second sequence’s TST (Fig. 12). This is succeeded by HST beds which extend another 9 m, and are followed by the start of a third sequence, ~28 m above the base of the Lincoln Peak Formation (Fig. 12). The exact location of the start of the third sequence is not entirely constrained, due to the gradual changes between the two Rhythmite Facies.

The sequence stratigraphy of the third sequence in the Lower Shale and Middle Limestone Members of the Lincoln Peak Formation is more difficult to reconstruct. This is due to the input of turbidity currents, which can obscure actual changes in sea level, and the generally more carbonate-rich nature of this part of the Lincoln Peak Formation. However, it seems that the TST extends from the Type A Rhythmites 28 m above the base of the Lincoln Peak Formation to a fault mylonite, which separates Type A Rhythmite packets, which comprise the TST, from overlying Type B Rhythmite packets (Fig. 12). The thickness of the TST deposits total ~9 m. The Type B Rhythmites above the fault mylonite likely represent HST. The alternating limestone and shale beds that form the Middle Limestone Member might belong to two systems tracts, separated by a hematite-stained hard-ground (Fig. 12). Those meter-scale beds below the hard-ground likely represent the Falling Stage Systems Tract (FSST). Those above the hard-ground represent a new Lowstand Systems Tract (LST), and with it the start of a fourth sequence. The hard-ground itself marks the zone when the area was at its lowest water-depth, and was perhaps aerially exposed. This, alongside metamorphism, may account for the
lack of meter-scale alternating beds of limestone and shale, and instead the dominance of limestone alone for the next 10 m.

The start of another Paper Shale Facies at the base of the Upper Shale Member of the Lincoln Peak Formation marks the continuation of the fourth sequence, which apparently spans the entirety of the Upper Shale Member of the Lincoln Peak Formation (Fig. 20). Here the base of the Paper Shale Facies, as with the Lower Shale Member’s first sequence, marks the MFS. This is followed by the start an extended early Highstand Systems Tract (eHST), which ends at the start of the first major limestone beds, as found at Cooper Canyon 40 m below the upper contact (Fig. 20). The lack of any hard-grounds or other signs of subaerial exposure in the uppermost Lincoln Peak Formation indicates that there was likely no FSST or LST preserved (Fig. 20). Instead, the exposures at Cooper Canyon likely represent the late Highstand Systems Tract (lHST). This mirrors the sequence stratigraphy of the Wheeler Formation, but post-dates it by several million years. However, a caveat to this model of the sequence stratigraphy of the Upper Shale Member of the Lincoln Peak Formation is that post-depositional tectonism affected the Upper Shale Member of the Lincoln Peak Formation much more than it did the Lower Shale and Middle Limestone Members. This tectonism could have destroyed or obscured evidence for other stratigraphic sequences in this unit, particularly as these deposits are condensed.

5.4. Controls on Cyclicity in the Lincoln Peak Formation

5.4.1. Connors Pass

The regularity and uniformity of the meter-scale packets of Limestone Facies and Shale Facies toward the top of the Middle Limestone Member of the Lincoln Peak Formation suggest a
cyclical cause. Such regularity has previously been attributed to Milankovitch forcing (Goldhammer et al., 1993; Preto et al, 2001; Langenberg, 2003). One argument in support of this is the observation that tectonic subsidence only occurs in regions of high tectonic instability (Langenberg, 2003). Another is the argument that oscillation caused by seismic activity cannot produce high-frequency cycles as observed at the Lincoln Peak Formation or Wheeler Formation, and that similar meter-scale cyclicity in units above the Marjum Formation were created after the House Range Embayment was filled in (Langenberg, 2003). Episodic tectonism in this case can produce laterally discontinuous cycles, but not laterally continuous cycles (Langenberg, 2003). The difference in cycle numbers between exposures of the Drum Mountains (19), and Marjum Pass (16) in this model is interpreted as the result of sub-tidal “missed beats”, due to the greater distance of Marjum Pass from the carbonate platform to the south (Langenberg, 2003).

Set against the above model is evidence for extensive tectonic activity, specifically in the form of earthquakes. Evidence within the embayment mainly comes from the various slumps and contorted beds found throughout the Lincoln Peak Formation and the Wheeler Formation, as well as the putative fault itself (Rees, 1986; Langenberg, 2003). More direct evidence comes from the presence of volcanic-ash layers of the same age in the Shoshone Range in central Nevada (Stewart and Suczek, 1977). The over-steepening of rhythmites, to which Langenberg (2003) attributed the cause of contorted bedding, may itself have been caused by the growth of one or more faults that created the House Range Embayment. This would be by the creation of a roll-over anticline present-day northwest of the fault, which would create conditions analogous to those of continental slopes, which faced to the south.
In addition, variations in the number of meter-scale packages can take place even within a carbonate platform, where one would expect the most complete set of meter-scale packages to exist. Examples of this have been observed in the Lower to Middle Triassic beds of the Latemär Platform, Italy (Egenhoff et al., 1999; Peterhänsel and Egenhoff, 2008). The variation in the number of packets there is attributed to pre-existing topography, with areas of lesser water depth more readily affected by small-scale oscillations in sea level than areas of greater water-depth (Peterhänsel and Egenhoff, 2008). Tectonism can also have an effect, simply through the alteration of the topography by uplift or subsidence (Peterhänsel and Egenhoff, 2008). The situation in the Middle Cambrian of Nevada is similar to that of the Middle-Triassic of the Latemär, as both underwent tectonic activity during deposition (Rees, 1986; Peterhänsel and Egenhoff, 2008). The meter-scale packages themselves may not be related to Milankovitch cycles, but instead could be sub-Milankovitch cycles, or be otherwise unrelated (Zühlke et al., 2003). For example, meter-scale cycles in the Latemär might have on average represented a period of less than 8,000 years or even as little as 2,000 years (Mundil et al., 1996; Mundil et al., 2003).

As the Lincoln Peak Formation was mostly deposited in a distal ramp setting, and its sequences are condensed relative to the Wheeler Formation, the lack of meter-scale packages except in the Middle Limestone Member and top of the Upper Shale Member can be attributed to a combination of the greater depth at which the Lincoln Peak Formation was deposited, and the relative lack of sediment input into the region. The presence of meter-scale packages in the Middle Limestone Member and top of the Upper Shale Member is interpreted to be the result of shallowing of the region, as the House Range Embayment was filled in. This allowed for minor oscillations in sea-level to have a greater effect on the deposition of these beds than it would
have in beds of either the Paper Shale or Rhythmite Facies. Conversely the greater number of cycles at outcrops of the Wheeler Formation can be attributed to the lesser depth at which the formation was deposited, as well as the more proximal location of the Wheeler Formation in the House Range Embayment.

5.5. Magnetostratigraphy and Gamma-Ray Stratigraphy

5.5.1. Magnetostratigraphy

The depressed levels of magnetic susceptibility in The Pole Canyon Limestone’s Thick-Bedded Limestone and Banded Limestone Facies are consistent with their predominantly carbonate composition (Hrouda et al., 2009). Negative values for some samples are likely errors created as values approach zero (Table 3). The increase in magnetic susceptibility in Ribbon Limestone Facies in the uppermost Pole Canyon Limestone is attributed to the increased iron content, associated with deposition of dolomite bands within the limestone beds (Fig. 15).

Particularly high levels of magnetic susceptibility in Paper Shale Facies of the Lower Shale Member relative to other facies are attributed to the abundance of iron, evident in the presence of hematite-after-pyrite nodules. The presence of pyrite is strongly indicative of a reducing environment, consistent with an overall dysoxic to anoxic setting (Egenhoff and Fishman, 2013).

Type A and B Rhythmites overlying the Paper Shale Facies possess lower levels of magnetic susceptibility compared to those of the Paper Shale Facies (Table 3). This is consistent with the increased deposition of calcisiltite.
The Limestone Facies and Shale Facies, which form the Middle Limestone Member show an elevated level of magnetic susceptibility, with values consistently higher than those of the Paper Shale Facies (Table 3). This can be explained by the presence of iron in these beds, which also created the red hard-ground associated with this facies.

Beds of the Upper Shale Member generally possess lower susceptibility compared to equivalent beds of the Lower Shale and Middle Limestone Members. This is attributed to elevated levels of carbonate deposition in the embayment from the carbonate platform to the south, and the carbonate ramps to the north and east (Robison, 1965). This is consistent with the Upper Shale Member’s predominantly calcisiltite lithology.

5.5.2. Gamma-Ray Stratigraphy

Low radioactivity in beds of the Pole Canyon Limestone is consistent with the high carbonate composition of the unit. The radioactivity of the Paper Shale Facies was low despite elevated %TOC and magnetic susceptibility, with values between 0.141 and 0.216 μCurries. Most of the radioactivity was from $^{40}$K. As $^{40}$K decays via alpha-decay, this means that there are negligible levels of gamma-radiation being produced by these facies. This indicates a lack of Uranium or Thorium, which normally would be expected for organic-rich shale. The cause of this lack of Uranium or Thorium is uncertain, but suspected to be due to the way organic material found in the Paper Shale Facies reached the present-day Schell Creek Range, with certain sources, such as coal or ash, able to produce similar results (Russel, 1945). The apparent carbonization of body fossils, particularly in the Paper Shale packets of the Lower Shale Member of the Lincoln Peak Formation, would in this case act in an identical manner to coal, and so produce little radioactivity.
Radioactivity in packets of Type A and B Rhytmite Facies are, as with magnetic susceptibility, lower in value than packets of Paper Shale Facies. This is consistent with the increased input of calcisiltite, particularly for packets of Type B Rhytmite. As with magnetic susceptibility for the Lower Shale Member, the highest values of radioactivity are in beds of Limestone and Shale Facies. This is striking for the shale beds of these facies. However, as with the Paper Shale Facies, the radioactivity values of these two facies are rather low. The radioactivity of the beds of the Upper Shale Member is considerably less than those in the Lower Shale Member (Table 3). This is interpreted to be the result of elevated levels of carbonate deposition, relative to the Lower Shale Member.

5.6. Chemostratigraphy

5.6.1. Total Organic Carbon

Only the lower 20 m of the Lower Shale Member have been tested for organic carbon. Three of the samples are from below the calcisiltite partings, and the other three are from parted shale beds, or Type A Rhytmite beds, or the 1.5 m shale lens (Table 4). Shale samples from below the transition have an average of ~1.1 %TOC (Table 3). An exception to this is the shale sample from just below the calcisiltite partings in the shale beds, which has ~2.1 %TOC. Shale beds from above the start of the calcisiltite partings exhibit more variability in their %TOC content (Table 4), but are consistently lower in %TOC than in those shales collected from before the start of the calcisiltite partings. The elevated %TOC just below the calcisiltite partings confirms that this area is associated with the MFS of the first sequence, as was the case for the Wheeler Formation in western Utah (Langenberg, 2005). The DICE is therefore also likely
present at some point just below the calcisiltite partings in the Paper Shale Facies of the Lower Shale Member of the Lincoln Peak Formation. The decline in %TOC of the shale packets is interpreted as the result of an increase in carbonate input during deposition of the shale beds above the MFS, associated with the start of HST in the Lower Shale Member.

Relative to values for organic δ¹³C from the Wheeler Formation (Fig. 24), values for the Lower Shale Member (Table 4) are less negative, with a range of values between -10 and -14, compared to -30 to -24 for the Wheeler Formation at Marjum Pass (Langenberg, 2003). Organic δ¹³C values obtained from the Lincoln Peak Formation are more negative than the carbonate δ¹³C values of the Wheeler Formation at Marjum Pass. The latter range from -2 to +2. As the samples were checked for any residual carbonate prior to testing via a 20% HCl bath, contamination seems unlikely to be the cause of the difference in these values. Instead, diagenesis is a likely cause. Whereas the level of diagenesis in the Paper Shale Facies appears to be minimal compared to the rest of the formation, thin section analysis found extensive calcite veins, and altered lime mud. These could have altered δ¹³C values. Balanced against this is observation that δ¹³C values (and %TOC) seem to correlate well with the magnetostratigraphic and gamma stratigraphy (Tables 3 and 4).

A more detailed comparison of δ¹³C curves, and of the nature of δ¹³C variation for the Lincoln Peak Formation itself, requires more thorough sampling than undertaken for this study, with a collection interval of perhaps 20-30 cm, instead of the current 1-1.5 m. A more accurate accounting for the effects of diagenesis is also required for future studies of the Lincoln Peak Formation. Finally, similar sampling must be undertaken for the Lincoln Peak Formation deposits at Patterson Pass, to compare with the samples obtained at Connors Pass.
Figure 23. Stratigraphic column of the Wheeler Formation at Marjum Pass, with the organic (A), and carbonate (B) $\delta^{13}$C values. The $\delta^{13}$C analysis used the Pee Dee Belemnite (PDB) as a standard. Used with permission of Langenberg, 2003.
5.7. Stratigraphic Correlation of the Lincoln Peak

A stratigraphic correlation of the Lincoln Peak Formation with the Wheeler Formation has been made, based on the presence of sequence boundaries, flooding surfaces, and changes in lithology in both units, as well as the suspected horizon where the DICE is found (Fig. 24). The basal correlation is at the first transgressive surface, in the upper Swasey Limestone and upper Pole Canyon Limestone, 20 and 10 m, respectively, below the base of the Wheeler Formation and Lower Shale Member of the Lincoln Peak. The second correlation is defined by the likely Maximum Flooding Surfaces in the Wheeler and Lincoln Peak Formations. For the Wheeler Formation, the MFS is 32 m above the lower contact at Marjum Pass, and 72 m above the lower contact at the Drum Mountains. For the Lincoln Peak Formation, the MFS is less than 9 m above its base (Fig. 24). A second sequence boundary marked by a flooding surface separates the lower Wheeler Formation from the upper Wheeler Formation, and separates the first and second sequences of the Lower Shale Member of the Lincoln Peak Formation. The third sequence boundary is marked by an increase in shale deposition 16 m above the base of the Lincoln Peak Formation, and respectively 90 m and 150 m above the base of the Wheeler Formation at Marjum Pass and the Drum Mountains, respectively. As the $\delta^{13}C$ signals at Lincoln Peak are different from those at either exposure of the Wheeler Formation, and are not as complete, these are not used. The same issue attends the use of magnetostratigraphy and gamma-stratigraphy, which have only been done for the upper half of the Wheeler Formation, (Halgedahl et al., 2009).

The third sequence present in the Lower Shale Member of the Lincoln Peak Formation cannot be compared to coeval sequences of the Marjum Formation because of the condensed
nature of the former. Also, the effects of tectonics have resulted in preservation of a single clear sequence coeval to the Marjum Formation, whereas the Marjum Formation itself preserves at least two sequences (Brett et al., 2009).
Figure 24. Sequence-stratigraphic correlation of the uppermost 50 m of the Pole Canyon Limestone and lowest Lincoln Peak Formation at Connors Pass (left), with the Wheeler Formation at Marjum Pass (right). The Lincoln Peak Formation is shown at a different scale than the Wheeler Formation, due to its condensed thickness. Red lines: sequences boundaries; Blue Lines: Maximum Flooding surfaces. Stratigraphic column of the Wheeler Formation at Marjum Pass from Langenberg (2003) used with the author’s permission. For symbols, see Figs. 10 and 12.
5.8. Depositional Environment

The Lower Shale Member of the Lincoln Peak Formation is dominated by fine-grained sediments. Thus, the portion of the Lincoln Peak Formation coeval to the Wheeler Formation is more dominated by shale, with approximately a third of the strata composed of the Paper Shale Facies. In addition, the upper part of the first sequence of the Lincoln Peak Formation has a higher siliciclastic input than the equivalent upper Wheeler Formation at Marjum Pass. This suggests that the present area of the Schell Creek Range was under greater water depth than at the present Marjum Pass and much greater than the Wheeler Formation at the Drum Mountains (Langenberg, 2003). The eHST deposits, which overlie the Paper Shale beds possess partings of calcisiltite, which then grade upward to Type A Rhythmites. This is interpreted as the beginning of early highstand shedding associated with the west- and southward encroachment of the carbonate platform. This shedding transported sediments from the carbonate platform into the House Range Embayment, via turbidity currents. As in the Wheeler Formation, contorted beds are localized in the Lower Shale Member of the Lincoln Peak Formation, and this is interpreted as a result of over-steepening of the shelf, seismic activity, or a combination thereof.

The highly-condensed nature of the Lower Shale Member of the Lincoln Peak Formation indicates that the House Range Embayment in the present area of the Schell Creek Range underwent sediment starvation. This trend becomes more pronounced to the west and southwest, as total sediment thickness decreases (Stewart and Suczek, 1977). The lack of sediment input may explain the relative lack of bioturbation in the Lower Shale Member, wherein insufficient organic material and oxygenated water entered the basin in the area of the present Schell Creek Range. The latter created a highly dysoxic environment, where few macro-organisms could
thrive. The fragmentary nature of the fossils found, which are largely in the calcisiltite beds, suggests that these remains were introduced into the basin via turbidity currents, and do not represent the local fauna. A similar environment seems to have existed for the section exposed at Patterson Pass (Kellogg, 1963; Streng and Holmer, 2006).

The data on current flow directions at Connors Pass, which were only from the uppermost 30 m of the Middle Limestone Member, indicate that the currents at the time flowed across the embayment at the Schell Creek Range site, rather than along its margin. The current direction on the seafloor prior to that point in time is unknown, though the extreme sediment starvation combined with winnowing observed in the Paper Shale Facies at the base of the Lincoln Peak Formation indicates that a generally weak current was present in the area then.

5.8.1. **Basin Morphology**

While further work on Lincoln Peak Formation exposures is required to improve the interpretation of this unit as a whole, enough is known to provide an overview of the morphology of the House Range Embayment in eastern Nevada during the Middle Cambrian. The well-developed Middle Limestone Member in exposures of Lincoln Peak Formation north of Connors Pass becomes thinner to the southwest, and is absent in the Grant and White Pine Ranges west of the study area. This suggests that water depth increased to the present-day west and southwest. This is consistent with the proposed geometry of the House Range Embayment (Rees, 1986), wherein the trough axis at present lies along a NE-SW line, from central Utah to eastern California. The presence of the well-developed, partly conglomeratic Middle Limestone Member at Patterson Pass (Member A of the Emigrant Springs Limestone; Kellogg, 1963) coeval to that at Connors Pass and the well-developed Middle Limestone Member at Cleve Creek Baldy, north
of Connors Pass, indicates similar water depth in all three sites, with the shallowest depths north and south of Connors Pass (Drewes, 1967). In addition, the lithology of most of the Lincoln Peak Formation is rather uniform, with the Lower Shale Member of the Lincoln Peak Formation composed of a succession of Paper Shale and Type A and B Rhythmite, and the Upper Shale Member largely composed of Type B Rhythmite beds. This at first appears to go against the current model of the development of the House Range Embayment, which implies that the trough along its southern margin had the greatest water depths (Rees, 1986). However, the deposits at Patterson Pass are over twice as thick as the coeval deposits at Connors Pass. Unless the sections were affected by tectonic thinning or thickening, this suggests that while the two sites were at similar depths for much of the history of the House Range Embayment, Patterson Pass received greater sedimentary input. This further suggests the accommodation space was greater along the southern margin of the House Range Embayment. This supports the presence of the down-NW or down-N fault proposed by Rees (1986). The presence of possible hemipelagic deposits to the northwest and west of the House Range Embayment, which were diagenetically altered to chert beds (Steward and Suczek, 1977), suggests the presence of a continental slope, parallel to the marginal fault, somewhere in central or northwestern Nevada. Both features are also parallel to a spreading center believed to have been somewhere present-day northwest (Sears and Price, 2003). Finally, there is possible evidence for a fracture zone on each side of the spreading center, which would have extended along the present-day northeastern and southwestern margins of the outer detrital belt (Sears and Price, 2003).

Therefore, a new interpretation is advanced for the western portion of the House Range Embayment (Fig. 25): A fault-controlled sedimentary trough was filled in such a way that the general water depth of the embayment varied little over the area of the western half of the
embayment in the time-period covered in this study, with perhaps slightly greater depth at
Connors Pass. The thicker shales observed nearer the southern margin of the embayment in
eastern Nevada are interpreted as a function of greater terrigenous sediment supply and
accommodation space rather than water depth.

![Figure 25](image)

**Figure 25.** Schematic isometric view of the structure of the House Range Embayment. Note that the eastern half of the embayment (left), represented by the Wheeler Formation, is shallower than the western half of the Embayment. Note the presence of a roll-over anticline in this model, which would have emulated a continental slope, and created the soft-sediment deformation associated with the embayment (direction marked with red arrows). The current flow itself either followed the direction of soft sediment deformation, as in the Middle Limestone Member, or along the embayment (direction marked with green arrows).

Deposition of the Upper Shale Member of the Lincoln Peak Formation in the area of
Schell Creek Range, when the rest of the original area of the House Range Embayment had filled
in indicates that subsidence continued there and to the areas west of the Schell Creek Range at a
rate sufficient to create accommodation space suited for the deposition of Type B Rhythmites.
As with the Lower Shale Member, The Upper Shale Member of the Lincoln Peak Formation is
thickest at Patterson Pass (Member B of the Emigrant Springs Formation; Kellogg, 1963).
Because the lithology and general stratigraphy at Connors Pass and Patterson Pass are similar, save for greater metamorphism at Connors Pass, the fault that created the House Range Embayment likely was still active after the House Range Embayment had been filled in Utah. Complete infilling of the western half of the embayment is interpreted as having taken place only at the end of the Aphelaspis biozone (i.e. Upper Cambrian).

Isopachous maps of the region created in the 1970s (Stewart and Suczek, 1977) showed that the thickest outer detrital belt deposits were around Patterson Pass, and near the Utah-Nevada Border (Fig. 26). These form a belt of thick deposits, which starts more or less parallel to the southern margin of the House Range Embayment, then curves northwest. When combined with the truncation of the Embayment to the southwest and northeast, this creates a rectangular shaped region around 400 km wide from southwest to northeast (Fig. 26). Each side was flanked by possible fracture zones. Therefore, a new interpretation is presented here, for the creation of the House Range Embayment. As with Rees’ (1986) model, the origin of the House Range Embayment can be found in the breakup of the Supercontinent of Pannotia. This would have created a spreading center, which ran present-day northeast from eastern California to present-day Oregon. A fracture zone then developed on either side of the spreading center (Sears and Price, 2003). The spreading center would have created oceanic crust, which on cooling subsided. That would cause isostatic rebound of the Laurentian plate along the present-day southern margin of the House Range Embayment, due to its lower density relative to oceanic crust. The result was the creation of a listric fault, parallel to the spreading center, down to the NW (Fig. 26). A roll-over anticline in the hanging wall is here proposed, which could simulate an opposing continental slope. As water depth was greatest to the southwest, and the thickest outer-detrital-
belt deposits are in eastern Nevada, it seems the fault may have had the greatest displacement there, which in turn created the greatest accommodation space.

The rapid infilling of the House Range Embayment in the present Wendover area, where it temporarily abutted the inner detrital belt, indicates that the least displacement of the marginal fault was there. This geometry explains in part why the basin filled from the east and north, i.e., sediment supply was greatest to the east and north, and this combined with the lower accommodation space and shallow local bathymetry to rapidly fill that part of the basin first. This also explains why the marginal fault appears to cease activity there at the end of the *Bolaspidella* biozone. The greatest vertical displacement and greatest rate of creation of accommodation space were achieved early in the embayment’s history. Once the rate of vertical displacement declined, the rate of deposition began to exceed the rate of creation of accommodation space.

Flooding of the western House Range Embayment during deposition of the Upper Shale Member of the Lincoln Peak Formation can be attributed to a reactivation of the marginal listric fault in eastern Nevada. This would have led to the continued movement of the hanging wall block away from the trough (Fig. 27). This would cause localized isostatic rebound of the carbonate platform, but not of areas north of the trough. The result would be creation of more accommodation space in the trough itself. As the Antler and Sevier orogenies severely affected the area between the end of the House Range Embayment and the creation of the Basin and Range Province, it is possible that some of the original normal faulting might have been “pushed back” or otherwise rotated. This could make the remains of the faults appear to be thrust faults, an idea espoused by Rees (1986) in her paper describing the House Range Embayment.
The infilling of the embayment itself, based on biostratigraphic data from all units in this study, would have occurred over a period of ~12 MA, from just before the start of the Drumian Stage to the end of the Paibian Stage of the Cambrian. Specifically, the House Range Embayment in western Nevada was filled in first, during the middle Drumian Stage (~502 MA). Initial infilling of the embayment in eastern Nevada occurred by the end of Guzhangian Stage (~497 MA), and is represented by the deposition of the Middle Limestone Member. This did not affect the embayment in the White Pine and Grant Ranges in the westernmost embayment. This infilling was followed by a second transgression of the embayment, which led to deposition of the Upper Shale Member of the Lincoln Peak Formation in Nevada. The embayment was then filled in for the second, and final time, no later than the end of the Paibian Stage (~494 MA) (Drewes and Palmer, 1957; McCollum and Miller, 1991; Langenberg (2003); Halgedahl et al, 2009; ICS, 2017).

Further research is required to better understand the House Range Embayment, and its context in the geography of the Cambrian Period. Further exploration of known outcrops should be undertaken, both in the sites used in this study (Connors Pass, Cooper Canyon, Patterson Pass), and remaining outcrops of the Lincoln Peak Formation (Grant and White Pine Ranges, the type locale, Cleve Creek Baldy). New work is needed on the suspected hemipelagic and pelagic deposits to the west and northwest of the embayment, especially exposures in the Shoshone Range, which can be dated due to the recorded presence of volcanic ash (Stewart and Suczek, 1977).
Figure 26. Non-palinspastic reconstruction of the environments of the House Range Embayment, and the extensional basin which contained it. The location of the putative fault which created the embayment is marked by a bold, thick red line. The isopachous lines (1,500 m thick), represent the distribution of the thickest sediment deposits associated with the embayment. Transform faults to the southwest offset the fault there. Possible hemipelagic/pelagic sediments are present to the west and northwest of the embayment, and possible small islands were present in present-day eastern California. The spreading center would have been off the map, to the northwest. Basin map and isopachous data modified from Stewart and Suczek (1977), with modifications based on Palmer and Hazzard (1956), and Osleger et al. (1996).
Figure 27. A possible model for the development of the House Range Embayment. A. Situation at the end of the Lower Shale Member of the Lincoln Peak Formation. B. Situation at the start of the deposition of the Upper Shale Member of the Lincoln Peak Formation.
6. Summary

1) The lower two members of the Lincoln Peak Formation represent at least three 3<sup>rd</sup>-order sequences, with the lower two sequences equivalent to the two 3<sup>rd</sup>-order sequences observed in the Wheeler Formation. Meter-scale packages in the Middle Limestone Member of the Lincoln Peak Formation represent small-scale changes in sea level which affected comparatively shallow bodies of water. The lack of observed meter-scale packages in the Lower Shale Member is related to the greater depth at which it was deposited compared to the Wheeler Formation.

2) The western House Range Embayment underwent sediment starvation, which created the condensed section at Connors Pass in the Schell Creek Range of Nevada. The sediment starvation was a combination of greater depth and greater distance from sediment supply. Sediment supply likely came from present-day east, with the mud which created the Paper Shale likely from the inner detrital belt, and the carbonates from the growing carbonate platform from the present-day east. Input from carbonate ramps from the south likely only became important during the deposition of the Middle Limestone Member, and during the deposition of the Upper Shale Member. Lack of current data prior to the Middle Limestone Member Formation is likely a reflection of deposition of most of the formation either by marine snow (shale), or turbidity currents (calcisiltite), below wave-base depth.

3) Initial infilling of the basin was likely a partial result of the growth of the carbonate belt, which first grew westward into the shallowest parts of the House Range Embayment, then extended southward to fill the embayment trough locally. The infilling was mostly through
the action of turbidity currents, which created the two Rhythmite Facies that dominate the Lower and Upper Shale Members of the Lincoln Peak Formation.

4) Deposits in distal basin environments reflect in a subdued manner the sequence stratigraphy of proximal basin deposits. These condensed distal deposits can also obscure “missed beats” found in shallower settings, but only during IHST. At Connors Pass, most recognizable meter-scale cycles are in the Middle Limestone Member of the Lincoln Peak Formation, coeval to the Upper Marjum Formation and Lower Weeks Limestone. A similar set of meter-scale cycles lies at the top of the Upper Shale Member of the Lincoln Peak Formation at Cooper Canyon, and the Upper Shale Member of the Lincoln Peak Formation in the Snake Range (Drewes and Palmer, 1957).

5) The bathymetry of the House Range Embayment was rather uniform in eastern Nevada throughout the Middle Cambrian, unlike bathymetries in western Utah.

6) A listric fault probably created the House Range Embayment, and it remained partially active through the end of the Aphelaspis biozone. This fault likely resulted from the creation of a spreading center northwest of the House Range Embayment, formed when Laurentia split from the rest of Pannotia. The greatest displacement appears to have occurred along its present-day southwestern portion in Nevada.

7) The House Range Embayment is a northeast-trending sedimentary trough, which is part of a larger, presently northwest-trending rectangular-shaped extensional basin. The southwestern and northeastern boundaries of this basin perhaps were fracture zones related to a spreading center to the northwest (Sears and Price, 2003). This spreading center was likely related to the volcanism which created the coeval ash deposits found in the Shoshone Range.
8) The Lincoln Peak Formation is correlative with both the Patterson Pass Shale, and almost all of the Emigrant Springs Limestone described by Kellogg (1963), based on their similar lithologies, coeval fossils, and geographic proximity (e.g., Connors Pass and Patterson Pass are both in the Schell Creek Range). Both units can be treated as part of a continuous stratigraphic unit deposited within a distinct geographic sedimentary trough that extended beyond eastern Nevada. Therefore, Patterson Pass Shale should be dropped as a name, and all exposures of it should be referred to the Lincoln Peak Formation.
7. References


8. Appendix

**Figure A-1.** A thin section (50 μm thick) of the Thick-bedded Limestone Facies. The original fabric has been metamorphosed, which has created small rhomboid crystals. A vein of diagenetic calcite is visible in the center of the image. The darker bands are slightly more argillaceous than the lighter areas. Top is up-section.
Figure A-2. A thin section (50 μm thick) of Ribbon Limestone, from just below the base of the Lincoln Peak Formation. The gray micritic laminae are fossiliferous, with an unidentified fossil pictured here. Silty dolomite laminae (top) preserve peloids, and are hematite stained. Top is up-section.
Figure A-3. A thin section (50 μm thick) of the Paper Shale at the base of the Lincoln Peak Formation. Part of a possible eocrinoid stalk is in the center of the image, with an unidentified fossil to the stalk’s bottom-left. View is from above the bedding surface.
Figure A-4. A thin section (20 μm thick) from the same Paper Shale as in Figure A-3, which shows distinct laminae. The matrix and grains do not exhibit a uniform orientation, though they still form laminae. A calcite vein is present in the bottom left of the image. Top is up-section.
Figure A-5. A thin section (50 μm thick) of a packet of Type A Rhythmite Facies, collected 12 m above the base of the Lincoln Peak Formation. The calcisiltite is recrystallized, but peloids stained red with hematite are still visible. These become scarcer up-section, as the packet grades upward into shale. The top of this image shows the base of a second packet, which displays abundant peloids. Top is up-section.
Figure A-6. A thin section (50 μm thick) of Type B rhythmite, ~10 meters below the base of the Middle Limestone Member. The laminae are rippled, as can be seen just below the contact between the silty dolomite (bottom) and calcisiltite (top). Recrystallization has produced rhombic crystals of calcite in the calcisiltite. Top is up-section.
Figure A-7. A thin section (50 μm thick) of the Limestone and Shale Facies, forms part of the Middle Limestone Member of the Lincoln Peak Formation. Darker grains are altered terrigenous mud and calcite, while the lighter portions are predominantly composed of calcite, which has recrystallized into rhombic crystals. Laminae are faintly visible. Top is up-section.
Figure A-8. A thin section (50 μm thick) of Paper Shale Facies from 3 m above the base of the Upper Shale Member of the Lincoln Peak Formation. Grains are aligned along the bedding plane. Two fracture fills in the middle of the figure are composed of rhombic calcite crystals, and were likely formed during diagenesis. Top is up-section.