

INTEGRATED SEQUENCE STRATIGRAPHY AND PALEOBIOLOGY OF THE
ELLIS GROUP OF MONTANA: IMPLICATIONS FOR THE HISTORY AND
COMMUNITIES OF THE SUNDANCE SEAWAY

by

SIERRA KRISTINE SWENSON

(Under the Direction of Steven Holland)

ABSTRACT

Few studies have quantitatively demonstrated the effects of large-scale environmental gradients on the fauna of ancient epicontinental seas. Here, quantitative abundance estimates integrated with a sequence-stratigraphic framework for the Jurassic Sundance Seaway are used to compare communities in the southern part of the seaway to those in the north. In central Montana, the history of the Sundance Seaway is preserved by the Piper, Rierdon and Swift formations of the Ellis Group. The Ellis Group contains five depositional sequences with four facies associations. The J-1 sequence preserves desert depositional environments, the J-1a, J-2, and J-3 sequences preserve carbonate depositional environments, and the J-4 sequence preserves siliciclastic, wave-dominated shelf and tide-dominated coastal depositional environments. The marine communities in central Montana are distinct from those in the same depositional environment in Wyoming and ordination of fossil occurrence data suggests these differences reflect latitudinal gradients such as temperature and salinity in the seaway.

INDEX WORDS: Ellis Group, Sundance Seaway, sequence stratigraphy, Jurassic, epicontinental sea, fossils, mixed siliciclastic-carbonate system

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DEDICATION

This thesis is dedicated to my family and friends, for their endless support and to Matt Hess who has been by my side since day one.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

The first and third chapter of this thesis will provide introductory and concluding remarks. The second chapter of this thesis was written to be read as a stand-alone manuscript written for submission to the journal *PALAIOS*. It includes an introduction, geologic background, methods, results, discussion, and conclusions. This first chapter provides a more general introduction, and the third chapter is a conclusion to the research project as a whole.

The first purpose of this study is to create a sequence-stratigraphic framework for the Jurassic Ellis Group of central Montana and correlate it to an existing sequence-stratigraphic framework for age equivalent rocks in Wyoming. This correlation creates a more complete picture of the sequence stratigraphy of the Jurassic Sundance Seaway. This paper establishes a direct connection between the depositional sequences and facies described in Wyoming and those found in central Montana.

The second purpose of this study is to determine in what ways marine fossil communities differ between the northern and southern parts of the Sundance Seaway and why by comparing data sets from Montana and Wyoming. An ordination using Montana and Wyoming samples shows departures between the two regions. These variations are presumed to be caused by the introduction of new species in the northern part of the basin, and they are best explained by latitudinal gradients such as salinity and temperature along the length of the Sundance Seaway.

Previous studies have been conducted on the lithostratigraphy and facies of the Ellis Group in the study area (Cobban 1945; Cobban et al. 1945; Gardner et al. 1946; Rayl 1956; Peterson 1957); but they are more than half a century old. Only one study has used a sequence-stratigraphic approach (Parcell and Williams 2005) and it mostly covers only the lower half of the Ellis Group. Similarly, although previous studies have described fossils of the Ellis Group in Montana (Imlay 1947, 1956, 1957; Lalicker 1950), none have analyzed paleocommunity structure or its relationship to depositional environments or sequences.

Several appendices provide supporting data or code. Appendix A contains a photo catalogue of the fossils described from the Ellis Group. Appendix B contains a table of taxa that were found in the Ellis Group but not included in the abundance data for the NMS because they could not be associated with a sample. Appendix C contains the taxon codes for the taxa included in the NMS. Appendix D contains the R code for the NMS and subsequent plots. Appendix E contains the abundance data for taxa found in the Ellis Group. Appendix F contains the sample properties for each fossil sample from the Ellis Group.

CHAPTER 2

INTEGRATED SEQUENCE STRATIGRAPHY AND PALEOBIOLOGY OF THE
ELLIS GROUP OF MONTANA: IMPLICATIONS FOR THE HISTORY AND
COMMUNITIES OF THE SUNDANCE SEAWAY ¹

¹ Swenson, S.K. and S.M. Holland. To be submitted to *PALAIOS*.

ABSTRACT

Ancient epicontinental seas are a widely studied geologic environment, but few studies have quantitatively demonstrated the effects of large-scale environmental gradients on the fauna of these seas beyond gradients related to water depth. Here I use quantitative abundance estimates integrated with a sequence-stratigraphic framework for the Jurassic Sundance Seaway to compare benthic communities in the southern Sundance Seaway to those in the northern Sundance Seaway. In central Montana, the history of the Sundance Seaway is preserved by the Piper, Rierdon and Swift formations of the Ellis Group, which contains abundant and diverse invertebrate fossil assemblages. The Ellis Group consists of four depositional environments: desert, carbonate ramp, siliciclastic wave-dominated coast, and tide-dominated coast. Within the Ellis Group there are five third-order depositional sequences. These facies and depositional sequences correspond to those described from Wyoming. Multivariate analysis shows that the invertebrate communities in the Ellis Group differ from those in Wyoming. Assemblages from Wyoming and from Montana show strong ties to water depth and age, but the Montana samples separate from the Wyoming samples along latitude. This is likely tied to gradients such as temperature and salinity in the Sundance Seaway: communities to the north, closer to the mouth of the seaway, would have experienced cooler and more normal salinity water. This pattern suggests that latitudinal gradients play an important role in community structure in shallow, epicontinental seas, and that these relationships can be observed using quantitative paleobiology within a sequence-stratigraphic framework.

INTRODUCTION

Although epicontinental seas are widespread in the geologic record, much remains to be learned about their environmental dynamics and faunal distribution patterns. Sequence stratigraphy is increasingly used in studies of ancient epicontinental sea communities to establish large-scale faunal patterns (e.g. Scarponi and Kowalewski 2004, Dominici and Kowalke 2007, Tomašových et al. 2014). The effects of factors such as temperature and salinity along a latitudinal gradient are especially significant in shallow epicontinental seas (Reynolds 1993; Russo and Artegiani 1996; Kaempf and Sadrasab 2006), but studies lacking stratigraphic context do not have the scope to address them, because they do not account for the effect of a laterally changing environment. A sequence-stratigraphic approach is necessary to isolate changes in communities caused by shifts in latitudinal gradients from changes caused by shifts in depositional environment (Patzkowsky and Holland 2012).

In this study, I present evidence for environmental gradients within the Sundance Seaway, a Middle to Late Jurassic epicontinental sea in the western United States. This study extends previous studies of Jurassic stratigraphy and paleoecology in Utah and Wyoming (Parcell and Williams 2005; McMullen et al. 2014; Clement and Holland 2016; Danise and Holland 2017, 2018) into the Ellis Group of central Montana. To isolate the effect of environmental gradients on marine communities within the seaway, I present a sequence-stratigraphic framework for the Ellis Group and correlate it with previous studies to the south (McMullen et al. 2014; Clement and Holland 2016; Danise and Holland 2017, 2018). These results support an increase in diversity in the northern part of the seaway, with larger and more open-marine fauna, owing to the proximity of

the sites to the mouth of the seaway compared with more interior regions of Utah and Wyoming.

GEOLOGIC CONTEXT

Tectonic and Paleogeographic Setting

The Sundance Seaway was an epicontinental sea that extended from the Northwest Territories of Canada to southern Utah during the Middle to Upper Jurassic (~170–155 Ma; Fig. 1; Imlay 1980; Blakey 2014). It formed in a retroarc foreland basin in the Bajocian (Brenner and Peterson 1994; Lawton 1994; Bjerrum and Dorsey 1995; Fuentes et al. 2011), and it remained a shallow, epicontinental sea until the late Oxfordian, when it was subsequently filled by the prograding Morrison coastal plain (Peterson 1994; DeCelles 2004). The foredeep of the basin was in western Wyoming and eastern Idaho, with the fold and thrust belt to the west (Brenner and Peterson 1994; Lawton 1994; Bjerrum and Dorsey 1995; Fuentes et al. 2011). The Ellis Group was deposited on ramp to the east of the foredeep (DeCelles 2004), and depositional environments along the seaway range from offshore to sabkha (Brenner and Davies 1974; Parcell and Williams 2005; McMullen et al. 2014; Clement and Holland 2016; Danise and Holland 2018). Throughout the history of the seaway, central Montana drifted northward out of arid climates and into cooler and more humid latitudes (Kocurek and Dott 1983; Saleeby and Busby-Spera 1992; Beck and Housen 2003; Blakey 2014). This shift is linked to the shift from a carbonate-evaporite system to a siliciclastic system in the earliest Oxfordian (Danise and Holland 2018).

Stratigraphy

In central Montana, the marine Jurassic is represented by the Ellis Group, which consists of the Piper, Sawtooth, Rierdon, and Swift formations (Fig. 2; Peale 1893; Cobban 1945; Cobban et al. 1945; Rayl 1956). These units correlate to the Gypsum Spring and Sundance Formations of Wyoming and South Dakota (Imlay 1952, 1956). The Ellis Group was originally described by Peale (1893), and the majority of Ellis Group studies were conducted in the 1940s and 1950s, including the designation of the type section (Cobban 1945; Cobban et al. 1945; Gardner et al. 1946; Imlay 1947, 1956, 1957; Lalicker 1950; Peterson 1957; Rayl 1956). These previous studies focused mainly on lithostratigraphy and biostratigraphy, and they all predate the origination of sequence stratigraphy, although some modern studies provide a framework for sequence-stratigraphic work (Pipiringos and O'Sullivan 1978; Parcell and Williams 2005). In addition, recently completed sequence stratigraphy in studies of the Gypsum Spring and Sundance Formations of Wyoming (McMullen et al 2014; Clement and Holland 2016; Danise and Holland 2017, 2018) provide key insights into the sequence stratigraphy of the Ellis Group.

The Bajocian to Bathonian Piper Formation is the lowermost member of the Ellis Group and consists of basal gypsum and red beds, a middle carbonate and shale unit, and an upper red bed unit (Cobban 1945; Gardner et al. 1946; Rayl 1956; Peterson 1957). The laterally equivalent Sawtooth Formation consists of sandstone, shale, and thin beds of limestone (Cobban 1945; Peterson 1957). The name change reflects the shift in lithology between the area southeast of the Sweetgrass arch of Montana (Piper) and the area to the northwest along the Sawtooth Range (Sawtooth; Peterson 1957). Both formations are

interpreted to overlie the regional J-2 erosional unconformity, characterized by the presence of chert pebbles and truncation of the underlying Bajocian Nesson Formation in the subsurface north of the study area (Pipiringos and O'Sullivan 1978).

The Bathonian to Callovian Rierdon Formation is interpreted to lie conformably on the Piper Formation (Cobban 1945; Rayl 1956; Pipiringos and O'Sullivan 1978). It consists mostly of carbonate shale and is capped by sandstone. The boundary between the Rierdon Formation and the overlying Swift Formation is inferred to be the J-4 unconformity (Pipiringos and O'Sullivan 1978), marked by truncation of the Rierdon Formation, the first appearance of belemnites, and an abrupt shift from carbonate to siliciclastic sediment (Pipiringos and O'Sullivan 1978).

The Oxfordian Swift Formation consists of a lower shale unit and an upper succession of glauconitic sandstone. The boundary between the Swift Formation and the overlying Morrison Formation is inferred to be the J-5 unconformity, which is visible elsewhere in the Western Interior (Pipiringos and O'Sullivan 1978). However, it has been noted that little evidence of erosion is present between the Swift Formation and Morrison Formation in Montana and Wyoming (Pipiringos and O'Sullivan 1978; Danise and Holland 2018).

Although the Ellis Group has never been placed in a regional sequence-stratigraphic context, the lower portion of it has been interpreted as transgressive and regressive cycles (Parcell and Williams 2005). Two cycles of transgression and regression were identified in the Piper Formation of the Ellis Group. Transgressive portions of these cycles are characterized by upward deepening peritidal to subtidal facies, while regressive portions contain upward shallowing supratidal and red bed facies.

The Bajocian cycle is inferred to be restricted marine, whereas the second cycle, which spans the Bajocian-Bathonian boundary, contains a wider range of facies, including more open-marine deposits. Three unconformities were recognized by Parcell and Williams (2005): one at the base of the Piper Formation, one between the two transgressive-regressive cycles, and one at the boundary between the Piper Formation and the overlying Rierdon Formation.

This interpretation of Parcell and Williams (2005) is partly consistent with interpretations of the Sundance Seaway in Wyoming (Clement and Holland 2016; Danise and Holland 2018). In a study of the Gypsum Spring Formation, the Wyoming equivalent to the Piper Formation, three depositional sequences and four sequence boundaries were identified, the J-1, J-1a, J-1b and J-2 (Clement and Holland 2016). The J-1 and J-1a each record transgression in the transgressive systems tract (TST) and regression in the highstand systems tract (HST), similar to the cycles identified by Parcell and Williams (2005), although Parcell and Williams (2005) did not identify the J-1b sequence boundary in the upper Gypsum Spring Formation, only the J-1, J-1a, and J-2.

Paleontology

The Ellis Group contains abundant and diverse marine invertebrate fossils (Cobban 1945; Imlay 1947, 1957, 1980; Lalicker 1950), and each formation in the Ellis Group has a characteristic fossil assemblage. The Sawtooth and Piper formations are dominated by bivalves, but also include gastropods, cephalopods, and corals (Cobban 1945; Imlay 1947, 1956, 1980). The Rierdon Formation fauna is more diverse, with ammonites, pelecypods, naticoid gastropods, and abundant microfossils such as

foraminifera and ostracods (Cobban 1945; Imlay 1947, 1956, 1980). In the Swift Formation, belemnites and ammonites are common, with rare corals (Cobban 1945; Imlay 1947, 1956, 1980).

The biostratigraphy of the Ellis Group is tied to ammonite zones and named for the characteristic ammonite of each zone (Imlay 1947, 1953). The Piper Formation is characterized by the *Defonticeras-Stemmatoceras* zone and the *Arctocephalites* zone (Imlay 1947). The Rierdon Formation is divided into the *Arcticoceras* zone, the *Gowericeras subitem* zone, the *Kepplerites* cf. *K. tychonis* zone, and the *Kepplerlites mclearni* zone (Imlay 1947). The Swift Formation is divided into the *Quenstedtoceras collieri* zone, the *Cardioceras cordiforme* zone, and the *Cardioceras* spp. zone (Imlay 1947). Ammonites from the Rierdon and Swift formations have been noted to reach a size of up to one foot in diameter (Imlay 1947).

In comparison with the Ellis Group, fossil communities in Wyoming and Utah are depauperate, and a single species usually dominates any given assemblage (McMullen et al. 2014; Danise and Holland 2017). Ammonites in Wyoming are rare (Danise and Holland 2017) and usually small (typically < 4 cm in diameter; personal communication, S. Danise and S. Holland 2019). The depauperate assemblages of the seaway have led to the hypothesis that the seaway was subject to strong axial gradients in salinity and temperature, suggesting that more normal marine conditions would exist northward in the seaway (Stanley 2010; Danise and Holland 2018).

METHODS

Field Data

Field data was collected over four weeks in central Montana, from July 7 to August 6, 2018. I measured fifteen stratigraphic columns along an east–west transect in the foothills of the Little Rocky Mountains, Big Snowy Mountains, and Little Belt Mountains of Montana (Table 1, 2; Fig. 3). Permissions for land use were obtained from the Bureau of Land Management (BLM) and the Forest Service for outcrops that fell on public land, and from private land owners. Outcrops were identified using localities reported previously (Cobban 1945; Gardner 1946; Imlay 1956; Brenner and Davies 1973; Brenner and Davies 1974; Pipiringos and O’Sullivan 1978; Lippert 1983; Parcell and Williams 2005) as well as outcrop maps of the Ellis Group provided by the BLM and the assistance of Jim Mitchell and Larry Eichhorn. Stratigraphic columns were measured using a Brunton compass and a Jacob staff. Lithologic features of each unit were recorded, including sedimentary structures, bedding, diagenetic minerals, grain size, and bioturbation.

I sampled for fossil data in a one square-meter grid where lithology allowed and on available slabs. On each grid or slab, counts of the abundance of species were made and, where possible, standard practices were used to determine the minimum number of individuals of each species (see Patzkowsky and Holland 2012). Taxa were identified to the lowest taxonomic level possible using previous identifications of Jurassic marine taxa of the western interior (Imlay 1947, 1953, 1957, 1980, McMullen et al. 2014; Danise and Holland 2017). Photos of fossil samples and lithologic features were taken in the field using an iPhone 8 Plus and a Lumix Lx100 digital camera (Fig. 5–7; Appendix A).

Samples were collected and sent to the University of Georgia for fossil identification. Photos of fossil samples were taken in the lab using a Nikon D3100 digital camera and a Canon Rebel XTi digital camera (Appendix A). The University of Florida Museum of Natural History is the repository for the fossils found on BLM or Forest Service Land.

Correlation

Outcrops of the Ellis Group in central Montana are scarce, incomplete, and often difficult to access, especially when located on private land, owing to difficulties in contacting land owners and obtaining permissions. As a result, outcrop data was used for facies interpretations, and correlation was accomplished mostly with well logs. I purchased the logs from MJ Logs, and using their program LogSleuth, located twelve wells on a north–south transect from my field area to the Bighorn Basin of Wyoming (Table 2; Fig. 3). The formation tops were obtained from the Montana Board of Oil and Gas Conservation (Montana Board of Oil and Gas Conservation 2011).

Quantitative Analysis

Using fossil abundance data, non-metric multidimensional scaling (NMS) was used to examine the controls on fossil occurrence and community structure. NMS and ordination methods in general reduce dimensionality and help determine sources of variation among samples. The NMS analysis in this study incorporates newly collected fossil data from central Montana as well as previously collected data from Wyoming (Danise and Holland 2017) to compare the northern faunas to the southern faunas. The data were culled to remove samples that had fewer than two taxa and taxa that occurred

in fewer than two samples, as these do not aid in establishing relationships among samples. These culled data were percent transformed to equalize the effects of different sample sizes and log transformed to reduce the influence of the most abundant taxa. I ran NMS using the metaMDS() function in the vegan package in R (R Core Team 2018), with a maximum restart of 100, three axes, and calculation of species scores by weighted averaging (Appendix D). Sample scores were coded for lithofacies, rock type, sequence, and region to understand the origin of ordination patterns.

ELLIS GROUP FACIES ASSOCIATIONS

Facies of the Ellis Group are divided here into four depositional systems: the desert of the Piper Formation, the carbonate ramp of the Piper and Rierdon formations, and the wave-dominated siliciclastic shelf and the tide-dominated siliciclastic coast of the Swift Formation (Tables 3–6; Fig. 4). The availability of outcrop for each of these systems was poor, and as a result, these facies associations are strongly tied to previous facies interpretations made in the Gypsum Spring and Sundance formations of Wyoming (McMullen et al. 2014; Clement and Holland 2016; Danise and Holland 2018). All four of the central Montana depositional systems are present in Wyoming, and the descriptions of the Montana facies have not substantially modified any previously described facies.

Desert Facies Associations

The desert facies of the Ellis Group forms much of the Piper Formation and is interrupted only by carbonate ramp deposition in the middle Piper Formation. Because of

outcrop availability, these facies are described from only two localities: Allied Steel and Burleigh Ranch (Fig. 3). There are three desert facies associations: desert mudflat (P1), sabkha (P2), and salina (P3; Table 3; Fig. 4B).

A structureless brown to gray siltstone facies with anastomosing, subhorizontal veins of gypsum makes up the mudflat association (P1; Table 3), suggesting deposition on an evaporitic mudflat (Handford 1981; Warren 2006). The gypsum nodules found in this facies are small (3–7 cm) and rare, and the veins are thin (1–3 cm), indicating periods of saturation (Kendall and Harwood 1996; Kendall 2010), most likely by continental brines (Clement and Holland 2016). The mudflat facies association has gradational contacts with the overlying and underlying sabkha association indicating a lateral facies relationship.

Red to gray siltstone facies that are distinguished from the mudflat association by planar lamination, large gypsum nodules, and subvertical veins of gypsum make up the sabkha association (P2; Table 3; Fig. 5). The presence of mosaic gypsum and larger gypsum nodules in this facies suggests a sabkha environment with continental brine infiltration (Warren and Kendall 1985; Kendall 2010; Clement and Holland 2016). The crinkly lamination in this facies suggests microbial mats may have grown on the sabkha (Fryberger et al. 1983; Goodall et al. 2000). This association has a lateral relationship with the mudflat association, and the two are distinguished by their color, gypsum morphology, and the presence of lamination.

A coarsely crystalline, massive gypsum facies, which suggests deposition in intermittent to perennial saline ponds (Kendall 2010), makes up the salina association (P3; Table 3). In Montana, this association was observed in outcrop only at Allied Steel.

It is not laterally continuous and thins over approximately 900 m into the paleosol facies (C6; Table 4). It has a sharp lower boundary with the peritidal association (C5; Table 4) and a sharp upper contact with the restricted shallow subtidal association (C4; Table 4).

Carbonate Ramp Facies Associations

The carbonate ramp facies associations of the Ellis Group are found within the Rierdon Formation and the middle Piper Formation. There are six carbonate ramp facies associations: deep subtidal (C1), open shallow subtidal (C2), ooid shoal (C3), restricted shallow subtidal (C4), peritidal (C5), and a paleosol (C6; Table 4; Fig. 4B).

A laminated lime mudstone to wackestone facies makes up the deep subtidal facies association (C1; Table 4) and was observed only in the Rierdon Formation in the northernmost part of the study area in the Little Rocky Mountains. The lack of physical sedimentary structures suggests minimal waves and currents, while the lack of pervasive bioturbation suggests deeper-water carbonate facies devoid of storm influence (Burchette and Wright 1992). This association contains a diverse fossil assemblage including the ammonite *Kepplerites mclearnii*, columnals of the crinoid *Isocrinus knighti*, and the bivalve *Astarte meeki*, which have all been previously described from deeper-water environments (Cobban 1945; Imlay 1947, 1957; Danise and Holland 2017), in particular muddy sand and calcarenite environments in the deep-subtidal (McKerrow 1978). This diversity is also suggestive of a deep-water carbonate ramp environment (Read 1985). The relationship of the deep-subtidal facies association to other carbonate associations in the Ellis Group is unclear, as it was observed in isolation in the Rierdon Formation. It is

unconformably overlain by siliciclastic offshore mudstone at Schwanky Lot (Fig. 3), the only location where the contact with the Swift Formation is exposed.

A gray wackestone to packstone facies makes up the open shallow subtidal facies association (C2; Table 4) and was observed only in the middle Piper Formation. It contains abundant skeletal grains and shell beds of the bivalves *Isognomon* and *Liostrea strigulecula*, which have been previously described from open shallow subtidal environments in the Sundance Seaway (Cobban et al. 1945; Imlay 1947, 1957; Danise and Holland 2017), and they are more broadly associated with muddy lime sand environments in the Jurassic such as the open shallow subtidal (McKerrow 1978). Abundant shell beds are interpreted as storm beds and indicate the system was open marine (Burchette and Wright 1992). The open shallow subtidal association has a sharp lower boundary with the restricted shallow subtidal association (C4; Table 4) and a gradational upper boundary with the peritidal association (C5; Table 4).

A skeletal ooid grainstone facies makes up the ooid shoal facies association (C3; Table 4) and was observed only in the middle Piper Formation at Burleigh Ranch (Fig. 3). This association contains shell beds of the bivalves *Isognomon* and *Liostrea strigulecula*, indicating similar conditions to the open shallow subtidal association (Fig. 5; McKerrow 1978). The thickness of the ooid unit (~1 m) and lack of sedimentary structures suggest deposition on an ooid shoal (Simone 1980; Burchette et al. 1990), and this laterally discontinuous facies is consistent with modern observations of laterally discontinuous shoals (Purser 1973). This association occurs in the same stratigraphic unit as the open shallow subtidal facies association of the neighboring Allied Steel locality (Fig. 3), indicating a lateral facies relationship. It shares a sharp lower contact with the

peritidal association and a gradational upper contact with the restricted shallow subtidal association.

A gray, unfossiliferous lime mudstone facies makes up the restricted shallow subtidal facies association (C4; Table 4) and was observed only in the middle Piper Formation. This association contains wavy to crinkly cryptalgal lamination, indicating an intertidal setting (James 1979). Syneresis cracks, which are subaqueous cracks caused by changes in salinity, indicate variability in salinity in this association, suggesting deposition on a tidal flat (Fig. 5; Burst 1965; Plummer and Gostin 1981). The lack of bioturbation indicates high salinity in this environment as well (James 1979; Ekdale 1988). Iron staining and hematite nodules are common in these facies, indicative of an oxic marine environment (Maynard 1982; Thomson et al. 1993). The restricted shallow subtidal association has sharp lower contacts with the peritidal association and the paleosol association, gradational lower contacts with the ooid shoal association, gradational upper contacts with the peritidal association, and sharp upper contacts with the open shallow subtidal facies and paleosol association.

An argillaceous, laminated lime mudstone facies makes up the peritidal facies association (C5; Table 4) and was observed only in the middle Piper Formation (Fig. 5). The argillaceous nature of this association, its very thin beds, high clay content, and cryptalgal lamination, suggest a tidal flat environment (James 1979; Pratt 2010). The sheet-like nature of the cryptalgal lamination indicates intertidal deposition in an arid environment (Read 1985). This association has gradational lower contacts with the open shallow subtidal association and restricted shallow subtidal association, sharp lower contacts with the sabkha association, and gradational upper contacts with the ooid shoal

association and restricted shallow subtidal facies. These contacts indicate lateral relationships with other carbonate ramp environments, which suggests a peritidal setting for this association. It is distinguished from other mudstone and siltstone facies by its lack of body or trace fossils and its argillaceous nature.

A red and gray mottled siltstone facies composes the paleosol facies association (C6; Table 4) and was observed only in the middle Piper Formation at Burleigh Ranch and Allied Steel. The paleosol is a mottled red and gray color that grades upwards into a band of gray siltstone capped by yellow siltstone (Fig. 6). It is internally structureless except for well-developed horizons that are visible in both exposures (Fig. 6). The paleosol has no visible root traces, trace fossils of other kinds, or body fossils. Using the classification system of Mack et al. (1993), it is interpreted as a gleyed calcisol. Gleyed refers to the mottling of red and gray colors in the lower portion of the paleosol, which indicates periodic saturation and drying (Mack et al. 1993). Calcisol refers to the abundance of calcium carbonate (Mack et al. 1993), determined by the reaction of the paleosol to hydrochloric acid, as well as the presence of carbonate nodules (Fig. 10). The paleosol does not have gradational contacts with any other association. It sharply overlies the peritidal facies and is sharply overlain by the restricted shallow subtidal facies.

Siliciclastic Shelf Facies Associations

Wave-dominated Shelf.—The wave-dominated siliciclastic shelf facies associations are found in the lower Swift Formation of the Ellis Group. This depositional system includes five facies associations reflecting offshore (SW1), shell bed (SW2), offshore transition (SW3) lower shoreface (SW4), and upper shoreface environments

(SW5; Table 5; Fig. 4A). Along with the tide-dominated shelf facies association, the offshore facies of the wave-dominated shelf association are the most widespread.

A homogeneous gray siltstone to mudstone facies makes up the offshore facies association (SW1; Table 5) and occurs in the lower 25 m of the Swift Formation. The fine grain size of this association and its lack of sedimentary structures suggests an offshore, quiet-water environment (Rautman 1975, Johnson 1992). The lack of lamination suggests pervasive bioturbation (Droser and Bottjer 1993). It contains an abundant and diverse fossil assemblage dominated by the belemnite *Pachyteuthis densus*, the bivalve *Gryphaea nebrascensis*, and the oyster *Deltoidium* sp., as well as rare ammonites such as *Cardioceras hyatti*, *Cadoceras* sp., and *Keplerites* (*Gowericeras*) *costicrassum*, which have previously been described from deep-water siliciclastic environments such as the silty clay community (McKerrow 1978). This association sharply overlies the deep subtidal association (C1; Table 4) of the Rierdon Formation.

A fine-grained sandstone facies densely packed with shells composes the shell bed facies association (SW2; Table 5) and is found between the offshore facies and the lower shoreface facies of the Swift Formation. The contact between the offshore facies and the shell bed is gradational at East Fork Reservoir and obscured at all other localities. The beds are very fine-grained sandstone, suggesting a shallower environment than the mudstone and siltstone of the offshore facies (Clifton 2006). They are predominantly monospecific, packed with the oyster *Deltoidium* sp., suggesting a silty clay community (McKerrow 1978). The densely packed nature of the fossils suggests they may represent storm events (Specht and Brenner 1979; Clifton 2006). The shell bed association has a

gradational lower contact with the offshore association and a gradational upper contact with the offshore transition association (SW3; Table 5).

A fine-grained sandstone with common *Ophiomorpha* represents the offshore transition facies association (SW3; Table 5; Fig. 7B), and it is found above the offshore and shell bed facies associations of the Swift Formation. The presence of the trace fossil *Ophiomorpha* indicates a *Skolithos* ichnofacies, which usually suggests deposition in a shallow water environment such as a shoreface, but *Ophiomorpha* can also be found in more distal facies as opportunistic traces associated with storm sedimentation (Pemberton et al. 1992). The fine-grained size of this association suggests deeper-water deposition with little storm activity (Plint 2010). The offshore transition association has a gradational lower contact with the shell bed association (SW2; Table 5) and the offshore association (SW1; Table 5).

A fine- to medium-grained, bioturbated sandstone facies forms the lower shoreface facies association (SW4; Table 5), which is found in the middle Swift Formation, and was observed only at Sapphire Road Cut (Fig. 3). This association shares a gradational upper contact with the upper shoreface and contains glauconite grains indicating a marine environment. The lower shoreface association is heavily bioturbated (ichnofabric index 5; Droser and Bottjer 1986), which obscures all sedimentary structures and suggests deposition on a low energy sandy shoreline (Raaf and van Gelder 1977; Reinson 1979; Pemberton et al. 1992; Clifton 2006). The lack of sedimentary structures, intense bioturbation, and medium to thick bedding distinguish it from the upper shoreface facies. The lower shoreface association has a sharp lower boundary as well as a gradational upper boundary with the upper shoreface association (SW5; Table 5).

A fine- to medium-grained sandstone facies makes up the upper shoreface facies association (SW5; Table 5), which is found in the middle Swift Formation. Glauconite grains indicate a marine environment (Maynard 1982), and large-scale trough cross stratification and vortex ripples are common, indicating an upper shoreface environment (Raaf and van Gelder 1977; Reinson 1979; Clifton 2006). The lack of bioturbation and trace fossils also suggest an upper shoreface environment (Reinson 1979; Pemberton et al. 1992). The upper shoreface association has a gradational lower boundary and a sharp upper boundary with the lower shoreface association.

Tidal Coastline.—The tidal coastline facies associations are found in the upper Swift Formation of the Ellis Group. This depositional system includes two facies associations reflecting tidal bar (TC1) and tidal sand flat (TC2) depositional environments (Table 6; Fig. 4A). The tide-dominated coastal facies are the most widely exposed of any of the facies association groups, owing to their resistance to weathering and tendency to form cliffs and ridges. The transition from wave-dominated facies to tide-dominated facies was not observed in the field, but in well logs the boundary between the lower and upper facies of the Swift Formation appears gradational (Fig. 8). The lack of substantial incision at the base of the Swift Formation in well logs indicates that the upper Swift Formation may represent a tidally modulated shoreface with tidal channels rather than an estuarine environment (Dalrymple and Choi 2007; Dalrymple 2010).

A very fine- to fine-grained sandstone facies makes up the tidal bar facies association (TC1; Table 6). It is a trough cross-stratified sandstone with several sedimentary structures indicating tidal processes. Coupled with other tidal indicators,

common mudstone rip-ups found on the bedding surfaces of this association suggest tidal channels and associated subaqueous bars (Fig. 7; Uhlir et al. 1988). Rare herringbone cross stratification, sigmoidal cross stratification, and reactivation surfaces in this association are consistent with tidal activity (Uhlir et al. 1988; Dalrymple and Choi 2007; Dalrymple 2010). The presence of the trace fossil *Ophiomorpha*, part of the *Skolithos* ichnofacies, is also consistent with a shallow marine environment (Fig. 7; Reinson 1979; Pemberton et al. 1992). The tidal bar facies association has a gradational lower boundary and sharp upper boundary with the tidal sand flat facies (TC2; Table 6).

A planar-laminated, very fine- to fine-grained sandstone facies makes up the tidal sand flat facies association (TC2; Table 6). It is distinct from the tidal bar facies in that it is planar-laminated sandstone indicative of the upper flow regime that commonly occurs at the top of sand flat bars (Dalrymple and Choi 2007; Dalrymple 2010). Current ripple lamination suggests unidirectional flow (Reineck and Singh 1980; Harms et. al. 1982) and common climbing ripples suggest rapid deposition at the edges of the sand flat (Fig. 7; Dalrymple and Choi 2007; Dalrymple 2010). The tidal sand flat and tidal bar associations form distinct parasequences with tidal bars at the base that fine upwards into the tidal sand flat association.

ELLIS GROUP DEPOSITIONAL SEQUENCES

Five depositional sequences are observed in the Ellis Group (Fig. 2). The J-1, J-1a and J-1b lie in the Piper Formation, the J-2 is in the Rierdon Formation and the J-4 is in the Swift Formation. These sequences have been previously described in Wyoming by McMullen et al. (2014), Clement and Holland (2016) and Danise and Holland (2018),

who tied their sequences to the regional unconformities of Pipiringos and O’Sullivan (1978). Outcrop availability in central Montana is not sufficient for regional correlations or sequence-stratigraphic interpretation. Thus, I used well logs on a north–south transect to describe the sequence-stratigraphic patterns of the Ellis Group. This approach allowed me to correlate and interpret the stratigraphy between the field localities in central Montana and the previously described stratigraphy of Wyoming (Table 2; Fig. 3, 8; Clement and Holland 2014; Danise and Holland 2018).

Sequence J-1.—The J-1 sequence unconformably overlies the Mississippian Amsden and Heath Formations (Gardner et al. 1946). This contact is not exposed in the field, but it is marked in well log by a flooding surface characterized by a decrease in radioactivity in several of the logs (Fig. 8A). It is interpreted as a sequence boundary because of the substantial hiatus between the Piper Formation and the underlying formations, as well as the progradational nature of the Piper Formation above the boundary. It may also be a transgressive surface because it is expressed as a flooding surface in well logs (Fig. 8A).

In well logs, the lower Piper Formation exhibits increasing radioactivity and resistivity, interpreted as progradation of desert mud flats (Fig. 8B). Given the sequence boundary at the J-1 unconformity, the progradation in this sequence may indicate that it falls in the highstand systems tract. If the J-1 unconformity is also the transgressive surface, it would be consistent with the highstand systems tract.

Sequence J-1a.— The J-1a sequence of the middle Piper Formation overlies the desert facies associations of the J-1 sequence. In outcrop, the boundary between the J-1 and J-1a is a significant flooding surface characterized by a shift in depositional

environment from desert to carbonate ramp, specifically from sabkha to peritidal facies (Fig. 9). In well log, this surface is recognized by a decrease in radioactivity and increase in resistivity, and these spikes are interpreted as gypsum beds (Fig. 8C). Because this surface represents a major flooding surface, it is interpreted as a coalesced sequence boundary and transgressive surface. This is also indicated by the retrogradational stacking visible above the gypsum interval in well log (Fig. 8D). The retrogradational trend in the well logs indicates this sequence lies within the transgressive systems tract.

Sequence J-1b.—Sequence J-1b lies in the upper Piper Formation. The lower bounding surface of this sequence is interpreted as a sequence boundary, recognized in outcrop by a thick (5 m) paleosol overlain by a paleokarst (Fig. 9). The paleokarst lies in the restricted shallow subtidal facies (Fig. 9). The paleosol and paleokarst represent times of significant subaerial exposure and weathering indicative of a sequence boundary (Kraus and Hasiotis 2006). This surface is represented in several well logs by a spike in resistivity (Fig. 8E). In outcrop, sabkha facies were observed in the J-1b sequence, but in well log the upper Piper Formation shows increasing radioactivity, indicating retrogradational stacking (Fig. 8F). Given the underlying sequence boundary, this suggests the J-1b sequence is in the transgressive systems tract.

Sequence J-2.— The J-2 sequence boundary is inferred to be the contact between the Piper Formation and the Rierdon Formation, consistent with the interpretation of Pipiringos and O’Sullivan (1978). In several of the well logs, this contact is a significant flooding surface, as indicated by the abrupt increase in radioactivity and resistivity (Fig. 8G). This suggests the J-2 unconformity is a transgressive surface merged with a sequence boundary. The majority of the well logs show little to no change in

radioactivity or resistivity in the entire Rierdon Formation (Fig. 8H). This suggests an aggradational trend in the formation. Aggradation can indicate either the highstand or the lowstand systems tract, but given the likelihood of a transgressive surface below, it is most likely that the J-2 sequence is represented by highstand deposits.

Sequence J-2a and J-3.—The J-2a and J-3 sequence boundaries were not observed in the field and cannot be distinguished in well log because of the aggradational nature of the Rierdon Formation. The J-2a sequence was not observed in the field at all, while the J-3 sequence was observed in the upper Rierdon Formation (Fig. 2). This part of the formation consists of deep subtidal carbonates but shows no parasequences or lateral facies relationships. The ammonite *Kepplerites mclearnii* was found in the deep subtidal facies association of the Rierdon Formation, indicating that this part of the Rierdon is Callovian in age (Imley 1947, 1953). Without any facies relationships or well log indicators, it is not possible to place the middle and upper Rierdon Formation in any particular systems tract with confidence.

Sequence J-4.—The J-4 sequence boundary is the boundary between the Rierdon and the Swift formations. In outcrop, this boundary is marked by an abrupt shift from deep subtidal facies to offshore facies, which indicates a significant time interval between the two facies as well as a substantial flooding surface (Fig. 10). The contact is also characterized by iron staining and, locally, by an iron-stained shell bed. A abrupt increase in radioactivity and decrease in resistivity characterizes this contact in well log, and this too is consistent with a significant flooding surface (Fig. 8I). The abrupt deepening and the well-log signature suggest this boundary is also a transgressive surface. The lower Swift Formation preserves a thin transgressive systems tract, with the maximum flooding

surface being recorded in the offshore facies association. In outcrop, most of the Swift Formation shows a progradational trend from offshore facies to tidal sand flat facies (Fig. 11). Steadily decreasing radioactivity and resistivity in several well logs indicate progradation as well (Fig. 8J). Several well logs also show blocks of low radioactivity with sharp bases, suggestive of tidal channels within the Swift Formation (Fig. 8K). The progradational stacking of most of the Swift Formation in outcrop and well log suggest the Swift Formation is largely within the highstand systems tract with the lowest part of the Swift being in the transgressive systems tract.

ELLIS GROUP COMMUNITY ECOLOGY

To understand patterns of community composition in the Sundance Seaway, I ordinated my central Montana fossil collections and previous collections from Wyoming (Danise and Holland 2018). The data set from central Montana is significantly smaller than the data set from Wyoming, and as expected does not change the overall patterns of the original ordination of Danise and Holland (2017). This allows direct comparison of communities in central Montana and Wyoming.

Lithology.— Coding by lithologic system shows that siliciclastic samples generally have higher axis one scores, while carbonates plot intermediately on axis one (Fig. 12A). Most siliciclastic samples have large axis one scores, as well as large axis two scores (Fig. 12A). Carbonate samples all plot near the center of axis one (Fig. 12A). Some siliciclastic samples plot intermediately, near the carbonates, indicating that some siliciclastic communities are more similar to carbonate communities than comparable siliciclastic communities (Fig. 12A). The separation of lithologic systems mostly along

axis one likely reflects the overall transition of the Sundance Seaway from carbonate dominated to siliciclastic through the middle and late Jurassic and it is the strongest environmental gradient present in this study.

Depositional Environment.—Coding by depositional environment, deeper marine environments such as offshore siliciclastic and deep subtidal carbonates have high axis two scores, while shallow environments have intermediate axis two scores (Fig. 12B). Deeper environments also have high to intermediate axis one scores, with siliciclastic offshore samples mostly plotting high on axis one while others plot near the deep subtidal carbonate samples (Fig. 12B). The shallowest environments, the ooid shoal and open shallow subtidal, plot intermediately on both axis one and axis two (Fig. 12B). These patterns suggest that water depth is also expressed on axis one, which is common for ordinations of marine invertebrates (Patzkowsky and Holland 2012). It is unclear from the Montana samples alone whether water depth is expressed on axis two as well, or if that pattern reflects some other characteristic of the samples.

Depositional Sequence.— Coding by depositional sequence, Upper Jurassic sequences such as the J-4 and J-3 have high axis two scores and high to intermediate axis one scores (Fig. 12C). Middle Jurassic samples such as the J-1a sequence have intermediate axis one and axis two scores. These relationships indicate that axis one and axis two express temporal changes in taxonomic composition. Some samples from sequence J-4 and J-3 plot close to each other, suggesting their faunas are similar.

DISCUSSION

Regional Facies Relationships

There are no facies associations in central Montana not previously reported in Wyoming (McMullen et al. 2014; Clement and Holland 2016; Danise and Holland 2018). All central Montana facies associations match well with the facies descriptions from Wyoming. This is to be expected, as the formations in Wyoming and Montana are coeval and should preserve the same environments resulting from the transgressions and regressions of the Sundance Seaway across the landscape of the retroarc foreland basin. In addition, Jurassic outcrop is scarcer in central Montana than in Wyoming, diminishing the chances of observing novel facies associations.

The only facies that appears to be uniquely developed in central Montana is the paleosol facies which is significantly different from what is reported in Wyoming (Clement and Holland 2016; Danise and Holland 2018). The paleosol in central Montana is well-drained whereas the paleosol in Wyoming is poorly drained, which may indicate a longer period of subaerial exposure in central Montana, or a difference in climate between the two regions. The paleosol found in the mudflat-sabkha facies in Wyoming was described as purple to deep maroon (Clement and Holland 2016; Danise and Holland 2018). The paleosol at Burleigh Ranch and Allied Steel in Montana has well-developed horizons with red and gray mottling, a gray horizon in the center, and a yellow horizon at the top (Fig. 6, 9). The deep purple of the Wyoming paleosol indicates that it is poorly drained (Kraus and Hasiotis 2006). The gray mottles and red siltstone of the Montana paleosol indicate a better-drained soil with iron-depleted rhizoliths (Kraus and Hasiotis

2006) while the yellow horizon indicates a higher goethite to iron ratio (Schwertmann and Taylor 1977; Schwertmann 1993).

In contrast, several facies associations in Wyoming were not observed in Montana. The tidal channel association, distal dryland river association, and eolian association were not observed in Montana. There remains a serious lack of outcrop in Montana as compared to the Wyoming outcrop belt, which may have contributed to the perceived absence of these facies. However, tidal channels would weather similarly to the tidal bar facies, so the absence of this facies in Montana is likely not because of outcrop availability or vegetation. They both have lateral facies relationships with multiple facies observed in the field, and their absence in outcrop does not reflect their absence from the wave-dominated shelf and tidal coast environments and these tidal channels are visible in well log (Fig. 8K). The dryland river and eolian facies that were not observed in Montana are desert to terrestrial deposits. This likely reflects the position of the shoreline, which may have been in the southern part of the seaway in Wyoming as the northern Sundance Seaway was more open marine (Imlay 1980; Blakey 2014).

Correlation

Sequence-stratigraphic correlation of the Ellis Group in central Montana to the Gypsum Spring and Sundance formations in Wyoming has not been attempted previously, although past studies have correlated regional unconformities into the Ellis Group (Pipiringos and O'Sullivan 1978). This regional framework based on unconformities has since been reevaluated in the southern part of the Sundance Seaway, in Wyoming (Kvale et al. 2001; McMullen et al. 2014; Clement and Holland 2016;

Danise and Holland 2018). Using the sequence-stratigraphic framework detailed in Danise and Holland (2018) as a baseline, several differences in the Ellis Group between recent works and Pipiringos and O’Sullivan (1978) become clear.

Piper Formation.—The Piper Formation falls into the J-1, J-1a, and J-1b sequences. Although early research placed the Piper Formation above the Wyoming Gypsum Spring Formation, and entirely in the J-2 sequence (Pipiringos and O’Sullivan 1978), it has since been identified as a lateral equivalent of the Gypsum Spring Formation (Parcell and Williams 2005; Clement and Holland 2016). Both consist of lower desert red beds, a middle carbonate member, and upper desert red beds (Parcell and Williams 2005; Clement and Holland 2016; Danise and Holland 2018).

The J-1a unconformity is marked in Wyoming at several localities by the abrupt appearance of carbonate ramp facies, just as in Montana (Danise and Holland 2018). Unlike in the Piper Formation, a maroon paleosol was also observed at this contact in Wyoming, and it was determined to be a sequence boundary as well as a transgressive surface (Danise and Holland 2018). The lack of evidence for subaerial exposure observed in the Piper Formation at the J-1a unconformity may be due to limited outcrop availability, as it was observed only at one locality, and it may be better exposed elsewhere. There are also several sequence stratigraphic hypotheses as to why no subaerial exposure was evident at the J-1a unconformity in the Piper Formation: the J-1a surface in the Piper Formation may be only a transgressive surface, and some of the desert facies below may represent the lowstand systems tract; the J-1a in the Piper Formation may be both the transgressive surface and the sequence boundary but it may record no subaerial exposure because it is a correlative conformity; or the J-1a in the

Piper Formation may be the transgressive surface only, with the sequence boundary being a cryptic surface located somewhere within the underlying desert facies.

The J-1b unconformity in Wyoming is a sequence boundary recognized by the presence of silcrete horizons interpreted as indicating periods of subaerial exposure (Clement and Holland 2016; Danise and Holland 2018) as well as a chert pebble lag that also represents subaerial exposure (Clement and Holland 2016; Danise and Holland 2018). In central Montana, this surface is represented by a thick, well-developed paleosol and paleokarst, which indicates subaerial exposure as well. This suggests the J-1b unconformity is a sequence boundary in Montana, with the overlying desert facies being part of the highstand systems tract.

Rierdon Formation.—Without any exposure of the J-2, J-2a, and J-3 contacts, it is difficult to compare these to equivalents in Wyoming. Based on the facies in the upper Piper Formation, and the facies observed in the Rierdon Formation, the J-2 unconformity is a shift from desert facies to carbonate ramp facies, suggesting the J-2 boundary is a transgressive surface. This is consistent with well logs in which the contact between the Rierdon and Piper formations has a strong increase in radioactivity, indicating a flooding surface. This contact in Wyoming has wind-faceted chert pebbles and silcrete horizons indicative of subaerial exposure (Clement and Holland 2016; Danise and Holland 2018).

There are several sequence-stratigraphic hypotheses that could also explain these differences in the expression of the J-2 unconformity: the J-2 may be a transgressive surface only in central Montana, with some of the underlying desert facies representing the lowstand systems tract; the J-2 in central Montana may be both the transgressive surface and the sequence boundary but does not record subaerial exposure because it is a

correlative conformity; or the J-2 in central Montana may be only the transgressive surface with the sequence boundary being a cryptic surface lying within the underlying desert facies.

Swift Formation.—The interpretation of the J-4 contact between the Rierdon Formation and the Swift Formation as both a sequence boundary and transgressive surface is consistent with observations from central Montana and Wyoming. In Wyoming, wind-faceted chert pebbles and an iron-stained paleosol indicate subaerial exposure (Danise and Holland 2018), while this is indicated in central Montana by iron-stained shell beds. The contact is also marked by an abrupt shift from carbonate ramp to offshore siliciclastics (Danise and Holland 2018), and well logs indicate a flooding surface at this boundary (Fig.8I). This indicates it represents a transgressive surface as well.

The upper contact of the Swift Formation with the Morrison Formation has previously been interpreted as the J-5 unconformity (Pipiringos and O’Sullivan 1978), but in central Montana the contact appears conformable. This contact was observed at Dill Lane Cut where it shows no evidence of an erosional surface separating the Swift Formation from the overlying Morrison Formation, and the coastal plain and lacustrine deposits of the Morrison Formation appear to gradationally overlie the tidal sandstone of the Swift Formation. An erosional surface has been recognized in northern Colorado by regional truncation of the formations underlying the Morrison (Pipiringos and O’Sullivan 1978). It is possible this trend persists in central Montana as well, but the erosional surface is cryptic in outcrop.

Community Ecology

The comparing and contrasting communities in the northern and southern parts of the Sundance Seaway was a key focus of this research. By using an NMS ordination combining samples from Montana and Wyoming, I was able to show how the Montana samples compare with the current understanding of the communities in Wyoming.

Lithology.—The Montana data set does not change the overall pattern of lithologic variation in the Wyoming samples, which reflects the long-term transition from carbonates to siliciclastics in the Sundance Seaway. Siliciclastic samples from Montana still have intermediate to high axis one scores, while carbonates have intermediate to low scores (Fig. 12A). The clusters of carbonate and siliciclastic samples do not change (Fig. 12A). The only difference is that siliciclastic samples from Montana have higher axis two scores than the samples from Wyoming, which encroach on those from the carbonates (Fig. 12A). This may be because of trends in depositional environment, age, or latitude, and will be discussed below.

Depositional Environment.—Coding by depositional environment reveals a departure of the Montana data set from the pattern of the Wyoming samples. The deep subtidal, ooid shoal, and open shallow subtidal facies of central Montana all plot similarly to their counterparts in Wyoming (Fig. 12B). The siliciclastic offshore samples of Montana have higher axis two scores than those from Wyoming. A few components drive these differences. The first is the introduction in Montana of additional species to these facies such as the ammonite *Cardioceras hyatti* (Table 7; Fig. 13). The second possibility is related to the first: that offshore facies of the Swift Formation in Montana differ environmentally from the offshore facies of the Redwater Shale in Wyoming and

that the differences between these regions are what allowed different groups of species to thrive. This suggests the northern Sundance Seaway may be either cooler or less saline than the southern Sundance, or possibly both. These two environmental changes would allow for different community structures.

Depositional Sequence.—Coding by depositional sequence also reveals differences between the Montana and Wyoming data sets. Samples from the J-1a sequence in Montana had intermediate axis one and axis two scores consistent with Wyoming J-1a samples, but samples from the J-4 and J-3 sequences of Montana have higher axis two scores than those from Wyoming (Fig. 12C). These cluster nearer to the J-2a sequence samples of Wyoming rather than the J-3 and J-4 samples of Wyoming (Fig. 12C). The J-3 sequence is represented by the deep subtidal facies of the Rierdon Formation. Although the J-3 appears out of place, the NMS coded for depositional environment shows that J-3 deep subtidal samples plot with the main cluster of Wyoming deep subtidal samples. Samples of the J-3 from Wyoming are from ooid shoal and peritidal environments. This suggests axis two also partly reflects gradients along water depth. Differences in the J-4 may be rooted in the environment and species composition of the northern part of the seaway, similar to the trends in depositional environment. The J-4 sequence is represented by siliciclastic offshore facies, which also plot separately from Wyoming samples of the same facies.

Interpretation.—The overall axis one trends of the NMS remain consistent when the Montana samples are added. Previously, axis one of the Wyoming NMS was identified as being driven by water depth as well as geologic age (Danise and Holland 2017). The samples from Montana support these axis one patterns.

The addition of the Montana samples adds new variation on axis two. This axis was the more cryptic of the two in the original ordination of Danise and Holland (2017), which suggested a combination of temporal and environmental changes in community composition were being preserved along axis two (Danise and Holland 2017). With the addition of the Montana samples, the pattern suggests latitude influenced variation along axis two. The samples from Montana have higher axis two scores than Wyoming samples with the same depositional environment.

Although latitude is the gradient along which the samples sort, the drivers of this variation are actually the environmental gradients that exist along latitudinal transects such as temperature and salinity (Stanley 2010; Danise and Holland 2017). This suggests that samples with high axis two scores from either Montana or Wyoming may also have had a more normal marine salinity and lower temperatures. This is supported by the position of carbonate offshore samples and deep subtidal samples from both Wyoming and Montana, which have high axis two scores. This pattern also suggests that if carbonate offshore samples were to be obtained from Montana, they would have higher axis two scores than those from Wyoming.

This hypothesis is also supported by the observation of increased size in the ammonites found in Montana as compared with Wyoming as well as the introduction of several new species in Montana. The ammonites observed in Wyoming have an average diameter of less than 4 cm (personal communication, S. Danise and S. Holland 2019) while the ammonites in Montana reach up to 33 cm in diameter. The fauna of Montana also contains many species that were not previously observed in the southern Sundance Seaway, some of which were not included in the ordination because of their rarity

(Appendix C, D) such as the ammonites *Kepplerites mclearnii* and *Arctocephalites sweetgrassensis*, an ichthyosaur vertebra found at Zortman Dump, and two terebratulid brachiopod species which have never been observed before in any region of the Sundance Seaway (Table 7; Appendix A, B; Imlay 1947, 1956, 1957; Lalicker 1950). Other species not previously observed in Wyoming were not included in the ordination because they were previously collected without locality data and could not be tied to sample properties such as the ammonite *Lilloetia* sp., and three species of *Cadoceras* ammonites (Table 7; Appendix A, B).

CONCLUSIONS

1. The Ellis Group of central Montana contains three formations representing the Jurassic Sundance Seaway and they record four facies associations: The Piper Formation records desert and carbonate ramp facies associations; the Rierdon Formation records carbonate ramp facies associations; the Swift Formation records siliciclastic shelf facies associations with both wave-dominated and tide-dominated shorelines.

2. The Ellis Group preserves five third-order depositional sequences. The Piper Formation preserves the J-1, J-1a, and J-1b sequences, and the Swift Formation preserves the J-4 sequence. Only one sequence, was recognized in the Rierdon Formation because of its aggradational nature in well log and lack of outcrop, and it represents the J-2, J-2a, and J-3 sequences of Wyoming. These depositional sequences have direct equivalents in Wyoming and correspond well to the surfaces and systems tracts described in Wyoming.

3. The fossil assemblages of the northern part of the Sundance Seaway reflect a departure from communities in the southern part of the seaway. Key species additions to the fossil assemblage from central Montana indicate a generally deeper-water environment and more diverse fauna, namely the abundance and diversity of ammonite fauna in the Rierdon and Swift formations. The NMS ordination demonstrates the difference between time contemporaneous northern and southern communities, reflecting a significant environmental difference in the northern part of the seaway relating to latitudinal position and caused by differences in temperature, salinity, or both.

CHAPTER 3

CONCLUSIONS

The Jurassic Ellis Group of central Montana contains three formations, the Piper, Rierdon, and Swift formations. These formations preserve four facies associations: the desert depositional environment and carbonate ramp depositional environment in the Piper and Rierdon formations, and the wave-dominated coast depositional environment and tide-dominated coast depositional environment in the Swift Formation. These facies record the transition of the Sundance Seaway from a carbonate dominated system to a siliciclastic dominated system.

The Ellis Group also preserves five third-order depositional sequences. The J-1, J-1a, and J-1b sequences are preserved in the Piper Formation, the Rierdon apparently represents one sequence equivalent to the J-2, J-2a, and J-3 of Wyoming, and the J-4 sequence is preserved in the Swift Formation. This sequence stratigraphy is largely consistent with the sequence-stratigraphic architecture of the Sundance Seaway in Wyoming.

When compared with Wyoming in an NMS ordination, the fossil communities in central Montana indicate variations along a latitudinal gradient such as salinity and temperature. The communities in Montana are nearer to the mouth of the Sundance Seaway and are interpreted to have experienced cooler temperatures, more normal marine salinities, or both. This is reflected in the NMS as separation along axis two, by the

introduction of new species in Montana, and an increase in size between the ammonites of Wyoming and ammonites of Montana.

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TABLE 1.—Field Localities

Locality	Latitude	Longitude
Burleigh Ranch	46.99164	-109.26282
East Fork Lake	46.97963	-109.29029
Dill Lane Cut	47.01698	-109.35503
Allied Steel	46.99836	-109.26809
Zortman Cut	47.91472	-108.53025
Star Hill	47.90665	-108.52458
Sapphire Road Cut	46.94387	-110.13473
Schwanky Lot	47.88148	-108.6608
Big Spring Hatchery	47.00914	-109.34972
Simpson Ranch	46.89531	-109.58824
Landusky Cut	47.90159	-108.61647
Zortman Dump	47.91325	-108.52084

TABLE 2.—Well log locations

Well log API	Latitude	Longitude
25-027-05086-0000	47.16986	-109.74896
25-045-05027-0000	47.06812	-109.79043
25-027-21262-0000	47.04668	-109.57943
25-027-21207-0000	47.18534	-108.74345
25-065-21778-0000	46.64421	-108.95468
25-065-05048-0000	46.52793	-108.83984
25-037-21065-0000	46.45527	-109.18143
25-037-05008-0000	46.16327	-109.30193
25-037-05011-0000	46.19252	-109.40081
25-095-21099-0000	46.06859	-109.26885

TABLE 3.—Facies associations of the desert depositional system of the Ellis Group

Facies association and interpretation	Lithology and bedding	Sedimentary Structures	Trace and Body Fossils	Context
P1, desert mudflat	Brown gray siltstone, rare gypsum nodules (3–7 cm) and thin (1–3 cm), anastomosing, subhorizontal veins of gypsum.	Internally structureless	Unfossiliferous	Occurs in the lower Piper Formation. Grades upwards into facies P2. Gradationally overlies facies P2.
P2, sabkha	Red to gray siltstone with abundant, large (3–20 cm) gypsum nodules and both subhorizontal and subvertical veins of gypsum (1–3 cm). Pyrite nodules and chert are common.	Thinly laminated	Unfossiliferous	Occurs in the lower Piper Formation. Grades upwards into facies P1 or C5. Gradationally overlies facies C5 and C4.
P3, salina	Massive, thick-bedded gypsum.	Structureless	Unfossiliferous	Occurs in the lower Piper Formation. Overlain by facies C6. Not laterally continuous, pinches out into facies C5.

TABLE 4.—Facies associations of the carbonate ramp depositional system of the Ellis Group

Facies association and interpretation	Lithology and bedding	Sedimentary Structures	Trace and Body Fossils	Context
C1, deep subtidal	Gray lime mudstone to wackestone, very thinly bedded.	Laminated	Rare body fossils, predominantly casts. Includes the bivalve <i>Astarte meeki</i> , ammonites, the crinoid <i>Isocrinus knighti</i> , and bivalves.	Occurs in the upper Rierdon Formation. Lower boundary is not exposed. Overlain by facies C2 and facies SW1 of the Swift Formation. Lower boundary is obscured.
C2, open shallow subtidal	Gray wackestone to packstone, very thinly bedded with wavy to crinkly cryptalgal lamination. Iron staining and pyrite nodules are abundant.	Laminated	May contain shell beds, predominantly whole valves of bivalves including <i>Isognomon</i> , and <i>Liostrrea strigulecula</i> .	Occurs in the middle Piper Formation and middle Rierdon Formation. Grades upwards into facies C4. Gradationally overlies facies C5.
C3, ooid shoal	Thin-bedded skeletal ooid grainstone	Laminated	May contain shell beds, predominantly whole valves of bivalves including <i>Isognomon</i> , and <i>Liostrrea strigulecula</i> .	Occurs in the middle Piper Formation. Associated with facies C2, grades upwards into facies C4. Gradationally overlies facies C5.
C4, restricted shallow subtidal	Gray lime mudstone with wavy to crinkly lamination. Pyrite nodules and staining common.	Cryptalgal lamination, syneresis cracks are locally present.	Unfossiliferous	Occurs in the middle Piper Formation. Grades upwards into facies C5. Gradationally overlies facies C2 and sharply overlies facies C6.
C5, peritidal	Argillaceous, dolomitic lime mudstone.	Laminated	Unfossiliferous	Occurs in the middle Piper Formation. Gradationally overlies facies C2, C3, and C4.
C6, paleosol	Gleyed Argillisol. Red and gray mottled siltstone grading into gray siltstone and yellow siltstone.	Internally structureless. Well-developed horizons: red and gray mottling at base (1.4 m), gray in the middle (1 m), and yellow at top (0.7 m).	No visible root traces, trace fossils, or body fossils	Occurs in the upper Piper Formation. Locally gradationally overlies facies C5. Sharply overlain by facies C4.

TABLE 5.—Facies associations of the wave-dominated shelf depositional system of the Ellis Group

Facies association and interpretation	Lithology and bedding	Sedimentary Structures	Trace and Body Fossils	Context
SW1, offshore	Gray siltstone to mudstone. No bedding visible.	No sedimentary structures visible. No bioturbation visible. Blue gray to rusty concretions common (5–30 cm), sometimes forming horizons.	Dominated by the belemnite <i>Pachyteuthis Densus</i> and the bivalve <i>Gryphaea nebrascensis</i> . The ammonite <i>Cardioceras hyatti</i> , the oyster <i>Deltoidium</i> , bivalves, <i>Ichthyosaur</i> bones, and burrow casts also present. Locally monospecific beds of the oyster <i>Deltoidium</i> . Preservation is nearly pristine with whole valves preserved, occasionally articulated.	Occurs in lower 25 m of the Swift Formation. Grades upwards into facies SW2 and SW3.
SW2, shell bed	Highly shelly, very fine sandstone. Typically 10–30 cm thick. Densely packed with shells of monospecific bivalves.	No sedimentary structures visible.		Occurs in the middle Swift Formation. Grades upwards into facies SW3 at one locality. The contact is locally obscured at others. Gradationally overlies facies SW1 at one locality, contact is obscured at others.
SW3, offshore transition	Fine-grained, thin-bedded, glauconitic, bioturbated sandstone.	Large-scale trough cross-stratification and planar lamination are common, with occasional tabular cross-stratification	<i>Ophiomorpha</i> are common. No body fossils.	Occurs in the middle Swift Formation. Upper contact was not observed in outcrop. Gradationally overlies facies SW2 and SW1.
SW4, lower shoreface	Fine to medium grained, medium- to thick-bedded, bioturbated sandstone.	No sedimentary structures visible because of pervasive bioturbation.	Trace fossils not identified, no body fossils	Occurs in the Middle Swift Formation. Grades upwards into facies SW4. Gradationally overlies facies SW4.
SW5, upper shoreface	Fine to medium grained sandstone, thin- to medium- bedded, glauconitic sandstone with thin mud interbeds.	Large-scale trough cross-stratification, tabular cross-are common.	No trace or body fossils.	Occurs in the middle Swift Formation. Sharply overlain by SW4, top of parasequence. Grades upwards into facies SW4.

TABLE 6. —Facies associations of the tide-dominated coast depositional system in the Ellis Group

Facies association and interpretation	Lithology and bedding	Sedimentary Structures	Trace and Body Fossils	Context
TC1, tidal bar	Very fine- to fine-grained sandstone, very thin- to thin-bedded sandstone.	Tabular and trough cross stratification. mudstone rip-ups common on bedding surfaces, clay drapes common, reactivation surfaces common. Herringbone cross stratification and sigmoidal cross bedding uncommon.	<i>Ophiomorpha</i> common. No body fossils present.	Occurs in the upper Swift Formation. Grades upwards into facies TC2. Gradationally overlain in some places by Morrison Formation. Sharply overlies facies TC2.
TC2, tidal sand flat	Very fine- to fine-grained sandstone, very thin-bedded interbedded mud common.	Mostly planar lamination and current ripple lamination with common climbing ripples. Wave ripples uncommon.	Unfossiliferous	Occurs in the upper Swift Formation. Gradationally overlies facies TC1, usually represents the top of a parasequence. Sharply overlain by facies TC1.

TABLE 7.—Community composition of the facies associations of the Ellis Group

Facies Association	Taxa	Percent Abundance
Open shallow subtidal	<i>Ostrea strigilecula</i>	29.9
	<i>Prororakia fontanellensis</i>	24.7
	Rhodolith indet.	18.2
	<i>Pleuromya newtoni</i>	13.0
	<i>Isognomon</i> sp.	11.7
	Tooth A	2.6
Ooid shoal	<i>Isognomon</i> sp.	48.0
	<i>Ostrea strigilecula</i>	20.0
	<i>Pleuromya newtoni</i>	16.0
	Rhodolith indet.	12.0
	<i>Prororakia fontanellensis</i>	4.0
Deep subtidal	<i>Gryphaea nebrascensis</i>	55.1
	<i>Prororakia fontanellensis</i>	11.8
	<i>Pachyteuthis densus</i>	9.4
	<i>Pleuromya subcompressa</i>	6.1
	<i>Astarte meeki</i>	5.3
	Burrow cast	2.4
	<i>Pholadomya kingi</i>	2.0
	<i>Astarte packardii</i>	0.8
	<i>Isocrinus knighti</i>	0.8
	<i>Kepplerites mclearni</i>	0.8
	Serpulid worm tubes	0.8
	Rhodolith indet.	0.4
	<i>Parachondroceras filicostatum</i>	0.4
	<i>Grammatodon inornatum</i>	0.4
	<i>Eumicrotis orbiculata</i>	0.4
	<i>Procerithium</i> sp.	0.4
	Trigonid sp.	0.4
	Arthropod A	0.4
	<i>Cadoceras</i> sp.	0.4
	<i>Lilloettia</i> sp.	0.4
	<i>Kepplerites</i> sp.	0.4
	<i>Arctocephalites sweetgrassensis</i>	0.4
Offshore	<i>Pachyteuthis densus</i>	38.7
	<i>Gryphaea nebrascensis</i>	34.1
	<i>Deltoidium</i>	18.8
	<i>Camptonectes</i> sp.	4.2
	Serpulid worm tubes	1.7
	<i>Cardioceras hyatti</i>	1.5
	<i>Pleuromya subcompressa</i>	0.5
	Burrow cast	0.2
	Terebratulid B	0.2
	<i>Chondroceras</i> cf. <i>C. allani</i>	0.1
	<i>Cadoceras</i> sp.	0.1
	Bryozoan sp.	0.1
Shell bed	<i>Deltoidium</i>	69.1
	Brachiopod A	30.9

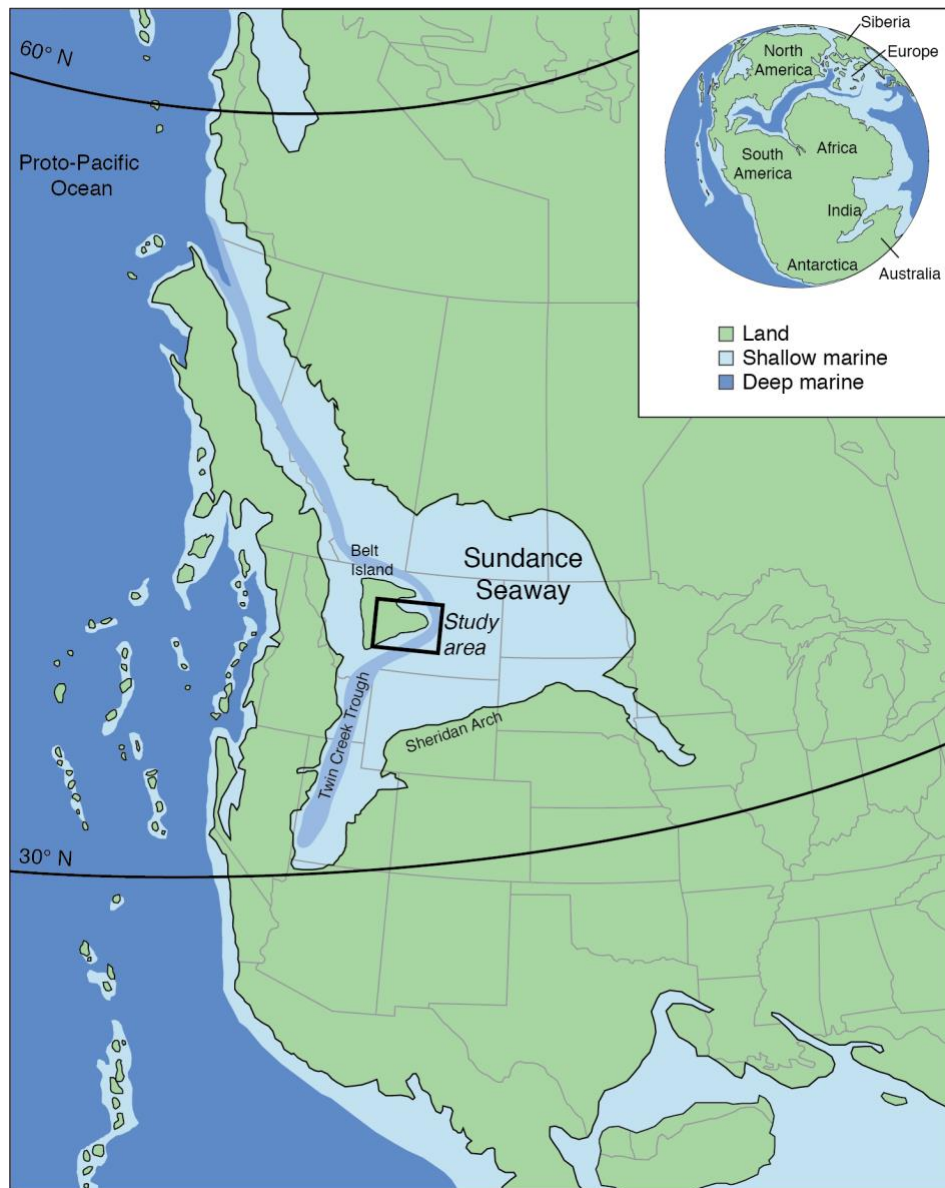


FIG 1.—Paleogeographic reconstruction of the Sundance Seaway, adapted from Clement and Holland (2016), based on the Late Jurassic map of North America by Blakey (2014).

FIG 2.—Stratigraphic framework of the Middle to Upper Jurassic of Wyoming. Chronostratigraphy is based on Imlay (1952, 1980), Pipiringos and O’Sullivan (1978), Brenner and Peterson (1994), Parcell and Williams (2005) and Danise and Holland (2018). The absolute time scale is from Cohen et al. (2013) Stratigraphic relationships illustrated here are considerably simplified. Nomenclature for depositional sequences is shown at right; following convention, sequence boundaries are named for the overlying depositional sequence. Kim. = Kimmeridgian.

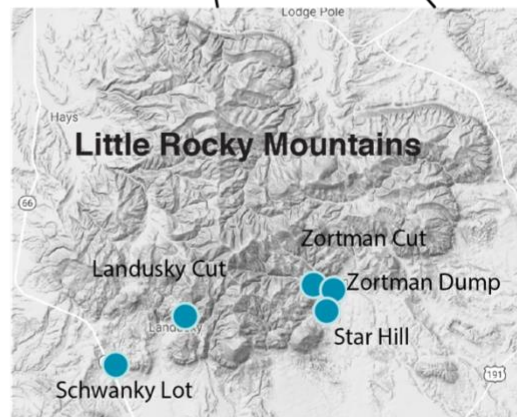
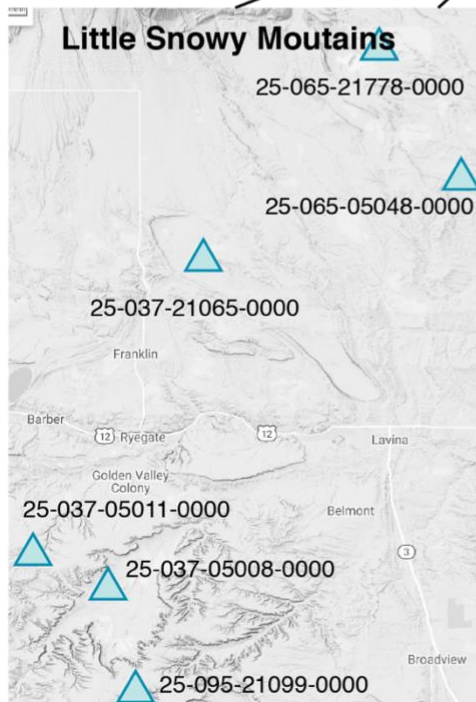
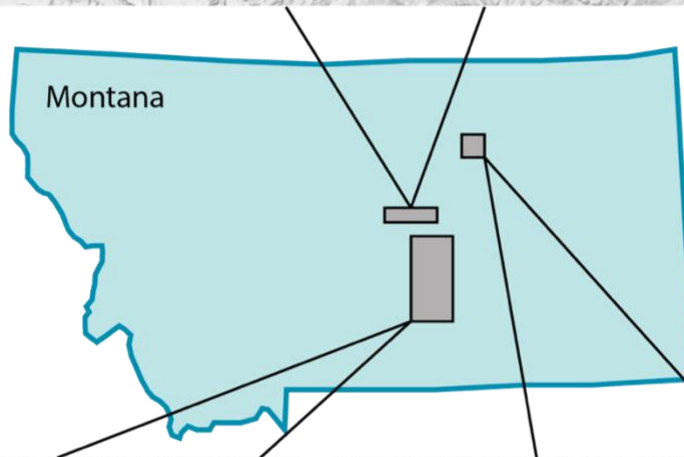
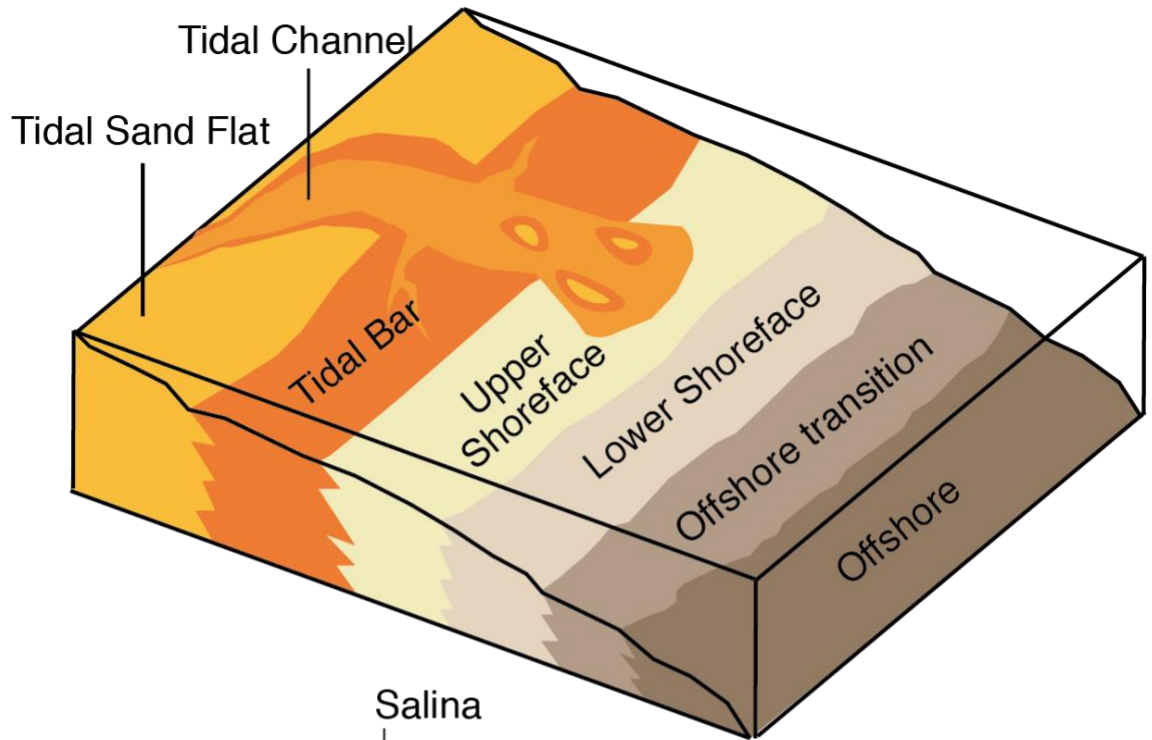


FIG. 3.— Map showing field localities (darker blue circles) and well log locations (lighter blue triangles). Coordinates of both are reported in tables 1 and 2.

A



B

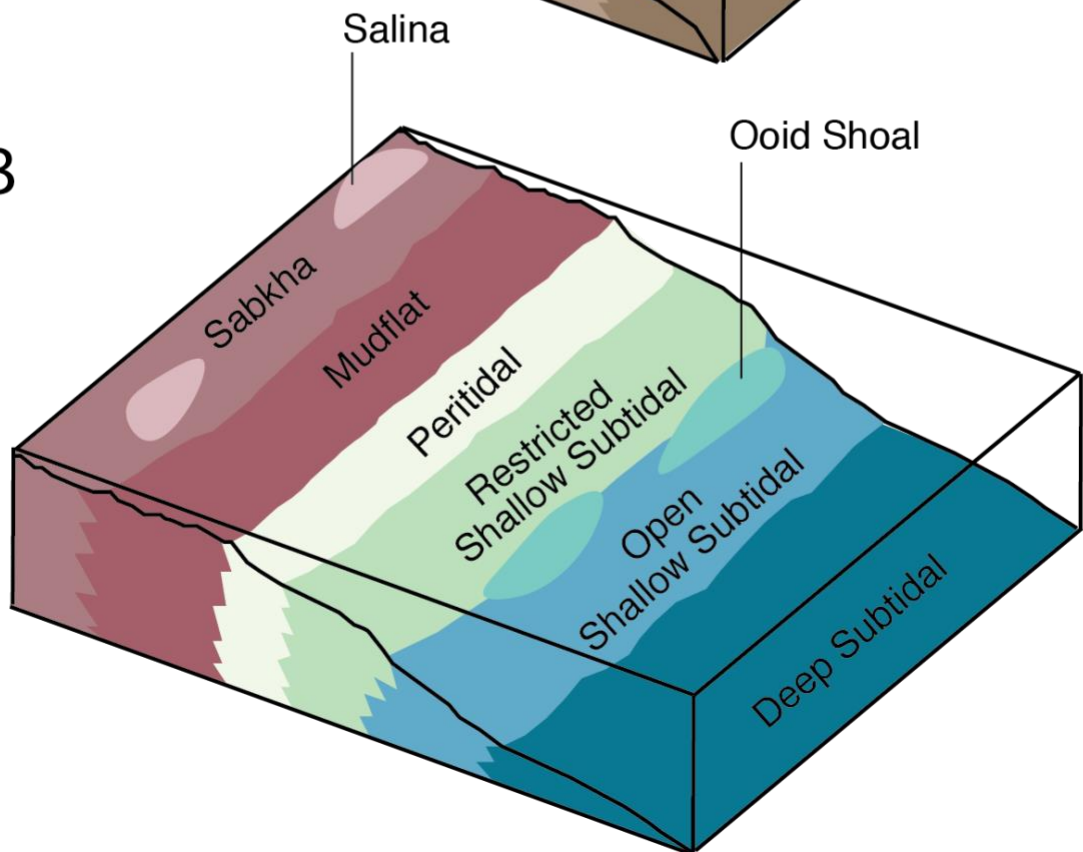


FIG. 4.—Block diagrams of depositional environments of the Ellis Group showing **A)** the siliciclastic shelf facies, and **B)** the carbonate ramp and desert facies.

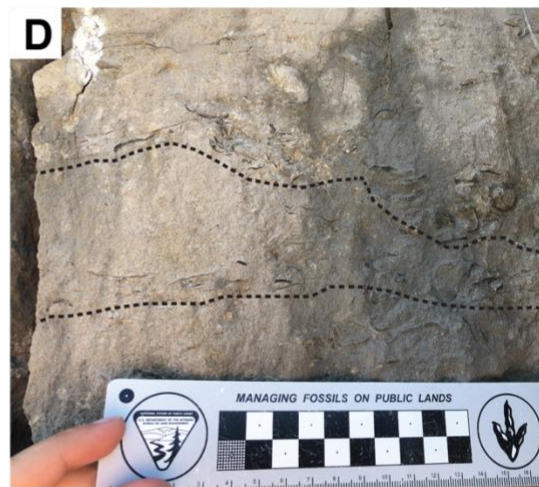
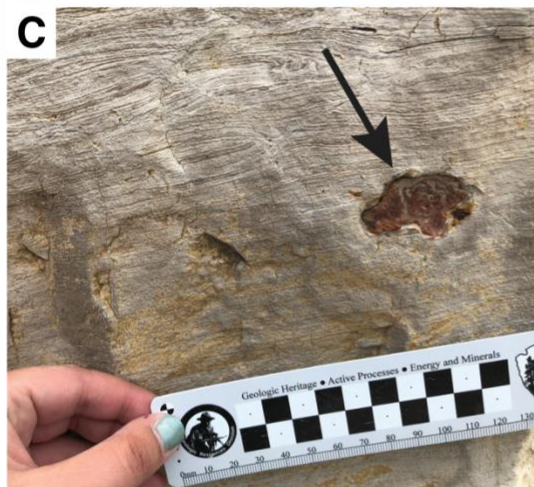
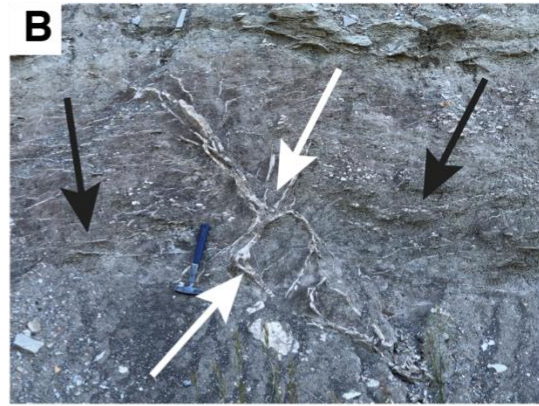


FIG. 5.—Photos showing sedimentary structures and bedding of the tide-dominated coast and the carbonate ramp facies associations. **A)** climbing ripples of the tidal sand flat facies at Burleigh Ranch. **B)** mosaic gypsum (large white arrows) and gypsum veins (small black arrows) in the sabkha facies at Allied Steel with a rock hammer (33 cm long). **C)** hematite nodule (arrow) and cryptalgal lamination in the restricted shallow subtidal facies at Allied Steel. **D)** shell beds (dashed lines above) in the ooid shoal facies at Burleigh Ranch. **E)** argillaceous lime mud laminae of the peritidal facies at Allied Steel. **F)** blocky bedding of the restricted shallow subtidal facies at Allied Steel. Scale bar in A, C–F has increments of 1 cm.

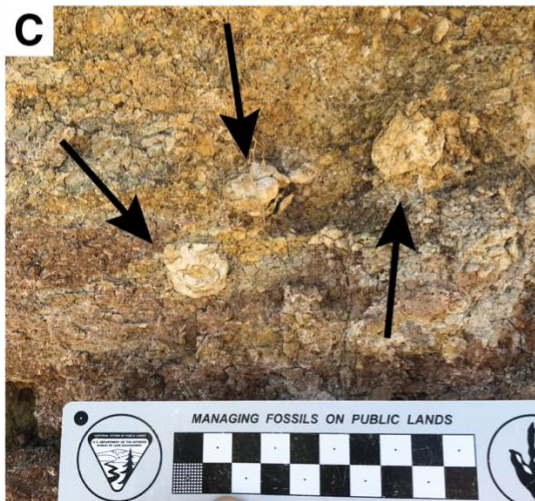


FIG. 6.—Photos showing the features of the paleosol at the Burleigh Ranch locality. **A)** yellow siltstone at the top of the paleosol. **B)** green and red mottling in the lower portion of the paleosol. **C)** small caliche nodules (arrows) at the boundary between gray and yellow siltstone. **D)** full view of the zonation of the paleosol with the tops of the mottled horizon and white horizon marked by dashed lines and a Jacob staff with increments of 10 cm for scale. Scale bar in A–C has increments of 1 cm.

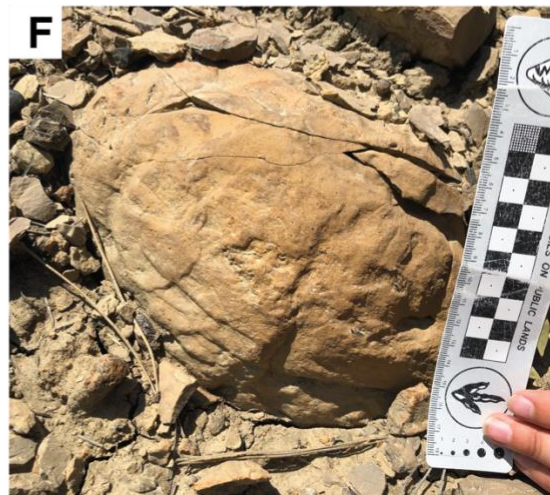
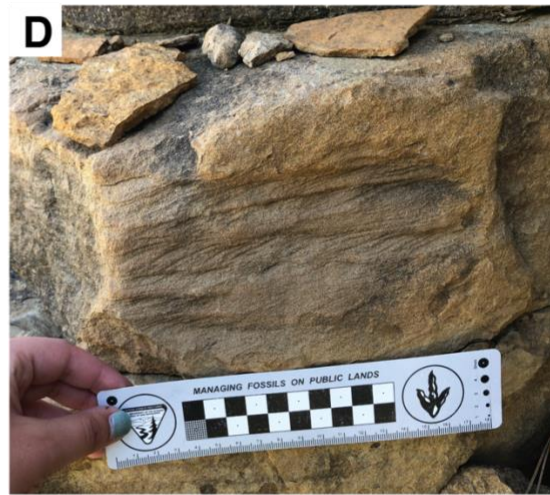
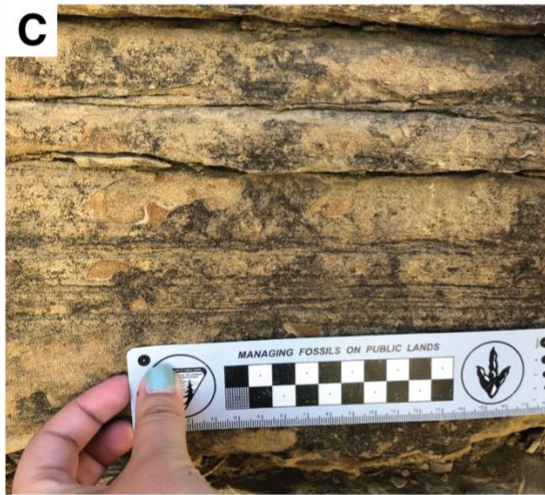
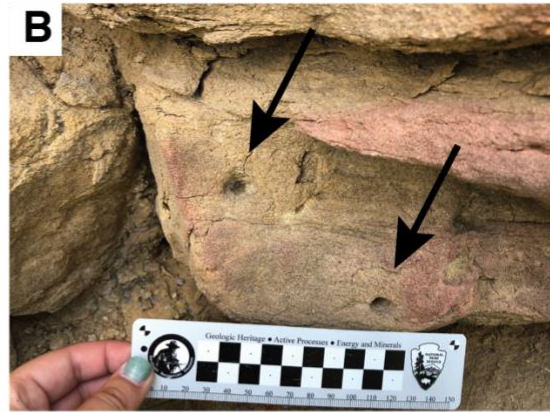


FIG. 7.—Sedimentary structure photographs of the Ellis Group. **A)** mud intraclasts (arrows) of the tidal bar facies at Dill Lane Cut. **B)** *Ophiomorpha* trace fossils (arrows) of the tidal bar facies at Allied Steel. **C)** planar lamination of the tidal sand flat facies at Burleigh Ranch. **D)** small-scale tabular cross stratification of the tidal sand flat facies at Burleigh Ranch. **E)** large-scale trough cross stratification of the tidal bar facies at Burleigh Ranch. **F)** a concretion found in the offshore facies at Zortman Dump. Scale bar in A–D, F has increments of 1 cm.



FIG. 8.—Well logs showing gamma ray, neutron density, resistivity, and spontaneous potential of the formations of the Ellis Group. The number below each well is the API number. **A)** Flooding surface at the base of the Piper Formation. **B)** progradational to aggradational stacking in the lower Piper Formation, **C)** gypsum signatures in the lower to middle Piper Formation. **D)** retrogradational stacking in the middle Piper Formation. **E)** resistivity spike in the upper Piper Formation representing the J-1b unconformity. **F)** retrogradational stacking in the upper Piper Formation. **G)** flooding surface at the base of the Rierdon Formation, the J-2 unconformity. **H)** aggradational stacking in the Rierdon Formation, **I)** flooding surface at the base of the Swift Formation, the J-4 unconformity. **J)** progradational stacking in the Swift Formation. **K)** tidal channels in the Swift Formation.

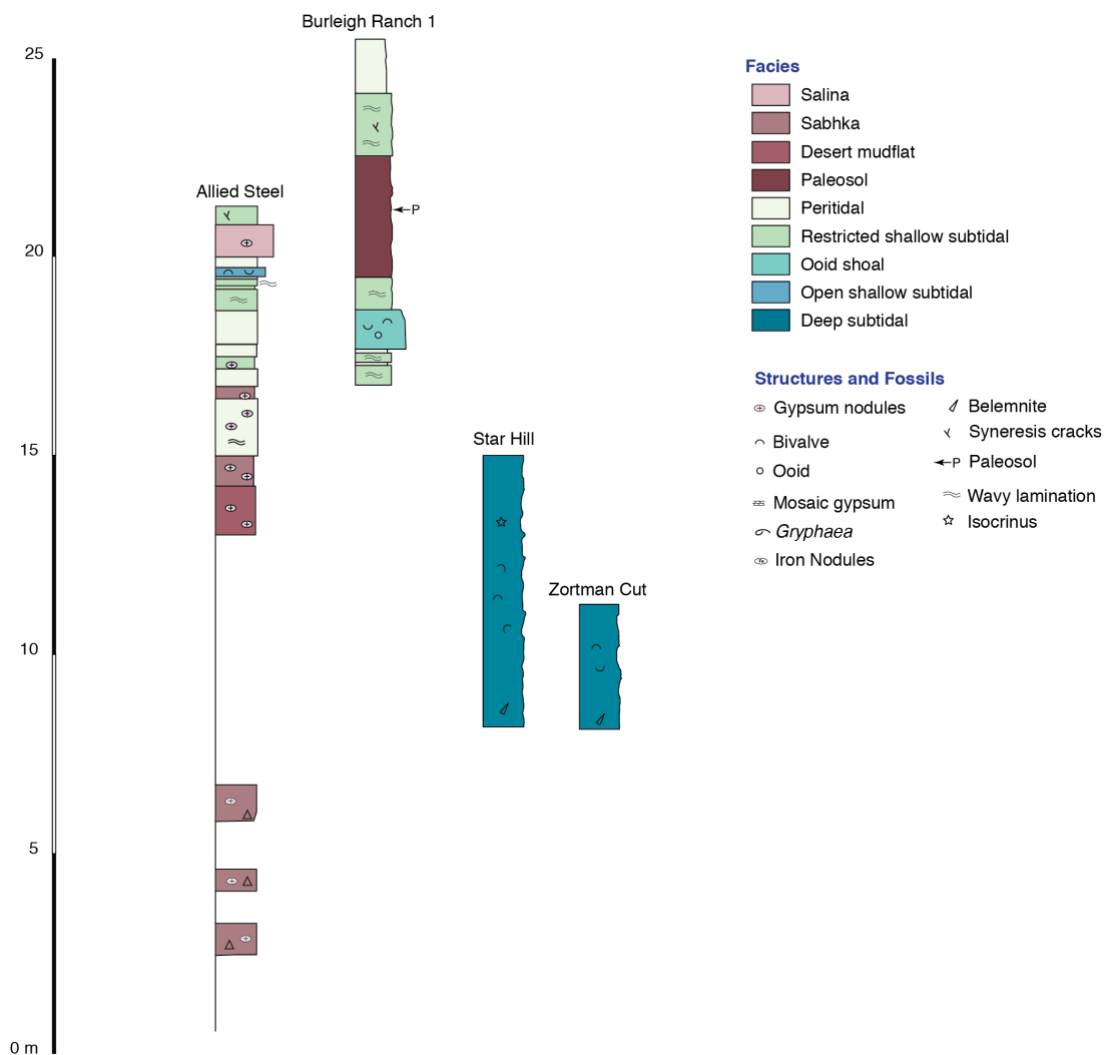


FIG. 9.—Stratigraphic columns showing all Rierdon and Piper formations measured sections excluding the Schwanky Lot locality, which is shown in figure 10.

Position of columns indicates general stratigraphic position, as precise correlation between these localities was not possible.

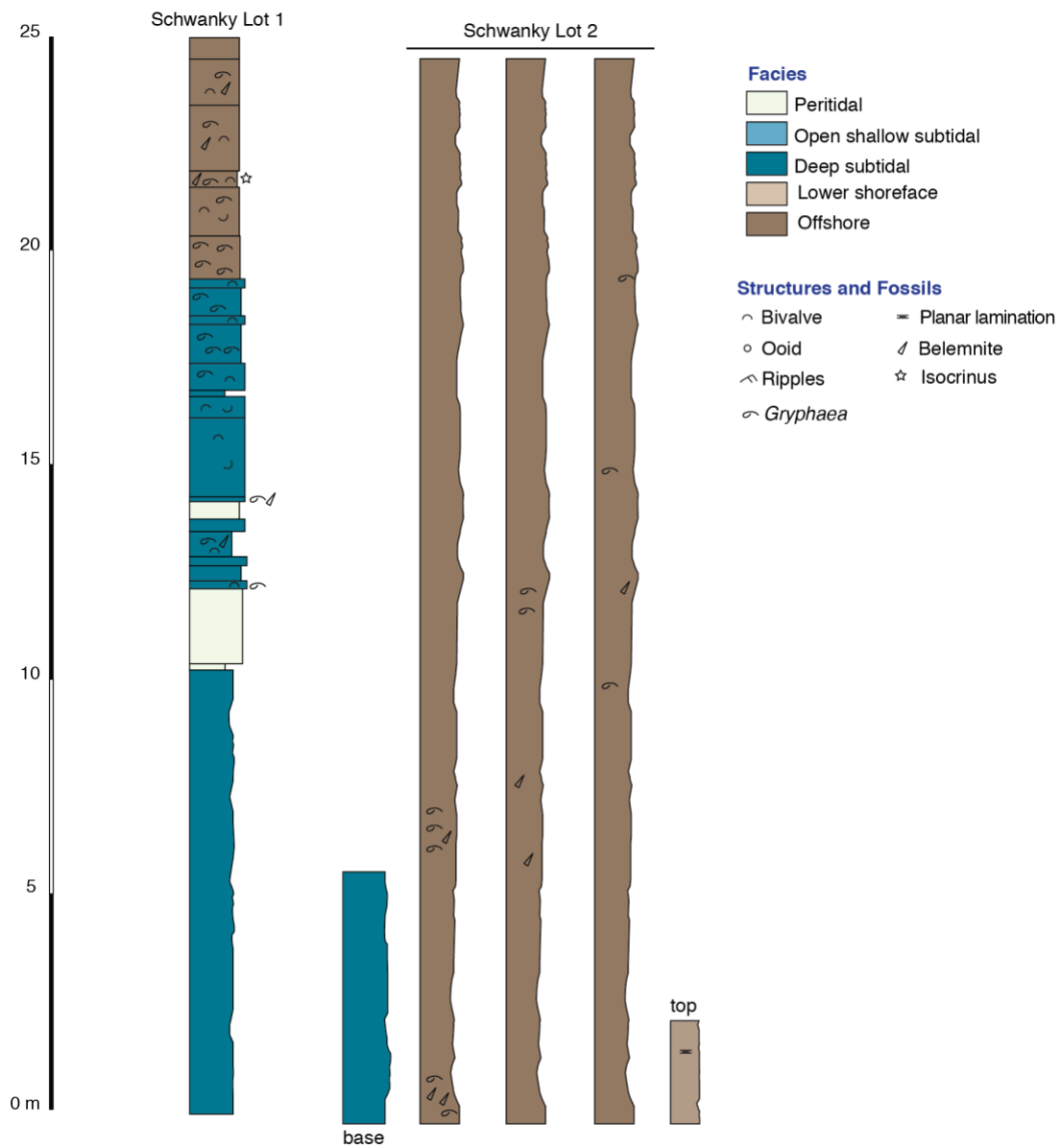


FIG. 10.—Stratigraphic columns of the sections measured at the Schwanky Lot locality.

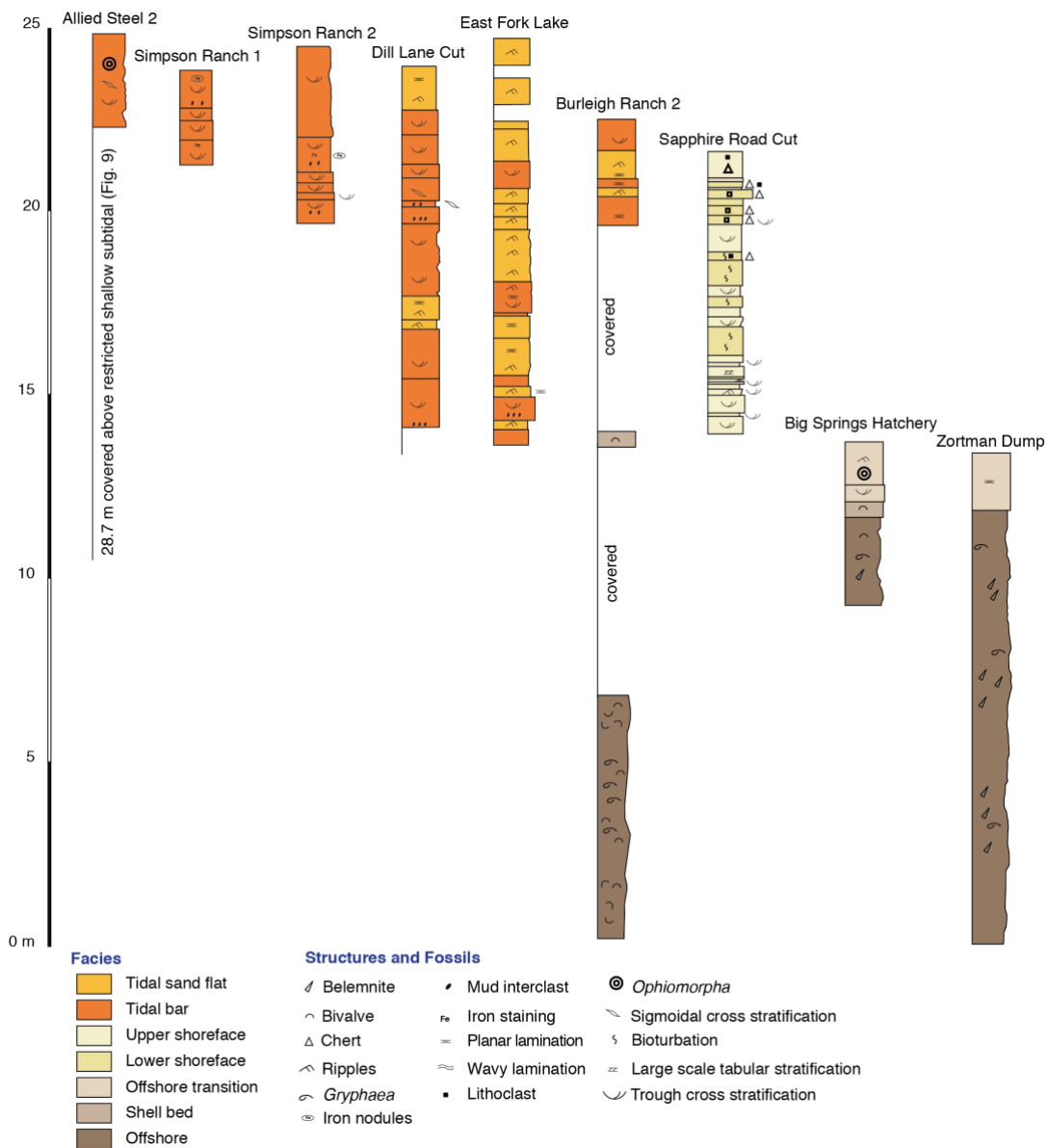


FIG. 10.—Stratigraphic columns showing all Swift Formation localities. Position of column indicates general stratigraphic position, correlation between localities was not possible.

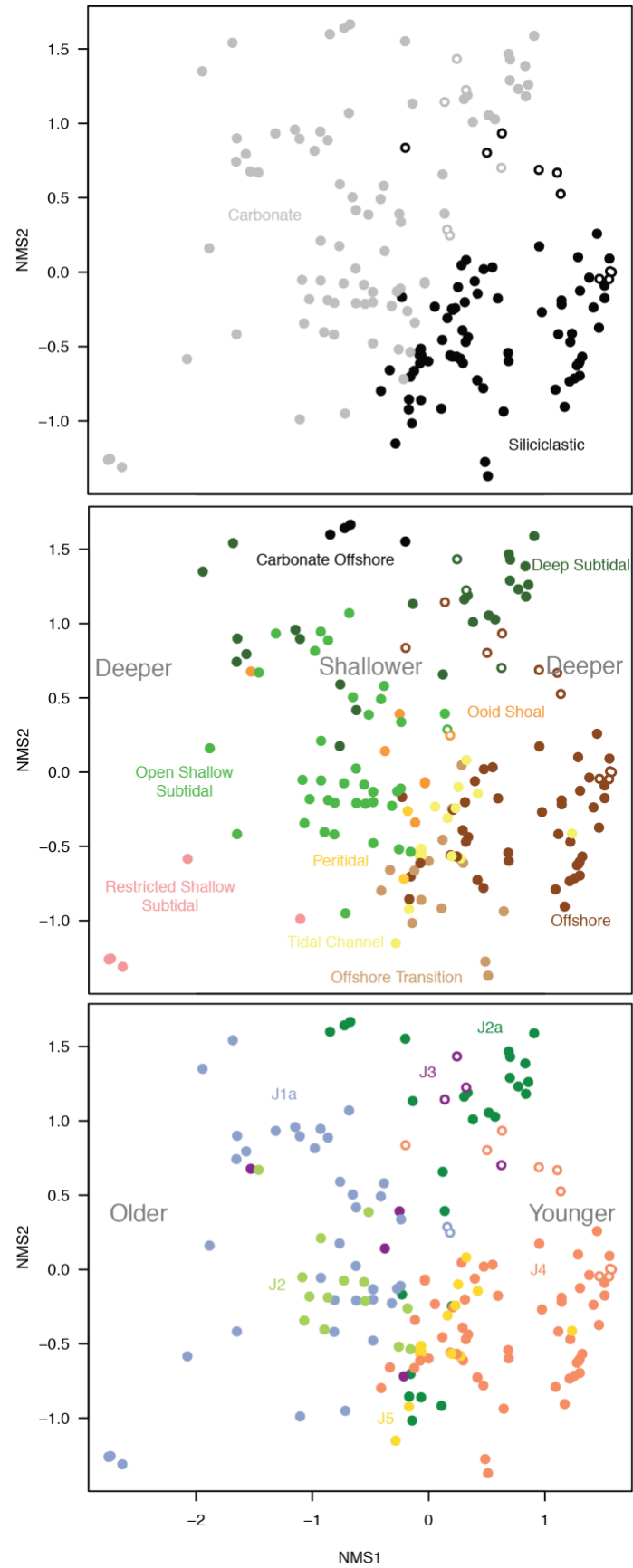


FIG. 12.—Plots of NMS ordinations of Wyoming and Montana fossil data with samples coded by **A)** lithology, **B)** depositional environment, and **C)** depositional sequence.

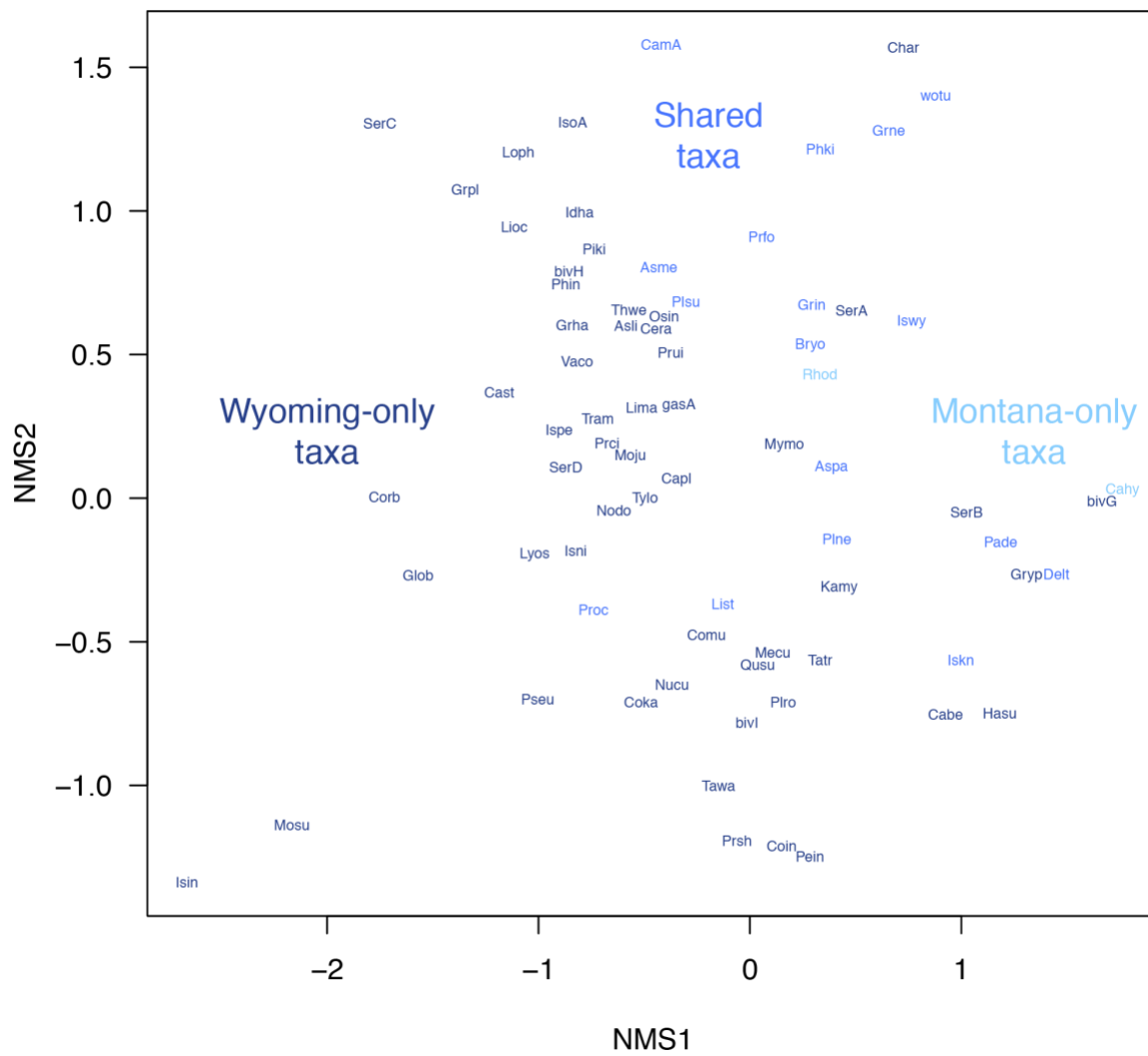
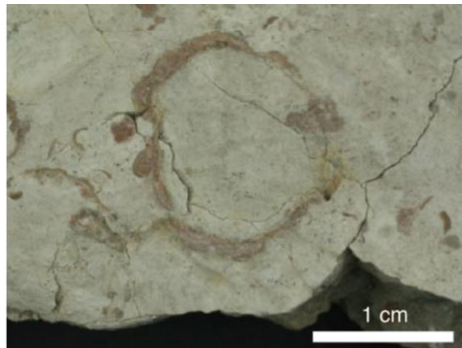


FIG. 13.—Taxon score plot of the combined NMS ordination of Wyoming samples and Montana samples. Species labels that overlap have been separated slightly for ease of viewing. See appendix C for taxon codes

APPENDIX A

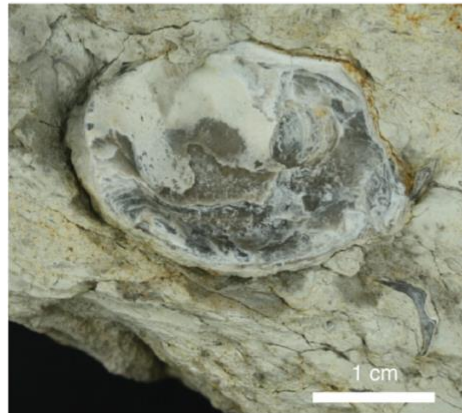
FOSSIL CATALOGUE OF THE ELLIS GROUP



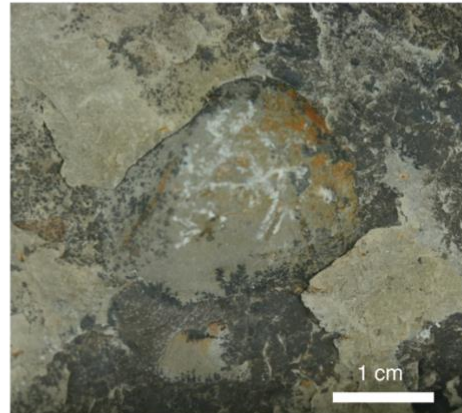
Rhodolith indet.



Isognomon sp.



Liostrea Strigelecula



Trigonid indet.



Pinna sp.



Pleuromya subcompressa



Gryphaea nebrascensis



Gryphaea nebrascensis



Gryphaea nebrascensis



Gryphaea nebrascensis with serpulid scours



Gryphaea nebrascensis with serpulid scours and a bryozoan (indet.)



Pachyteuthis densus



Cadoceras sp.



Cadoceras sp.



Cardioceras hyatti



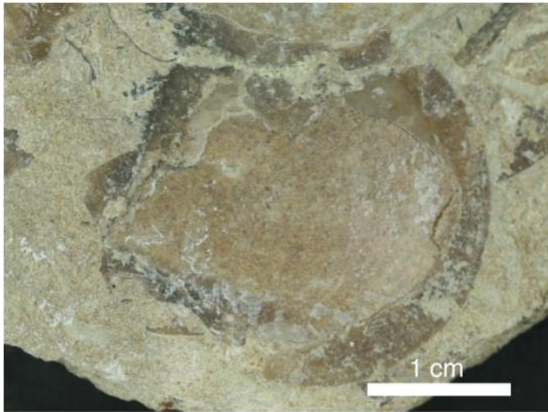
Arctocephalites sweetgrassensis



Arctocephalites sweetgrassensis



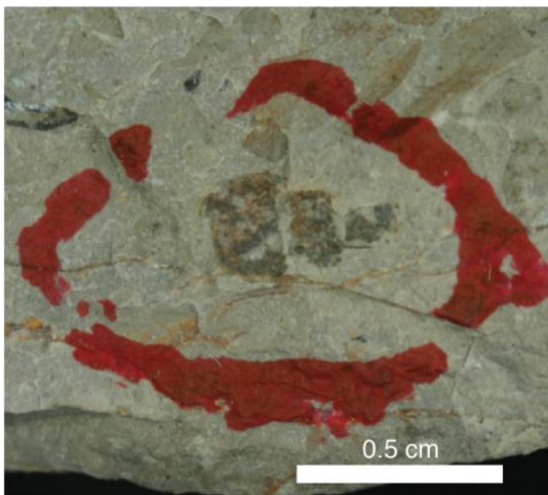
Arthropod indet. possible cuticle from shrimp or lobster



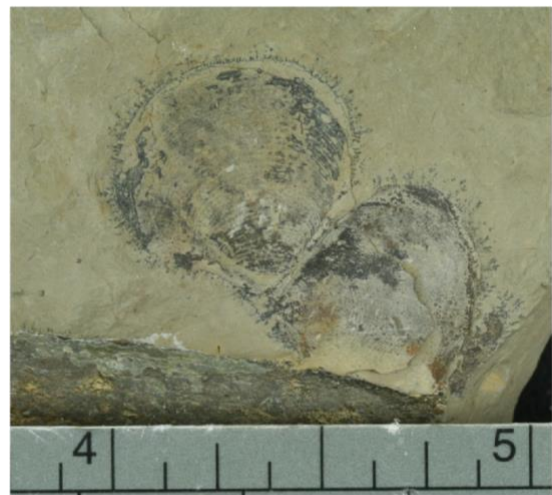
Camptonectes sp.



Eumicrotis orbiculata



Procerithium sp.



Astarte meeki



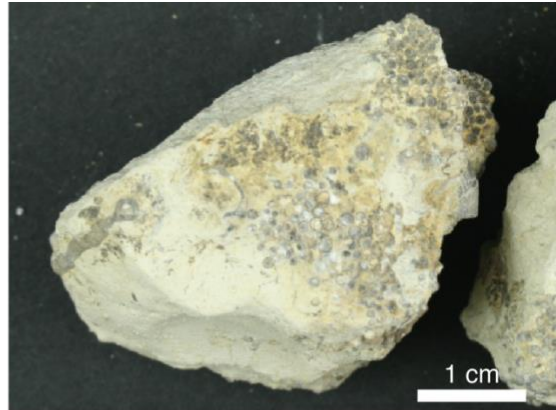
Terebratulid indet. A



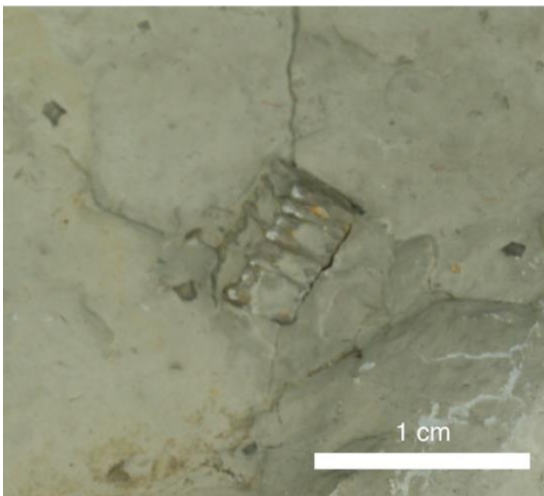
Terebratulid indet. A



Serpulid tubes



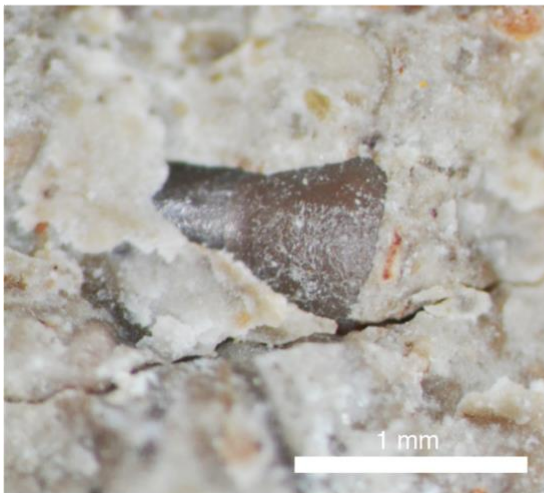
Serpulid tubes



Isocrinus kingi



Terebratulid indet. B



Tooth indet.



Tooth indet.



Deltoidium sp.



Deltoidium sp.



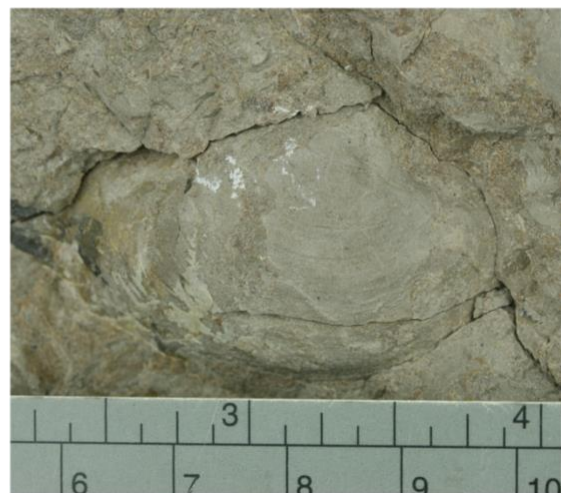
Prorokia fontanellensis



Phalodomya kingi



Grammatodon inornatum



Pleuromya newtoni



Keplerites sp. from the collection of L. Eichhorn



Cadoceras sp. from the collection of L. Eichhorn



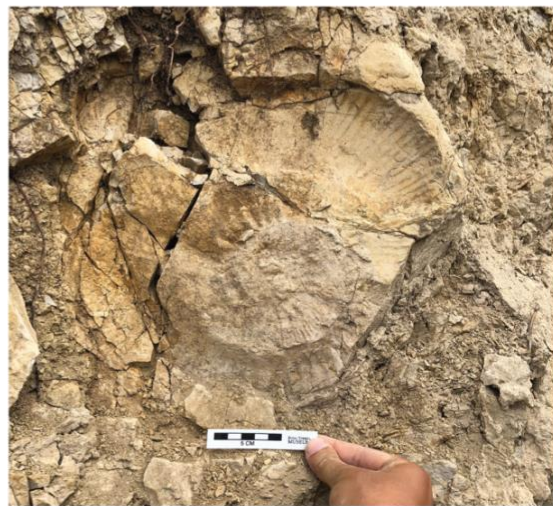
Lilloetia sp. from the collection of L. Eichhorn



Cadoceras sp. from the collection of L. Eichhorn



Keplerites (Gowericeras) costicrassum from the collection of J. Burleigh



Keplerites mclearnii



ichthyosaur indet. vertebra (not collected)



ichthyosaur indet. vertebra (not collected)



ichthyosaur indet. vertebra (not collected)



ichthyosaur indet. vertebra (not collected)



ichthyosaur indet. vertebra (not collected)

APPENDIX B

TAXA NOT INCLUDED IN FAUNAL CENSUS

APPENDIX B.—Taxa that were collected in Montana but not included in faunal census

Taxa	Locality	Formation	Sequence	Facies	Lithology	Collector
Ichthyosaur indet.	Zortman Dump	Swift	J-4	Offshore	Siliciclastic	S. Swenson
<i>Kepplerites</i> (<i>Gowericeras</i>) <i>costicrassum</i>	Burleigh Ranch	Swift	J-4	Offshore	Siliciclastic	J. Burleigh
<i>Cadoceras</i> sp. A	NA	Swift	J-4	Offshore	Siliciclastic	L. Eichhorn
<i>Cadoceras</i> sp. B	NA	Swift	J-4	Offshore	Siliciclastic	L. Eichhorn
<i>Kepplerites</i> sp.	NA	Rierdon	NA	NA	Carbonate	L. Eichhorn
<i>Lilloetia</i> sp.	NA	Rierdon	NA	NA	Carbonate	L. Eichhorn
<i>Cadoceras</i> sp. C	Burleigh Ranch	Swift	J-4	Offshore	Siliciclastic	S. Holland

APPENDIX C

TAXON CODES FOR NMS

APPENDIX C.—Taxon codes for NMS

Taxon Code	Taxon	Higher Taxon	Wyoming	Montana
Asli	<i>Astarte livingstonensis</i>	Bivalve	x	
Asme	<i>Astarte meeki</i>	Bivalve	x	x
Aspa	<i>Astarte packardi</i>	Bivalve	x	x
bivG	<i>Bivalve indet. G</i>	Bivalve	x	
bivH	Bivalve indet. H	Bivalve	x	
bivI	Bivalve indet. I	Bivalve	x	
Bryo	Bryozoa indet.	Bryozoa	x	x
Burr	Burrow Cast	Trace Fossil		x
Cabe	<i>Camptonectes bellistriatus</i>	Bivalve	x	
Cahy	<i>Cardiocearas hyatti</i>	Cephalopod		x
CamA	<i>Camponectes</i> sp. A	Bivalve	x	x
Capl	<i>Camptonectes platessiformis</i>	Bivalve	x	
Cast	<i>Camptonectes stygius</i>	Bivalve	x	
Cera	cf. <i>Ceratomya</i> sp.	Bivalve	x	
Char	<i>Chariocrinus</i> sp.	Crinoid	x	
Coin	<i>Corbicellopsis</i> cf. <i>inornata</i>	Bivalve	x	
Coka	<i>Cossmannia? Kanabensis</i>	Gastropod	x	
Comu	<i>Corbula</i> cf. <i>munda</i>	Bivalve	x	
Corb	<i>Corbicellopsis</i> sp.	Bivalve	x	
Delt	<i>Deltoidium</i> sp.	Bivalve	x	x
gasA	Gastropod indet. A	Gastropod	x	
Glob	<i>Globularia?</i> sp.	Gastropod	x	
Grha	<i>Grammatodon haguei</i>	Bivalve	x	
Grin	<i>Grammatodon inornatum</i>	Bivalve	x	x
Grne	<i>Gryphaea nebrascensis</i>	Bivalve	x	x
Grpl	<i>Gryphaea planoconvexa</i>	Bivalve	x	
Gryp	<i>Gryphaea</i> sp.	Bivalve	x	
Hasu	<i>Hamulus subquadratus</i>	Scaphopod	x	
Idha	cf. <i>Idonearca haguei</i>	Bivalve	x	
Isin	Isocyprinidae indet.	Bivalve	x	
Iskn	<i>Isocrinus knighti</i>	Crinoid	x	x
Isni	<i>Isocrinus nicoleti</i>	Crinoid	x	
IsoA	Isocrinidae indet. A	Crinoid	x	
Ispe	<i>Isognomon</i> cf. <i>perplana</i>	Bivalve	x	x
Iswy	<i>Isocrinus wyomingensis</i>	Crinoid	x	
Kamy	<i>Kallirhynchia myrina</i>	Brachiopod	x	

Lima	<i>Lima</i> sp.	Bivalve	x	
Lioc	<i>Lima (Plagiostoma)</i> cf. <i>L. occidentalis</i>	Bivalve	x	
List	<i>Liostrea strigilecula</i>	Bivalve	x	x
Loph	<i>Lopha</i> sp.	Bivalve	x	
Lyos	<i>Lyosoma</i> sp.	Gastropod	x	
Mecu	<i>Meleagrinella curta</i>	Bivalve	x	
Moju	<i>Modiolarca jurassica</i>	Bivalve	x	
Mosu	<i>Modiolus subimbricatus</i>	Bivalve	x	
Mymo	<i>Myophorella montanaensis</i>	Bivalve	x	
Nodo	<i>Nododelphinula?</i> sp.	Gastropod	x	
Nucu	<i>Nucula</i> sp.	Bivalve	x	
Osin	Ostreidae indet.	Bivalve	x	
Pade	<i>Pachyteuthis densus</i>	Cephalopod	x	x
Pein	Pectinidae indet.	Bivalve	x	
Phin	<i>Pholadomya inaequiplicata</i>	Bivalve	x	
Phki	<i>Pholadomya kingi</i>	Bivalve	x	x
Piki	<i>Pinna kingi</i>	Bivalve	x	
Plro	<i>Platymya rockymontana</i>	Bivalve	x	
Plne	<i>Pleuromya newtoni</i>	Bivalve	x	x
Plsu	<i>Pleuromya subcompressa</i>	Bivalve	x	x
Prci	<i>Pronoella cinnabarensis</i>	Bivalve	x	
Prfo	<i>Prorokia fontanellensis</i>	Bivalve	x	x
Proc	<i>Procerithium?</i> sp.	Gastropod	x	x
Prsh	<i>Protocardia</i> cf. <i>shumardi</i>	Bivalve	x	
Pru	cf. <i>Pronoella uintahensis</i>	Bivalve	x	
Pseu	<i>Pseudomelania?</i> sp.	Gastropod	x	
Qusu	<i>Quenstedtia sublevis</i>	Bivalve	x	
Rhod	Rhodolith indet.	Aglae		x
SerA	Serpulidae indet. A	Polychaete	x	
SerB	Serpulidae indet. B	Polychaete	x	
SerC	Serpulidae indet. C	Polychaete	x	
SerD	Serpulidae indet. D	Polychaete	x	
Tatr	<i>Tancredia transversa</i>	Bivalve	x	
Tawa	<i>Tancredia warrenana</i>	Bivalve	x	
Thew	<i>Thracia weedi</i>	Bivalve	x	
Tram	<i>Trigonia americana</i>	Bivalve	x	
Tylo	<i>Tylostoma?</i> sp.	Gastropod	x	
Vaco	<i>Vaugonia conradi</i>	Bivalve	x	
wotu	Worm tubes	Polychaete	x	x

APPENDIX D

R CODE FOR NMS AND SUBSEQUENT PLOTS

```
##The vegan package is needed to run the multidimensional scaling
library(vegan)

## There are two data files
## counts.csv reports the species found in each sample in Wyoming and Montana
## sampleProperties reports the locality, formation, sequence, facies, lithology, and
## collector of each sample collected from Wyoming and Montana
counts <- read.table(file='counts.csv', header=TRUE, row=1, sep=',')
sampleProperties <- read.table(file='sampleProperties.csv', header=TRUE, row=1, sep=',')

## cullingFunctions.R contains a routine for removing species that occur in too few
## samples and samples that have too few species
## Code written by Steven Holland, included in the supplemental material for Danise &
## Holland 2017 - R script - lnMDS & cluster.txt
source('cullingFunctions.R')
culledCounts <- cullMatrix(counts)
## Keep only the samples in the culled counts
culledSampleProperties <- sampleProperties[intersect(rownames(sampleProperties),
rownames(culledCounts)), ]

## two data transformations were performed
## a percent transformation was performed on rows to standardize for sample size
## a log transformation was performed to deemphasize highly abundant taxa
counts.tot <- decostand(culledCounts, 'total')
counts.log <- decostand(counts.tot, 'log')

## NMS
NMS <- metaMDS(counts.log, trymax=100, autotransform=FALSE, k=3)
NMS$stress

## Flipping orientation of axes to match the ordination of Danise and Holland 2017
## In some runs, flipping the axes may not be necessary
sampleScores <- NMS$points * -1
speciesScores <- NMS$species * -1

## The Danise samples were primarily from Wyoming, the Swenson samples are all from
## central Montana
montanaSamples <- culledSampleProperties$Collector=='Swenson'
wyomingSamples <- culledSampleProperties$Collector=='Danise'

## Figure 12A
# Plot NMS sample scores coded by Lithology
# Check how many Factors there are in Member and in which exact order. Then create a
# palette with the colors you want for each facies in the same order.
levels(culledSampleProperties$Lithology)
lithologyColors <- palette(c('grey', 'black'))
plot(sampleScores[, 1], sampleScores[, 2], xlab='NMS1', ylab='NMS2', main='Log
Transformed NMS', type='n', las=1)
points(sampleScores[, 1], sampleScores[, 2], col=culledSampleProperties$Lithology,
pch=19, cex=1.2, cex.lab=1)
points(sampleScores[montanaSamples, 1], sampleScores[montanaSamples, 2], col='white',
pch=20, cex=0.7, cex.lab=1)
legend('bottomleft', legend=levels(sampleProperties$Lithology), box.lty=0,
text.col=palette(lithologyColors))

## Figure 12B
# Plot NMS sample scores coded by Depositional Environment
# Check how many Factors there are in Facies and in which exact order. Then create a
# palette with the colors you want for each facies in the same order.
levels(culledSampleProperties$Facies)
faciesColors <- palette(c('black', '#336600', 'saddlebrown', '#CC9966', '#FF9933',
'#33CC00', '#FFCC33', '#FF9999', '#FFFF66'))
plot(sampleScores[, 1], sampleScores[, 2], xlab="NMS1", ylab="NMS2", main='Log
Transformed NMDS', type='n', las=1)
```

```

points(sampleScores[, 1], sampleScores[, 2], col=culledSampleProperties$Facies, pch=19,
cex=1.2, cex.lab=1)
points(sampleScores[montanaSamples, 1], sampleScores[montanaSamples, 2], col='white',
pch=20, cex=0.7, cex.lab=1)
legend('bottomleft', legend=levels(sampleProperties$Facies), box.lty=0,
text.col=palette(faciesColors), cex=0.5)

## Figure 12C
# Plot NMS sample scores coded by Depositional Sequence
# check how many Factors there are in Sequence and in which exact order. Then create a
palette with the colors you want for each facies in the same order.
levels(culledSampleProperties$Sequence)
sequenceColors <- palette(c('#8DA0CB', '#A6D854', 'green4', 'magenta4', '#FC8D62',
'#FFD92F'))
plot(sampleScores[, 1], sampleScores[, 2], xlab='NMS1', ylab='NMS2', main='Log
Transformed NMS', type='n', las=1)
points(sampleScores[, 1], sampleScores[, 2], col=culledSampleProperties$Sequence, pch=19,
cex=1.2, cex.lab=1)
points(sampleScores[montanaSamples, 1], sampleScores[montanaSamples, 2], col='white',
pch=20, cex=0.7, cex.lab=1)
legend('topleft', legend=levels(sampleProperties$Sequence), box.lty=0,
text.col=palette(sequenceColors))

## Figure 13
# identify species present in only wyoming, only montana, or both
wyoming <- 1:157
montana <- 158:174
counts.wyoming <- culledCounts[wyoming, ]
counts.montana <- culledCounts[montana, ]
wyomingPresent <- colSums(counts.wyoming)
montanaPresent <- colSums(counts.montana)
# Identify species that occur only in Wyoming, only in Montana, shared between both
areas, or are not present in either area (this of course should not happen)
wyomingSpecies <- which(wyomingPresent > 0 & montanaPresent == 0)
montanaSpecies <- which(wyomingPresent == 0 & montanaPresent > 0)
sharedSpecies <- which(wyomingPresent > 0 & montanaPresent > 0)
neverPresent <- which(wyomingPresent == 0 & montanaPresent == 0)
# import vector of sample name codes
species <- c(Nucu, Grha, Grin, Idha, Lima, Lioc, Mosu, Moju, Grpl, Grne, Gryp, List,
Delt, Osin, Loph, Mecu, Cabe, Capl, Cast, CamA, Pein, Ispe, Piki, Vaco, Mymo, Tram, Prci,
Pru, Prsh, Asme, Asli, Aspa, Prfo, Comu, Isin, Coin, Corb, Qusu, Tawa, Tatr, Plsu, Plne,
Phin, Phki, Thwe, Cera, Plro, bivG, bivH, bivI, Tylo, Coka, Proc, Lyos, Nodo, Pseu, Glob,
gasA, wotu, SerA, SerB, SerC, SerD, Hasu, Pade, Iswy, Iskn, Isni, Char, IsoA, Kamy, Bryo,
Rhod, Burr, Cahy)
# plot NMS variable scores
plot(speciesScores[, 1], speciesScores[, 2], xlab="NMS1", ylab="NMS2", cex.lab=1,
type='n', las=1)
text(speciesScores[wyomingSpecies, 1], speciesScores[wyomingSpecies, 2],
labels=species[wyomingSpecies], cex=0.5, col='royalblue4')
text(speciesScores[montanaSpecies, 1], speciesScores[montanaSpecies, 2],
labels=species[montanaSpecies], cex=0.5, col='skyblue1')
text(speciesScores[sharedSpecies, 1], speciesScores[sharedSpecies, 2],
labels=species[sharedSpecies], cex=0.5, col='royalblue1')

```

MONTANA FAUNAL CENSUS

Nucula sp., *Nuculanidae*? , *Grammatodon* *haguei*, *Grammatodon* *inornatum* , *Parallelodontidae* *indet.*, *cf.* *Idonearca* *haguei*, *Lima* sp., *cf.* *Lima* (*Plagiostoma*) *occidentalis*, *cf.* *Ctenostreon* sp., *Ctenostreon* *cf.* *gikshanensis*, *Modiolus* *subimbricatus* , *Modiolus*? sp. *A*, *Modiolus*? sp. *B*, *Modiola* *pertenuis*, *Gervillia*? *montanensis* , *Modiolarca* *jurassica* , *Gryphaea* *planoconvexa* , *Gryphaea* *nebrascensis* , *Gryphaea* sp., *Exogyrinae*? , *Liostrea* *strigilecula* , *Deltoideum* sp., *Ostreidae* *indet.*, *Lopha* sp., *Meleagrinella* *orbiculata* , *Meleagrinella* *curta*, *Camptonectes* *bellistriatus* , *Camponectes* *platessiformis* , *Camponectes* *stygius*, *Camponectes* sp. *A*, *Pectinidae* *indet.*, *Isognomon* *cf.* *perplana* , *Pinna* *kingi* , *Vaugonia* *conradi*, *Vaugonia* *strurgisensis* , *Myophorella* *montanaensis*, *Trigonia* *elegantissima*, *Trigonia* *americana*, *Pronoella* *cinabarensis*, *cf.* *Pronoella* *uintahensis*, *cf.* *Cyprina* *iddingsi*, *Anisocardia*? , *Protocardia* *cf.* *shumardi* , *Astarte* *meeki* , *Astarte* *livingstonensis*, *Astarte* *packardii* , *Prorokia* *fontenellensis*, *Opis* (*Trigonopsis*) sp., *Mesomiltha*? sp., *Unicardium*? , *Corbula* *cf.* *munda*, *Isocyprinidae* *indet.*, *Corbicellopsis* *cf.* *inornata*, *Corbicellopsis* sp., *Quenstedtia* *sublevis*, *Quenstedtia* *arcuata*, *Quenstedtia* sp., *Tancredia* *warrenana* , *Tancredia* *transversa* , *Tancredia*? sp., *Pleuromya* *subcompressa* , *Pleuromya* *newtoni* , *Pleuromya* *cf.* *subelliptica* , *Pleuromya* *cf.* *uralensis* , *Pholadomya* *inaequiplicata*, *Pholadomya* *kingi* , *Pholadomya*? , *Homomya* *gallatinensis* , *Thracia* *weedi*, *cf.* *Ceratomya* sp., *Platymya* *rockymontana* , *cf.* *Platymya* *rockymontana* , *Bivalve* *indet.* *A*, *Bivalve* *indet.* *B*, *Bivalve* *indet.* *C*, *Bivalve* *indet.* *D*, *Bivalve* *indet.* *E*, *Bivalve* *indet.* *F*, *Bivalve* *indet.* *G*, *Bivalve* *indet.* *H*, *Bivalve* *indet.* *I*, *Bivalve* *indet.* *J*, *Tylostoma*? sp., *Cossmannia* *imlay*, *Cossmannia*? *kanabensis*, *Cossmannia*? sp., *Procerithium*? sp., *Rhabdocolpus* *viriosus* , *Lyosoma* sp., *Neritina* *wyomensis* , *Nododelphinula*? sp., *Pseudomelania*? sp., *Cylindrobullina*? sp., *Trochacea*? sp., *Globularia*? sp., ""Naticid"" *gastropod* *indet.* , *Gastropod* *indet.* *A*, *Worm* *tubes* *indet.*, *Serpulidae* *indet.* *A*, *Serpulidae* *indet.* *B*, *Serpulidae* *indet.* *C*, *Serpulidae* *indet.* *D*, *Serpulidae* *indet.* *E*, *Hamulus* *subquadratus* , *Pachyteuthis* *densus*, *cf.* *Holectypus* *pealei*, *Isocrinus* *wyomingensis* , *Isocrinus* *knighti*, *Isocrinus* *nicoleti*, *Chariocrinus* sp., *Isocrinidae* *indet.* *A*, *Isocrinidae* *indet.* *B*, *Isocrinidae* *indet.* *C*, *Isocrinidae* *indet.* *D*, *Kallirhynchia* *myrina*, *Lingula* *brevirostris*, *Bryozoa* *indet.*, *Microeciella* sp., *Eryma* sp., *Coenastrea* *hyatti*, *Rhodolith* *indet.*, *Tooth* *indet.*, *Cardioceras* *hyatti*, *Terebratulid* *indet.* *A*, *Kepplerites* *mclearni*, *Arctocephalites* *sweetgrassensis*, *Trigonid* *indet.* *A*, *Terebratulid* *indet.* *B*, *Parachondroceras* *filicostatum*, *Arthropod* *indet.*, *Pinna* *indet.*, *Ichthyosaur* *indet.*

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APPENDIX F

MONTANA SAMPLE PROPERTIES

The sample properties for Wyoming are included in the supplemental materials for Danise and Holland (2017). This is part of the file “sampleProperties.csv” in Appendix D.

Samples, Locality, Formation, Sequence, Facies, Lithology, Collector
AS-L2, Allied Steel, Piper, J1a, Open Shallow Subtidal, Carbonate, Swenson
BR-D, Burleigh Ranch, Piper, J1a, Ooid Shoal, Carbonate, Swenson
BR-m1, Burleigh Ranch, Swift, J4, Offshore, Siliciclastic, Swenson
BR-m2, Burleigh Ranch, Swift, J4, Offshore, Siliciclastic, Swenson
BR-m3, Burleigh Ranch, Swift, J4, Offshore, Siliciclastic, Swenson
BR-m4, Burleigh Ranch, Swift, J4, Offshore, Siliciclastic, Swenson
BR-m5, Burleigh Ranch, Swift, J4, Offshore, Siliciclastic, Swenson
BR-U, Burleigh Ranch, Swift, J4, Offshore Transition, Siliciclastic, Swenson
BSH-A1, Big Springs Hatchery, Swift, J4, Offshore, Siliciclastic, Swenson
BSH-A2, Big Springs Hatchery, Swift, J4, Offshore, Siliciclastic, Swenson
BSH-A3, Big Springs Hatchery, Swift, J4, Offshore, Siliciclastic, Swenson
BSH-B, Big Springs Hatchery, Swift, J4, Offshore Transition, Siliciclastic, Swenson
LC-Am, Landusky Cut, Rierdon, J3, Offshore, Carbonate, Swenson
LC-I, Landusky Cut, Rierdon, J3, Offshore, Carbonate, Swenson
SH-A, Star Hill, Rierdon, J3, Deep Subtidal, Carbonate, Swenson
SH-Am, Star Hill, Rierdon, J3, Deep Subtidal, Carbonate, Swenson
SH-bottom, Star Hill, Rierdon, J3, Deep Subtidal, Carbonate, Swenson
SH-top, Star Hill, Rierdon, J3, Deep Subtidal, Carbonate, Swenson
SL-A1, Schwanky Lot, Rierdon, J3, Deep Subtidal, Carbonate, Swenson
SL-L, Schwanky Lot, Swift, J4, Offshore, Siliciclastic, Swenson
SL-P, Schwanky Lot, Swift, J4, Offshore, Siliciclastic, Swenson
SL-Q, Schwanky Lot, Swift, J4, Offshore, Siliciclastic, Swenson
SL-S, Schwanky Lot, Swift, J4, Offshore, Siliciclastic, Swenson
SL-W2, Schwanky Lot, Swift, J4, Offshore, Siliciclastic, Swenson
SL2-A, Schwanky Lot, Swift, J4, Offshore, Siliciclastic, Swenson
ZD-E, Zortman Dump, Swift, J4, Offshore, Siliciclastic, Swenson