THE OCCURRENCE OF VERTEBRATE AND INVERTEBRATE FOSSILS IN A SEQUENCE STRATIGRAPHIC CONTEXT: THE JURASSIC SUNDANCE FORMATION, BIGHORN BASIN, WYOMING, USA

by

SHARON KATE MCMULLEN

(Under the direction of Steven M. Holland)

ABSTRACT

Fourteen outcrops and six supplemental partial outcrops of the Middle to Upper Jurassic Sundance Formation were measured and described along the eastern flank of the Bighorn Basin, Wyoming to develop a sequence stratigraphic interpretation and to evaluate the occurrence of marine fossils. The Sundance Formation contains four depositional sequences with three distinct facies associations. The lowest two sequences preserve a carbonate ramp, the third sequence preserves a siliciclastic low-energy wave-dominated margin, and the final sequence preserves an estuarine incised-valley fill. Preservation of marine vertebrates and invertebrates in the Sundance is governed by both facies and sequence stratigraphic architecture. Invertebrates in the lower Sundance are distinct from invertebrates in the upper Sundance. Vertebrates occur only in the upper Sundance and can be found on flooding surfaces, within mudstone, or in a channel lag. Vertebrate preservation is best along a maximum flooding surface that preserves partially articulated specimens within fine-grained concretions.

INDEX WORDS: Sundance Formation, Middle Jurassic, sequence stratigraphy, fossils, mixed siliciclastic-carbonate system

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

This thesis is best read as one chapter, given that it is written in the form of a manuscript intended for submission to the journal *PALAIOS*. The second chapter includes the discussion of the previous literature, geologic background, methods, results, interpretation, discussion, and conclusions. The third chapter concludes the research.

The purpose of this study was to create a sequence stratigraphic interpretation of the Middle Jurassic Sundance Formation exposed along the eastern flank of the Bighorn Basin, Wyoming and to develop an understanding of the relationship of fossil occurrences to this sequence stratigraphic framework. This paper established three facies models and four depositional sequences. The invertebrate and vertebrate fossil occurrences were evaluated based on stratigraphic surfaces they occur on or the facies in which they were found. Fossil preservation quality and abundance were also evaluated to determine the effects of sequence stratigraphic and facies control on fossils in the Sundance.

Previous research has reported on the sequence stratigraphic occurrences of invertebrate fossils (Holland, 1995; Holland, 2000; Brett, 2000) but few studies have been done on the sequence stratigraphic occurrences of vertebrate fossils (Rogers and Kidwell, 2000; Peters et al., 2009). While previous workers have noted facies (Pipiringos, 1968; Imlay; 1956; Uhlir et al., 1988; Kilibarda and Loope; 1997; Wright, 1973; Kvale et al., 2000) and fossil occurrences (Wright; 1973; Kvale et al., 2001; Wahl et al., 2007;

O’Keefe and Street, 2009) within the Sundance, a sequence stratigraphic interpretation of the facies and fossil occurrences has not been conducted.

CHAPTER 2

THE OCCURRENCE OF VERTEBRATE AND INVERTEBRATE FOSSILS IN A SEQUENCE STRATIGRAPHIC CONTEXT: THE JURASSIC SUNDANCE FORMATION, BIGHORN BASIN, WYOMING, USA[1]

[1] McMullen, S.K, Holland, S..M., O'Keefe, F.R., and Cameron, C.S. To be submitted to *PALAIOS*.

INTRODUCTION

Sequence stratigraphy provides a framework to understand the distribution of fossils (Brett, 1995; Holland, 1995). Studies of invertebrate fossils have recognized abrupt changes in abundance, community structure, and morphology at major flooding surfaces and sequence boundaries (Holland, 2000; Kidwell and Holland, 2002). Fewer comparable analyses of vertebrate fossils are available, but they demonstrate disarticulated elements on major flooding surfaces, well-preserved fossils in the falling stage systems tract, and skeletal lags at erosional surfaces (Rogers and Kidwell, 2000; Peters et al., 2009). Because marine vertebrate fossils differ from invertebrates in size, abundance, durability, and composition (Peters et al., 2009), a better understanding of how these differences effect preservation and stratigraphic distribution is needed. By understanding preservational controls, we can gain an understanding of where it is stratigraphically most probable to find rare articulated vertebrates and the more common invertebrate fossils.

The Middle Jurassic Sundance Formation of the western United States is an ideal setting to compare sequence stratigraphic controls on both invertebrates and vertebrates because it is extensively exposed and it contains a diverse invertebrate and vertebrate fauna (Imlay, 1965; O'Keefe et al., 2009). This study presents a sequence stratigraphic interpretation of the Sundance Formation in the Bighorn Basin of Wyoming, and uses it to understand the stratigraphic controls on invertebrate and vertebrate preservation to better understand taphonomic biases in the fossil record.

This study is significant at a regional level as well, because understanding the sequence stratigraphy of the Sundance Formation helps to resolve correlation in the

Sundance Formation. The Sundance Formation is composed of seemingly complex isolated siliciclastic and carbonate bodies, whose correlation is uncertain (Imlay, 1965; West, 1985). Previous workers have not considered the relationship between systems tracts (DeJarnette and Utgaard, 1986; Kilibarda and Loope, 1997). By studying lithofacies of the Sundance Formation from a sequence stratigraphic perspective, the interpretation of depositional systems is straightforward.

GEOLOGIC CONTEXT

Middle Jurassic Stratigraphy of the Bighorn Basin

The Bathonian to Oxfordian (169-155 Ma; Imlay, 1956) Sundance Formation is a cyclic, mixed siliciclastic-carbonate deposit composed of isolated sand and carbonate bodies exposed on a series of hogbacks along the eastern flank of the Bighorn Basin (Fig. 1; Parcell and Williams, 2005). The Sundance Formation overlies the late Bajocian Gypsum Spring Formation, or in some localities, the early Bathonian Piper Formation (Fig. 2). The Sundance Formation is overlain by terrestrial deposits of the Late Jurassic (155-135 Ma) Morrison Formation (Imlay, 1962; Pipiringos, 1968; Imlay, 1980).

The lithostratigraphic divisions of the Sundance Formation are complex (Fig. 2; Imlay, 1947; Pipiringos, 1968; Wright, 1973; Imlay, 1980; West, 1985; Kvale et al., 2001). Up to seven members of the Sundance Formation are locally identifiable (Pipiringos, 1968). The Sundance in the Bighorn Basin is divided informally in to lower and upper units because these members cannot always be distinguished here (Imlay, 1956; Wright, 1973; Rautman, 1976). The lower Sundance in the Bighorn Basin is divided in to the lower carbonate submember, Stockade Beaver Shale member, and upper

carbonate submember (Imlay, 1956). The upper Sundance is divided in to two members: the Redwater Shale and the Windy Hill Sandstone (Imlay, 1957; Pipiringos, 1968). The uppermost unit, the Windy Hill Sandstone, is sometimes regarded as the basal member of the Morrison Formation because the contact with the Morrison is often gradational (Pipiringos, 1968). In this study, the Windy Hill will be treated as part of the Sundance.

Paleogeography

During the middle Bathonian to middle Oxfordian, the Bighorn Basin and surrounding areas were inundated by the Sundance Seaway, a shallow epeiric sea that extended southward from the Arctic Ocean into Canada and along the western margin of the United States (Fig. 3; Imlay, 1957; West, 1985; Kvale et al., 2001). The seaway was bounded to the east by the North American craton and it was separated to the south from the Gulf of Mexico by the Ancestral Rockies uplift (Kvale et al., 2001). Within the Bighorn Basin, the depositional slope was to the northwest (Imlay, 1980). Paleogeographic reconstructions place Wyoming at 15°N to 20°N during the Middle Jurassic (e.g., Saleeby and Busby-Spera, 1992).

Sea-level Changes

Jurassic strata in the Western Interior record at least four major eustatic fluctuations: one in the Early Jurassic (Pliensbachian-Toarcian), two in the Middle Jurassic (Bajocian-Early Callovian), and one in the Late Jurassic (early Oxfordian; Fig. 2; Imlay, 1957; Pipiringos, 1968; Pipiringos and O'Sullivan, 1978; Kvale et al., 2001). As

eustatic sea level fluctuated, each successive transgression pushed the shoreline farther to the southeast (Pipiringos and O'Sullivan, 1978; Kvale et al., 2001).

The Bajocian to Early Callovian (171-164 m.y.) lower Sundance Formation in the Bighorn Basin represents the third of these transgressions (Imlay 1980; West, 1985; Kvale et al., 2001). Recent work suggests that three third-order (1-10 m.y.) eustatic subcycles are nested within the second-order (10-100 m.y.) cycle of the lower Sundance Formation in the Bighorn Basin (Fig. 2; Kvale et al., 2001). Each of these cycles and subcycles is bounded by an unconformity (Kvale et al., 2001). The Late Callovian and Early Oxfordian (163-155 Ma) upper Sundance Formation in the Bighorn Basin records the fourth and final second-order cycle of eustatic fluctuation. This final second-order cycle is also bounded by unconformities (Imlay 1980; Kvale et al., 2001).

METHODS

Field-section measurements

Stratigraphic columns of the Sundance Formation were measured along a ~240 km northwest to southeast trending transect on the eastern margin of the Bighorn Basin in Wyoming (Fig. 1). Localities were chosen where vertebrate fossils were previously excavated and where there was good exposure (Appendix A). Fourteen nearly complete stratigraphic columns and six supplemental partial stratigraphic columns were measured. Most columns were closely spaced (i.e., 5-15 km) but the three southernmost columns were spaced at greater distances to evaluate how the stratigraphy changed to the south.

At each section, beds were described for physical sedimentary structures, color, lithology, grain size and angularity, sorting, continuity, thickness, digenetic minerals,

bioturbation, ichnofossils, and body fossils. The Ingram (1954) logarithmic scale for bedding thickness was used in this study: a very thin bed is 1-3 cm, a thin bed is 3-10 cm, a medium bed is 10-30 cm, a thick bed is 30-100 cm, a very thick bed is 100-300 cm, and a massive bed is over 300 cm. Siliciclastic rock names follow the classification system from Pettijohn et al. (1987). Carbonate rock names follow Duhnam (1962) for classification.

Censuses of invertebrate (Appendix B) and vertebrate fossils were conducted in the field on bedding planes and weathered shale surfaces, depending on the lithofacies. Faunal censuses were performed for 15-20 minutes per unit area to provide a consistent sampling effort. Unit areas consisted of 1-2 square meters. Faunal abundance of each species was recorded as rare (1-2 specimens), common (3-10 specimens), abundant (10-20 specimens), or very abundant (>20 specimens). A total of 185 faunal censuses were made (Appendix C).

A total of twenty thin sections were prepared from samples from to characterize lithology. Samples were also collected for fossil identification.

Quantitative paleoecology

Ordination analysis was used to identify and describe faunal gradients in the invertebrate and vertebrate data, and to determine any associations between fossil assemblages and lithofacies. Data were ordinated with both Non-Metric Multidimensional Scaling (MDS) and Detrended Correspondence Analysis (DCA) to determine trends in faunal assemblages. Both methods have been previously successful in identifying ecological gradients (Jongman et al., 1995), but for this study, MDS more

successfully distinguished gradients so only the results for MDS are presented here. MDS analyses were performed with the metaMDS function in the VEGAN package of the open source statistical software R version 2.13.1 (R Development Core Team, 2011). The Wisconsin double standardization transformation was applied to the data prior to the analysis to avoid the ordination focusing on different sample sizes and to put species on an equal footing to account for species that are dominant. Prior to ordination, species that occurred in only one sample and samples that contained only one taxon were culled because such samples provide no information on faunal gradients. This culling reduced the number of samples from 185 to 53. Twenty restarts were used in the analysis to avoid local minima in the ordination by repeatedly choosing random positions.

SUNDANCE FACIES ASSOCIATIONS

Facies were identified in the field and petrographically based on lithology, grain size, sedimentary structures, body fossils, ichnofossils, and facies association. Separate facies models were constructed for the predominantly carbonate lower Sundance, the siliciclastic upper Sundance, and the incised valley fill deposits of the Windy Hill Sandstone (Fig. 4).

Facies Association C: Lower Sundance Carbonate Ramp

The lower Sundance contains four facies: offshore (C1), deep subtidal (C2), shallow subtidal (C3), and lagoonal (C4; Fig. 4, top; Fig. 5, A). The lower carbonate (Fig. 2) is represented by shallow subtidal deposits, the Stockade Beaver Shale is represented

by offshore deposits, and the upper carbonate is represented by shallow subtidal and lagoonal deposits.

Facies C1: Offshore

Description.--Facies C1 consists of beds of tan to gray arenaceous mudstone with abundant shells of *Gryphaea nebrascensis* (Fig. 5, B). These shells are commonly disarticulated and abraded, except in rare cases. Facies C1 lacks physical and biogenic sedimentary structures. At the top of the unit, the mudstone contains pyrite that coats *Gryphaea nebrascensis*, and pyrite also occurs as 0.5 cm nodules.

Microfossils present include abundant benthic foraminifera, abundant ostracods, and common echinoid spines. One unidentified microfossil fish tooth was found at the Sheep Mountain-*Pantosaurus* Site near Greybull, Wyoming.

Facies C1 ranges from 5 to 30 meters thick and generally thins to the southeast. In the northernmost outcrops near Lovell, Wyoming (i.e., Little Sheep Mountain A, B, C, and D outcrops) Facies C1 is sharply overlain by Facies C4, a lagoon. In all other outcrops where Facies C1 is present, Facies C3, shallow subtidal deposits, sharply overlies it. Facies C1 is not present south of Hyattville.

Interpretation.--Facies C1 is interpreted as having been deposited in an offshore environment on a carbonate shelf below storm wave base, indicated by its mudstone lithology, lack of sedimentary structures, thickness, and lateral continuity (cf. Read, 1985). A relatively calm depositional environment is indicated by grain size, the lack of physical sedimentary structures, and the lack of bioturbation (Burchette and Wright,

1992). Fe-oxides are interpreted as oxidation of pyrite by modern groundwater. Pyrite is typical of reducing marine porewater (Maynard, 1982).

The thinning of Facies C1 to the southeast, observed in this study, likely indicates structural thinning onto the Sheridan Arch, a topographical and structural high recognized by previous workers (Peterson, 1954; Imlay, 1956; West, 1985; and Kvale et al., 2001).

Facies C2: Deep Subtidal

Description.--Facies C2 consists of very thinly laminated gray to brown calcareous mudstone and siltstone that grade into a variable skeletal packstone to wackestone (Fig. 5, C). Within the mudstone and siltstone, no recognizable body fossils, trace fossils, or sedimentary structures were observed. Lingulid brachiopods have been reported (West, 1985). Intervals and siltstone are generally 0.5 to 5 m thick.

The mudstone and siltstone coarsen upward into laterally discontinuous beds of packstone to wackestone (Fig. 5, C) with common shell hash of well-to-moderately sorted unidentifiable bivalves and common fragments of the crinoid, *Chariocrinus*. *Myopholas*, a bivalve, is common in Facies C2. The wackestone to packstone is typically heavily bioturbated, destroying any laminations. Pyrite staining is common on the limestone. Rare to common ooids increase in abundance upsection. Quartz silt also increases upsection. Rarely, partially articulated *Chariocrinus* are preserved. Common large gastropod molds (2-3 cm) are present at the Shell-Red Gulch Dinosaur Tracksite outcrop and common small gastropods (<1 cm) are present at the Dirty Annie's and Trapper Creek localities. Abundant 1 cm pisoids were observed at the Shell-Trapper Creek Road locality and are developed around neomorphosed bivalve fragments. In

outcrop, beds of the skeletal wackestone to packstone are 0.1 to 0.5 m thick and generally thicken upsection.

In thin section, common-to-abundant subangular to subrounded very fine to fine-grained quartz and rare-to-common coarse chert grains are present, and both increase in abundance upsection. Abundant skeletal and quartz grains have been coated with spongiostromate (Flügel, 2004). Rare to common codiacean algae and rare ostracods are also present.

Typically, three distinct shallowing-upward cycles of mudstone and siltstone grading to wackestone to packstone can be observed in the field (Fig. 5, C). The top bed of the wackestone to packstone is often wave-ripple laminated, contains abundant ooids, and abundant quartz silt to very-fine sand. At Shell-Red Gulch Dinosaur Tracksite, this capping bed has firmgrounds that preserve tridactyl dinosaur footprints on the surface and contain traces belonging to the *Skolithos* ichnofacies (Kvale et al., 2001). Facies C2 is not present south of Hyattville. Facies C2 lies at the base of the Sundance and gradationally overlies red mudstone and siltstone deposits of the Piper Formation. Facies C3, an ooid shoal, gradationally overlies Facies C2 (Fig 5, A).

Interpretation.--Facies C2 is interpreted as a deep subtidal depositional environment on a carbonate shelf between storm and fair-weather wave base. Mudstone to siltstone beds with common storm beds are typical of a carbonate deep subtidal depositional environment (cf. Read, 1985). Fragmented, abraded, and moderate to well sorted skeletal material reflects storm reworking (cf. Choi and Simo, 1998). Abundant bioturbation destroyed any sedimentary structures in the skeletal wackestone to packstone with the exception of the uppermost units that display wave-ripple lamination (cf. Read,

1985). Pyrite nodules are indicative of reducing marine porewater (Maynard 1982). Codiacean algae are commonly associated with shallow-water platform carbonates during periods of non-deposition, allowing time for firmgrounds to develop (Flügel, 2004). The *Skolithos* ichnofacies represents a sandy environment with strong waves and currents (Seilacher; 2007).

An increase in ooids and quartz in the uppermost unit suggests a more proximal deep subtidal depositional environment; with some input of ooids and quartz from Facies C3, which gradationally overlies Facies C2. Increase of quartz silt present in the packstone to wackestone southward suggests a southern source.

Facies C3: Shallow Subtidal

Description.--Facies C3 consists of an oolitic quartz-rich packstone to a grainstone. Bivalve and crinoid shell hash, pebble-sized chert, and pyrite nodules are rare to common. Shell hash includes common abraded *Gryphaea nebrascensis* from the underlying Facies C1. Facies C3 is often lenticular, and exhibits wave-ripple lamination overlain by planar lamination and large-scale cross stratification (Fig. 5, D). Commonly beds appear uniform with no laminations or sedimentary structures discernable. At the Hyattville outcrop, *Gryphaea nebrascensis* coated with spongiostromate (Flügel, 2004) are common.

These deposits are typically ~5 m thick and occur in outcrop from Sheep Mountain-County Road 1138 to Hyattville. The base is always in sharp contact with Facies C1, and Facies C3 is always sharply overlain by Facies S1.

In outcrops south of Lovell and north of Shell (Sheep Mountain-County Road 1138, Sheep Mountain, Sheep Mountain-*Pantosaurus*, and Shell-Horse Creek Road), the oolitic packstone to grainstone exhibits large-scale trough cross stratification in cosets up to 12-m thick, as well as planar lamination (Kilibarda and Loope, 1997). The laminae within the cross stratification is inversely graded. Reworked bivalves, intraclasts, and ooids are preferentially aligned along foresets of large-scale trough cross-stratification. Wave-ripple lamination is also sometimes present in the uppermost ~5 cm above the large-scale cross-stratification (i.e., Shell-Horse Creek Road).

Petrographically, abundant ooids, abundant very fine- to fine-grained subrounded quartz, common pyrite nodules, rare chalcedony, and rare gastropods are present. Ooids often occur in groups cemented by micrite as composites or grapestones. Vadose cements have been recognized in some of the deposits (Kilibarda and Loope, 1997).

Facies C3 thickens and then thins from north to south, with a maximum thickness of ~12 m at the Dirty Annie's locality. Facies S1 sharply overlies Facies C3.

Interpretation.--Facies C3 represents an ooid shoal that formed on a shallow subtidal carbonate shelf (Choi and Simo, 1998). The ooid shoal sediments were subsequently subaerially exposed and climbing wind ripples formed eolian large-scale trough cross stratification present south of Lovell, Wyoming and to the north of Greybull, Wyoming (Fig. 5, D; Kilibarda and Loope, 1997). Recognition of vadose cements in deposits indicates subaerial exposure (Kilibarda and Loope, 1997). Pyrite nodules likely represent pyrite that has been reworked from the underlying Facies C1. The reworked *Gryphaea nebrascensis* and chert pebbles are also likely from the underlying facies because they are only present in the lower portion of the facies exposure. The lack of

sedimentary structures or laminations in some beds is interpreted to be the result of pervasive bioturbation.

Previously these deposits were interpreted as marine, oolitic sand bodies (Stone and Vondra, 1972). Current ripples in the uppermost portion of these exposures caused previous workers to identify these deposits as entirely marine. The current ripples likely formed after the eolianites were subsequently inundated (Kilibarda and Loope, 1997).

Facies C4: Lagoon

Description.--Facies C4 is represented by very thinly to thinly bedded, planar-laminated gray lime mudstone with flaser to lenticular laminations (Fig. 5, F). The planar-laminated lime mudstone contains abundant fine-grained quartz sand, and it is interbedded with beds of unconsolidated, quartz-poor lime muds. Insects, ostracods, and abundant fossil fish have been reported from bedding planes of Facies C4 in southern Montana (DeJarnette and Utgaard, 1986).

Bed thickness increases upsection and to the south. Total thickness in outcrops ranges from ~5 m to ~12 m. Facies C4 is restricted to the northernmost sections at Little Sheep Mountain, Wyoming. The base of Facies C4 sharply overlies Facies C1 and is sharply overlain by Facies S2 (i.e., Little Sheep Mountain A and B outcrops) or by Facies S1 (i.e., Little Sheep Mountain D and C outcrops).

Interpretation.--Facies C4 is interpreted as a lagoonal depositional environment on a carbonate ramp. Facies C4 was deposited on the landward side of an oolitic shoal (Facies C3) that protected it from waves, allowing for settling of silt and clay from suspension and the formation of thin (1-2 mm) laminations. Facies C4 can be

distinguished from a tidal flat based on the lack of subaerial exposure features, and a faunal association of ostracods and fish scales. Previous studies have also interpreted this depositional environment as a restricted lagoon (Imlay, 1965; DeJarnette and Utgaard, 1986; Kilibarda and Loope, 1997).

Summary

The lower Sundance was deposited on a homoclinal epeiric-sea carbonate ramp in a foreland basin (Imlay, 1956; Choi and Simo, 1998; Burchette and Wright, 1992). No modern analogs exist for comparison but during the Jurassic there was extensive development of carbonate ramps (Burchette and Wright, 1992). Modeling of two well-exposed Jurassic platforms suggest that production of shallow-water carbonates was 1-2 orders of magnitude less than what is predicted for modern open-marine carbonate platforms (Aurell et al., 1995). The lower Sundance is similar to the general framework of other Jurassic carbonate ramps with fossiliferous offshore mudstone deposits, grading into deep subtidal deposits with frequent skeletal wackestone to packstone storm beds, passing into ooid shoals that protect tidal flats or lagoons (Aurell, 1991; Azeredo, 1998).

There have been several previous studies on the facies of the lower Sundance (Stone and Vondra, 1972; Wright, 1973; West, 1984; Dejarnette and Utgaard, 1986; Brenner and Peterson, 1994; Kilibarda and Loope, 1997; Kvale et al., 2001). Initially, the lower Sundance was considered to be much deeper (Stone and Vondra 1972; Wright, 1973; West, 1984; Dejarnette and Utgaard, 1986) than recent studies suggest (Kilibarda and Loope, 1997; Kvale et al., 2001). While not all previous studies have identified Facies C1 as an offshore facies, previous work does recognize the need for a low-energy

depositional setting (West, 1984). This study's interpretation of Facies C2 as a deep subtidal depositional setting with frequent storm beds is also supported by previous studies (West, 1984; Wright, 1973; Kvale et al., 2001). A locally preserved dinosaur megatracksite indicates subaerial exposure and the formation of a microbial mat, creating a firmground, which caps the top of Facies C2 (Kvale et al., 2001). Facies C3 was originally thought to represent only ooid shoals (Stone and Vondra, 1972; West, 1984) but recent studies have noted diagnostic eolian structures (Kilibarda and Loope, 4997) that are also recognized in this study. Facies C4 has been interpreted as both a tidal flat (West, 1984) and a lagoon (Imlay, 1965; Dejarnette and Utgaard, 1986; Kilibarda and Loope, 2001). This study identifies Facies C4 as a lagoon facies based on laminations, limited regional extent, lack of evidence for subaerial exposure, and reports of fish scales from this facies.

Facies Association S: Upper Sundance Wave-Dominated Siliciclastic Margin

The lower Sundance contains two facies: offshore and transition zone (Fig. 4, middle). Both of these facies are included in as the Redwater Shale (Fig. 2; Pipiringos, 1968).

Facies S1: Offshore

Description.--Facies S1 is characterized by an olive gray mudstone that grades upwards into a tan sandy mudstone with localized *Ostrea* beds. The mudstone is often glauconitic, giving the facies an olive color. In outcrop, two gray-to-tan coarsening-upwards sequences are present representing an upward decrease in glauconite and

increase in quartz sand. Locally discontinuous oyster shoals cap the first coarsening-upward sequence, and the second succession is capped by unfossiliferous fine-grained concretions. The boundaries of these successions can be identified by a change in lithology and color (Fig. 6, A). This lithologic change can often be recognized at a distance by a line of vegetation that develops at this contact. There are no apparent sedimentary structures in Facies S1.

Invertebrate and vertebrate fossils occur in localized beds, as shoals, in the mudstone, and within concretions below oyster shoals. Fine-grained concretions occur both below and above oyster shoals but only the concretions below the oyster shoals are fossiliferous. The fossiliferous concretions occur in the northernmost outcrops and are either not present or are unfossiliferous south of Shell-Trapper Creek Road. Invertebrate fossils that occur within concretions include abundant bivalves such as *Astarte* and *Pleuromya*, and *Vaugonia*, and common belemnites. The ammonite, *Cardioceras*, occurs rarely to commonly. Invertebrate fossils are often recrystallized or occur as internal molds. Vertebrate fossils occur rarely within concretions and include disarticulated and partially articulated ichthyosaurs and plesiosaurs (Fig. 6, B, C). In the upper Sundance, the ichthyosaur *Opthamalosaurus natans* (Fig. 6, D) is present, as are the plesiosaurs *Pantosaurus striatus* and *Tatenectes laramiensis*. Ichthyosaurs comprise 70% of museum-accessioned marine reptiles from the Sundance, while plesiosaurs only account for 30% (Wahl et al., 2007). The trace fossils, *Planolites* (Fig. 6, E) was commonly observed within concretions.

Fossils occur along beds, as shoals, and within the mudstone in Facies S1. Thin (0.1-0.2 m) localized beds of the scallop, *Camptonectes bellistriatus*, occur above and

below the oyster shoals (Fig. 6, F). The scallop shells are commonly partially broken to whole. Rarely, belemnites can be observed in the scallop beds in the field, and rarely dasyclads can be observed petrographically. Abundant disarticulated and broken *Ostrea* occur in discontinuous mounds as oyster shoals. Belemnites are abundant immediately below the oyster shoals and decrease in abundance 1-2 m below the oyster shoals. Regular echinoids occur rarely below oyster shoals at the Little Sheep Mountain localities and Shell-Red Gulch Dinosaur Tracksite (Fig. 7, A). Above the oyster shoals, belemnites are rare to common. Rare to common vertebrate material occurs within the mudstone and is commonly disarticulated and rarely partially articulated (Fig. 7, B).

Facies S1 is present at all localities and is gradationally overlain by transition zone to lower shoreface facies (Fig. 7, C). Facies S1 is typically ~40 m thick in outcrop but ranges from ~15 m at Hyattville to ~65 m at Little Sheep Mountain C and Sheep Mountain. In outcrop, Facies S1 usually has one oyster shoal present. Sheep Mountain Anticline has two oyster shoals present, and there was no oyster shoal present at Little Sheep Mountain B. The occurrence of two oyster shoals at Sheep Mountain Anticline may be the result of a thrust fault hidden within the mudstone, as this area is faulted and folded. Since oyster shoals are locally discontinuous, an oyster shoal may have been present near the Sheep Mountain B locality but not along the line of measured section.

Interpretation.--Facies S1 is interpreted as having been deposited in a low-energy offshore environment below storm wave base. The lack of distal storm beds suggests that this is a low-energy rather than a high-energy offshore depositional environment (Clifton, 2006). Additionally, laterally continuous offshore shoals form in

low-energy systems where silt and sand is deposited during storm events but wave-energy is not high enough to remove the sediment (Tanner, 1961).

Similar *Camptonectes* beds occur in Upper Oxfordian deposits of Milne Land, East Greenland and have been interpreted as offshore storm events that reworked *Camptonectes* beds (Fürsich and Heinberge, 1983). Additionally, the only abundant trace fossil from Facies S1, *Planolites*, is commonly found in offshore environments in association with the rarely observed *Rhiozocorallium* (Clifton, 2006). The ammonite *Cardioceras* dates Facies S1 as middle Callovian (Calloman, 1982; Fig. 6, B).

Facies S2: Transition Zone

Description.--Facies S2 is composed of a light tan fine-grained sublitharenite to litharenite (Pettijohn and Potter, 1987) that is often argillaceous and occurs in very thin (<3 cm) to thin (3-10 cm) beds that are interbedded with thin-to-thick (30-100 cm) light brown siltstone beds. In outcrop, sandstone beds thicken upsection and become more frequent, while beds of siltstone become less frequent and thin (Fig 7, C). Sandstone beds commonly have wave-ripple lamination (Fig. 7, D), planar lamination, current-generated ripple lamination, and rarely sigmoidal crossbedding. These sedimentary structures usually occur in very thin beds. Sometimes beds lack laminations or sedimentary structures. *Planolites*, *Chondrites*, and indistinguishable lined unbranching curved vertical burrows rarely occur in the sandstone beds (Fig. 7, E, F; Fig. 8, A). Facies S2 contains rare poorly preserved bivalves and bivalve molds. Rarely, deformed and partially articulated vertebrate material is present. A partially articulated plesiosaur,

Tatenectes laramiensis, was found near the Dirty Annie's locality in Facies S2 (O'Keefe and Street, 2009).

Abundant fine-grained subrounded quartz grains, common glauconite, common black chert, and rare feldspar that are moderately sorted make up this sublitharenite to litharenite. Grains are cemented with abundant carbonate cement and rare goethite cement. Pyrite coatings of the sandstone are common.

Facies S2 gradationally overlies the offshore deposits of Facies S1 and is erosively overlain by the lag deposits of I1 (Fig. 8, B). The total thickness of Facies S2 varies among outcrops from ~0.5 to 10 m, owing to incision prior to overlying incised valley fill deposits.

Interpretation.--Facies S2 was deposited in a transition zone depositional environment. Facies S2 gradationally overlies the offshore facies (Facies S1), suggesting that it should be the transition zone based on Walther's Law. The interbedded sandstone with mudstone represents temporally fluctuating deposition and is a diagnostic feature of transition zone deposits. An increase of sandstone to mudstone beds upsection suggests that the environment is becoming more proximal, and it may grade into distal shoreface deposits. The abundance of wave-ripple lamination suggests frequent disturbance by waves (Raaf and van Gelder, 1977; Clifton, 2006). The lack of hummocky cross-stratification suggests a relatively low-energy margin (Clifton, 2006). The lack of sedimentary structures or laminations in some beds is interpreted to be the result of bioturbation.

Summary

The upper Sundance was deposited on a low energy wave-dominated siliciclastic margin and can be divided into two facies: an offshore facies (Facies S1) and a transition zone facies (Facies S2). Low-energy wave-dominated coasts vary from high-energy coasts, in that low-energy systems generally have thinner deposits, the maximum grain size is typically fine-grained, and deposits lack upper flow regime sedimentary structures (Clifton, 2006). Modern low-energy analogs are present in southeastern Spain and along the Georgia coast (Howard et al., 1972; Clifton, 2006). Studies from the Georgia mesotidal coast indicate that the largest grain size seen in low-energy coasts is typically fine-grained sand because the wave-energy is not sufficient to transport coarser sediment (Howard et al., 1972). Similarly, the largest grain size in the Sundance is fine-grained sand. Shoreface deposits are not preserved in this study area and would presumably be found in updip deposits. Incision prior to the overlying incised valley fill deposits may have removed any shoreface facies that were deposited in the study area.

Facies Association I: Incised Valley Fill

Incised valley fill deposits of the Windy Hill erosively overlie the upper Sundance facies (Facies S1 and S2) and are characterized by a basal shell-hash sandstone that is overlain by estuarine deposits filling in an incised valley fill (Fig. 3, bottom; Fig. 8, B). It is often difficult to distinguish where the boundary lies between the Windy Hill and the overlying Morrison Formation (Fig. 8, B).

Facies I1: Lag Facies

Description.--Facies I1 is represented by a calcite-cemented, fine-to-medium-grained sublitharenite that commonly contains reworked skeletal material and pebble intraclasts. The sublitharenite is composed of subangular clasts of fine upper- to medium lower-sized quartz, glauconite, and black chert. Sand- to pebble-sized mudstone intraclasts coated in hematite cement are common. Reworked crinoids, belemnites, the bivalve *Tancredia*, the scallop *Camptonectes*, and *Ostrea* are all common. Rare are the bivalve *Quenstedtia*, the bivalve *Ceratomya*, marine reptile bones, coal, and petrified wood. Bivalve fragments range in size from very coarse sand to pebbles, and they are often recrystallized or moldic (Fig. 8, C), but whole, abraded valves are common. Much of the reworked skeletal material cannot be identified, owing to abrasion or neomorphism. Trace fossils were not observed in Facies I1.

Facies I1 exhibits 0.5-1.5 m high lateral accretion surfaces (Fig. 8, B), contains large-scale trough cross stratification, or is locally massive. In the Sundance, is often difficult to distinguish lateral accretion surfaces from large-scale trough cross stratification in outcrop, but they differ in their paleocurrent direction (Fig. 8, B; Uhlir et al., 1988). Forests of large-scale cross stratification dip primarily eastward and westward while large-scale trough cross-lamination trends northwest to southeast (Uhlir et al., 1988).

All localities have Facies I1 present, but deposits vary in thickness and occurrence based on locality, as does composition. At Little Sheep Mountain B and D, Sheep Mountain-County Road 1138, Sheep Mountain, and Sheep Mountain-*Pantosaurus*, Facies I1 occurs more than once in the stratigraphic section. The facies is typically 0.2 to

1.0 m thick with a maximum thickness at the Hyattville outcrop of 3 m. The crinoid *Isocrinus* is abundant in Facies S1. The size of shells and intraclasts deposited in the lag is highly variable among outcrops. Shell size ranges from very coarse sand to 3 cm and shell size appears to be largely related to the type of shells present to be reworked. Shell-Trapper Creek Road contains many small *Tancredia* whereas nearby localities such as Dirty Annie's and Red Gulch Dinosaur contain larger bivalves. The Tensleep locality contains more fragmented bivalves, with few whole valves preserved. Bivalve molds are common at many outcrops but abundant at Dirty Annie's and Hyattville localities. Coal and petrified wood commonly occur at outcrops outside of Greybull and Shell, Wyoming including Sheep Mountain-Country Road 1138, Sheep Mountain-*Pantosaurus* Site, Shell-Dirty Annie's, and Shell-Red Gulch Dinosaur Tracksite. Marine reptile bone fragments are rarely found at the Sheep Mountain-*Pantosaurus*, Shell-Horse Creek Road, and Shell-Dirty Annie's localities (Fig. 8, D).

Facies I1 erosively overlies Facies S2 and is marked by a sharp increase in grain size. Facies I2, incised valley fill sandstone, gradationally overlies Facies I1 at most localities.

Interpretation.--Facies I1 is interpreted as lag deposits within channels. The coarse texture, fragmented skeletal grains, mudstone intraclasts, and pebbles are typical of lag deposits in the base of a channel, where shear stress would have been the greatest (Uhlir et al., 1988). Mudstone intraclasts coated in hematite represent mudstone rip-up clasts from underlying deposits. Lateral accretion surfaces represent migration of the tidal inlets. Large-scale trough cross stratification suggests a relatively high shear stress within the lower flow regime. The variable nature of deposits is typical of lag deposits because

incorporated material often depends largely on the underlying deposits (Kidwell and Rogers, 2000).

Facies I2: Channel-Fill Sandstone Facies

Description.--Facies I2 is a heterolithic moderately-sorted medium-grained tan litharenite to a moderately well-sorted fine sublitharenite, interbedded with mudstone. Climbing small-scale current ripple lamination is abundant. Foresets on large-scale trough cross-bedding with clay drapes and planar lamination are common. Large-scale trough cross stratification dips primarily northwest to southeast (Fig 8., E; Uhlir et al., 1988). Some beds are massive, owing to pervasive bioturbation. Meter-scale upward bed thickening is present at the Sheep Mountain outcrop. Rare *Diplocraterion* (Fig. 8, F) ichnofossils were observed, as were rare lined vertical burrows.

Facies I2 overlies lag deposits of Facies I1 and is gradationally overlain by terrestrial deposits of the Morrison.

Interpretation.--Facies I2 represents estuarine deposits filling in an incised valley fill. Large-scale trough cross stratification with rare to common clay drapes suggests tidal influence. Common planar lamination in Facies I2 may represent laterally adjacent foreshore deposits. This interpretation fits with previous studies that recognize the deposits of Facies Association I as a tidal inlet sequence (Uhlir et al., 1988).

Previously, Facies S2 was interpreted as offshore storm beds (Brenner and Davies, 1974; Brenner et al., 1985). The gradational contact between Facies Association I and the overlying terrestrial Morrison Formation indicates that previous offshore depositional models (Brenner and Davies, 1974; Brenner et al., 1985) are not plausible.

Summary

Facies I1 and I2 are interpreted to represent a nearshore, tide-dominated, depositional environment. This interpretation conforms to previous studies (Uhlir et al., 1988; Kvale et al., 2001). The shell-hash lag and sandstone deposit features are similar to both modern and other ancient tidal inlet signatures. The mudstone intraclasts suggest that the underlying unit being eroded contains mud, suggesting that incision cut into underlying transition zone facies (Facies S2). Abundant current ripples and large-scale trough cross-bedding suggest a tide-dominated depositional environment for Facies I2.

SUNDANCE SEQUENCE STRATIGRAPHY

The Sundance Formation is composed of four depositional sequences. The first two contain deposits of the lower Sundance carbonate ramp (Facies Association C), the third sequence represents the wave-dominated siliciclastic margin (Facies Association S), and the final sequence contains the incised valley fill deposits (Facies Association I).

Sequence J2a

Sequence J2a corresponds to the lower carbonate of the lower Sundance Formation (Fig. 2). A sequence boundary occurs at the base of this unit where it overlies the Gypsum Spring or Piper Formation (Fig. 9). This contact is noticeable by a diagnostic color change of mudstone from a pale red to light gray in outcrops north of Tensleep. At the Tensleep outcrop, reworked well-rounded, 2-5 cm white to yellow chert nodules are found immediately above this surface (Pipiringos, 1968; Pipiringos and O'Sullivan,

1978). Approximately 80 km to the south, the sequence boundary between the Gypsum Spring and Sundance is marked by cross-bedded fine-grained sandstone.

Overlying the sequence boundary are 1-3 parasequences represented by deep subtidal mudstone beds that grade upward into beds of skeletal wackestone and packstone (Facies C2). Well-log correlations also indicate the presence of these parasequences (Fig. 10). These parasequences are interpreted as being progradationally-stacked based on the upward decrease in the thickness of deep-water facies and corresponding increase in shallow-water facies. In addition, the capping beds of each parasequence become more ooid-rich upsection, suggesting input of ooids from the updip shallow subtidal deposits and their transport to a proximal deep subtidal setting. Progradational stacking suggests that these parasequences primarily represent the highstand systems tract. Since the parasequences overly a sequence boundary, the first parasequence in the succession may represent the transgressive systems tract. The lack of any lowstand systems tract and possibly transgressive systems tract suggests that the basal sequence boundary is also the transgressive surface. If this is correct, the lowstand systems tract should be preserved depositionally downdip to the west.

The skeletal wackestone to packstone that caps the parasequence set is litholgically distinct from the underlying limestone, in that it contains abundant ooids and abundant fine-grained quartz, suggesting a shallower environment of deposition. The top of this limestone also contains microbial mats, traces belonging to the *Skolithos* ichnofacies, dinosaur trackways, and desiccation cracks, which collectively indicate subaerial exposure (Kvale et al., 2001). The top of this parasequence set is therefore interpreted as a sequence boundary based on the features that indicate subaerial exposure.

Sequence J2b

Offshore mudstone (Facies C1) sharply overlies the exposure surface capping Sequence J2a indicating an abrupt landward shift in facies (Fig. 9). The initial ~5 m of the offshore mudstone is tan and lacks *Gryphaea nebrascensis*. Well-log correlations also indicate this abrupt change in lithology (Fig. 10). Above the tan mudstone is 10-25 m of gray mudstone with abundant *Gryphaea nebrascensis*. While offshore deposits are generally too far down-dip to show expressions of surfaces, the tan to gray color change and increase in fossil abundance indicating deeper-water facies can be correlated to the transgressive systems tract. No other diagnostic features in outcrop indicate stacking patterns or a maximum flooding surface, which may suggest that transgressive systems tract offshore mudstone passes imperceptibly into highstand systems tract mudstone. Stacking patterns and flooding surfaces might be observable up-dip to the east of this transect where shallower water facies may be present.

The offshore mudstone (Facies C1) is overlain abruptly by lagoonal deposits (Facies C4) at the northernmost outcrops near Lovell, Wyoming (Little Sheep Mountain A, B, C, and D). South of Lovell to Hyattville, Wyoming (Sheep Mountain-County Road 1138 to Hyattville), oolitic shoal and oolitic eolian deposits (Facies C3) abruptly overlie offshore mudstone, with pyrite nodules and pyrite-stained *Gryphaea nebrascensis* in the top ~1-2 m (Facies C1). This surface indicates the first sign of abrupt shallowing in the sequence and is interpreted as the basal surface of forced regression. In the north, the lagoonal mudstone (Facies C4) increase in quartz-content and thickness upsection indicating a shallowing-upward succession. To the south, subaerially exposed oolitic eolian deposits overlie oolitic shoals (Facies C3). Shallowing-upward in both deposits in

the north and south suggest that the lagoonal deposits (Facies C4) and oolitic shoal and eolianites (Facies C3) represent the falling stage systems tract. The sharp juxtaposition of these facies on offshore mudstone also suggests that the upper portion of this offshore facies likely reflects the highstand systems tract.

Sequence J4

Overlying the lagoonal (Facies C4) and oolitic (Facies C3) falling stage systems tract is transition zone sandstone (Facies S2) or offshore mudstone (Facies S1). Transition zone sandstone deposits (Facies S2) are present only at the Little Sheep Mountain A and B outcrops and the Shell-Trapper Creek Road outcrop (Fig. 9). This sharp shift in facies is interpreted as a sequence boundary. At all other outcrops, the falling stage systems tract is overlain by offshore mudstone (Facies S1). Subaerial exposure of the oolitic shoals to form oolitic eolianites and an abrupt landward shift in facies indicates that this contact is a combined sequence boundary and transgressive surface. This combined surface represents a major reorganization of facies from a carbonate ramp to a wave-dominated siliciclastic shelf margin and separates the lower Sundance from the upper Sundance.

Above the combined surface are offshore belemnite-rich gray mudstone deposits (Facies S1), which are capped by fossiliferous concretions. At Little Sheep Mountain B, the lower ~5 m of the mudstone is interbedded with thin beds of sandstone, indicating overall deepening upsection corresponding to the transgressive systems tract. Fossiliferous concretions include both invertebrates and vertebrates and are interpreted to represent a period of stratigraphic condensation that correlates to the maximum flooding

surface. Concretions are not present south of Shell-Trapper Creek Road and therefore the maximum flooding surface cannot be recognized in the south and the transgressive systems tract is not present to the south.

These oyster shoals occur above the maximum flooding surface. Often, the maximum flooding surface occurs directly below an oyster shoal (Fig. 9). Well-log correlations also express an increase in grain size that has been correlated to the presence of oyster shoals (Fig. 10). The maximum flooding surface in Facies Association S is expressed in northern outcrops by concretions of very fine-grained sandstone that often include abundant vertebrate and invertebrate fossils, as well as, trace fossils. These concretions represent a period of stratigraphic condensation where fossils accumulated on the seafloor. To the south, these concretions are not present.

Above the maximum flooding surface, there are two parasequences of gray mudstone that grade upsection into tan sandstone. The first parasequence begins at the base of the maximum flooding surface and is capped by locally discontinuous oyster shoals. Laterally, where the oyster shoals are not present, an increase in grain size can be observed by orientation of vegetation along that bedding plane. A flooding surface occurs above the oyster shoals, overlain by a second parasequence that grades from gray offshore mudstone (Facies S1) into interbedded transition zone sandstone and mudstone (Facies S2). The decrease in thickness of the gray mudstone in the upper parasequence indicates progradational stacking, suggesting that these are highstand systems tract deposits.

Sequence J5

At the base of Sequence J5, a channel lag (Facies I1) erosively overlies transition zone deposits (Facies S2; Fig. 9). The lag is relatively planar and laterally continuous in outcrop. It contains reworked skeletal material and mudstone intraclasts. At some localities, the lag overlies wave-rippled sandstone, while at other localities, it overlies interbedded mudstone and very thin wave-ripple laminated sandstone (Facies S2). The relief and regional extent of this erosional surface is interpreted as indicating a sequence boundary that marks a relative fall in sea level.

Overlying the lag deposits are incised valley sandstone (Facies I2). These deposits were deposited in the estuary that developed as relative sea level rose and flooded the incised valley. These deposits represent predominately the lowstand systems tract but the upper portion of the channel fill may contain transgressive systems tract deposits where the transgressive surface is correlative. These deposits grade upwards into the terrestrial deposits of the Morrison.

SUNDANCE FOSSIL DISTRIBUTION

Biofacies

Non-metric multidimensional scaling of faunal censuses reveals several patterns. First, sample scores distinctly separate into the lower and upper Sundance along axis 1 (Fig. 11, top). This separation indicates that the faunal assemblage in the lower Sundance differs markedly from the faunal assemblage in the upper Sundance.

Second, sample scores separate by the following lithofacies: deep subtidal (C2), shallow subtidal (C3), offshore (S1), and lag (I1). The offshore facies (S1) has variation

within it and can be further subdivided into an offshore mudstone, oyster shoal, concretion, and *Camptonectes* bed (Fig 11, top). Along axis 1, sample scores appear to separate based on stratigraphic location. Along axis 2, sample scores appear to separate based on a depth gradient. Deeper depositional environments tend to have higher axis 2 sample scores than shallow environments. Lithofacies-related trends are well distinguished because there is often little overlap of the fauna that occur in various lithofacies. Where fauna overlap into multiple lithofacies, the relationship is recognized in the MDS plots (Fig. 11, middle). Overlap of lithofacies reflects an overlap in depositional environment (offshore), a gradational contact (offshore mudstone and oyster shoal), an erosive contact (channel lag and offshore) or too few data points (deep and shallow subtidal). The tidal lag erosively overlies the offshore mudstone and contains reworked material from the underlying units, but also contains two distinct taxa (i.e., *Tancredia* and *Isocrinus*) that help separate the unit from others.

Third, taxa examined for this study, have a distribution where taxa that are found in association with one another group more closely in space (Fig. 11, bottom). Taxa sort along axis 1 by stratigraphic location, with taxa that are found in the same lithofacies having similar axis 1 scores (Fig. 11, bottom). This distinguishes the lower Sundance taxa from the upper Sundance taxa. Along axis 1, the taxa with the lowest scores include *Tancredia, Ophthalmosaurus natans*, *Isocrinus*, *Ostrea*, *and Pantosaurus striatus*. All of these fossils are found within the Windy Hill Sandstone, the uppermost member of the Sundance. Taxa with the highest scores along axis 1 include large and small bivalves, *Chariocrinus*, *Gryphaea*, gastropods, and echinoids. All of these taxa are distinct to the lower Sundance. Along axis 2, taxa sort by the depth at which they occur

(Fig. 11, bottom) creating a gradient where shallow taxa have a lower taxa score than deep taxa. Along axis 2, taxa with the lowest scores include *Tancredia*, *Isocrinus*, echinoids, *Pantosaurus striatus*, and *Camptonectes*. These taxa all occur at shallow depths in either the lower or upper Sundance. The taxa along axis 2 with the highest scores include *Myopholas*, gastropods, *Gryphaea*, and *Ostrea*—all occur in relatively deeper water.

Vertebrate Fossils

Vertebrate fossils occur only in upper Sundance deposits, where they are found in three sequence stratigraphic locations in the Sundance: along flooding surfaces, within offshore mudstone (Facies S1) and transition zone interbedded sandstone (Facies S2) of the transgressive and highstand systems tract, and along sequence boundaries.

Vertebrate fossils are found along the maximum flooding surface in the upper Sundance in northern outcrops, these fossils are preserved in fine-grained concretions and are often partially disarticulated and show some weathering (Fig. 6, B and C). Vertebrate fossils found in these concretions include the ichthyosaur, *Ophtalmosaurus natans*, and the plesiosaur, *Pantosaurus striatus* (pers. comm. R. O'Keefe, 2011; Wahl et al., 2007). Recently, a plesiosaur with ichthyosaur embryo stomach contents was discovered at this study's Sheep Mountain-*Pantosaurus* Site (O'Keefe et al., 2009). Flooding surfaces are commonly expressed by a period of non-deposition or sediment bypass resulting in stratigraphic condensation (Kidwell, 1991). Stratigraphic condensation represents a long period of time, resulting an increase in time for vertebrate bones to accumulate. With low sedimentation rates, the rate of burial is also reduced, increasing the probability of

disarticulation by mechanical and biological processes such as scavenging and bioturbation. This accounts for the accumulation of partially articulated material along the maximum flooding surface of the upper Sundance.

Vertebrate material found in undifferentiated offshore mudstone (Facies S1; Fig. 6, D; Fig. 7, B) and in the transition zone interbedded sandstone and mudstone (Facies S2) of the highstand and transgressive systems tract in the upper Sundance is frequently abraded and disarticulated. This material is sometimes found partially articulated but is usually fragmented or abraded. Material found in the offshore mudstone (Facies S1) is often preserved directly below oyster shoals (<1 m) and includes specimens of *Ophthalmosaurus natans, Pantosaurus striatus*, and the pliosaur, *Megalneusaurus rex* (Wahl et al., 2007). This may indicate a habitat that is slightly distal of the oyster shoals for the marine reptiles present. Disarticulated to partially articulated vertebrate material can also be rarely found in the interbedded mudstone and sandstone beds of the transition zone deposits in the highstand systems tract (O'Keefe and Street, 2009). A partial skeleton of the plesiosaur, *Tatenectes laramiensis*, has been described from these deposits near this study's Dirty Annie's locality outside of Shell, Wyoming. Elements were closely associated but not articulated (O'Keefe and Street, 2009). Preservation of *Tatenectes laramiensis* in transition zone deposits may indicate a shallow habitat for the plesiosaur. This idea is supplemented by the morphology of *Tatenectes laramiensis* that is stable in turbulent environments (O'Keefe et al., 2011). Abundant wave-ripple lamination suggests that wave agitation disarticulated, and abraded the skeleton before deposition occurred.

Abraded and reworked marine vertebrate material is rarely to commonly found in channel lag deposits (Facies I1) overlying a sequence boundary near the top of the upper Sundance. Material found in the lag deposit is entirely disarticulated and disassociated. Often, the bone is so reworked that it can no longer be identified. Lag deposits generally incorporate material from the underlying strata as channel incision occurs. This material may be carried for some distance, becoming abraded. As a result, the vertebrate material in the channel lag of the upper Sundance indicates that the underlying facies contains vertebrate material but is not useful in providing in-situ information, such as faunal association or preservation.

Invertebrate fossils

Invertebrate fossils occur in both the lower and upper Sundance on flooding surfaces, along surfaces of forced regression, and within undifferentiated mudstone.

In the lower Sundance, invertebrate fossils occur on flooding surfaces at the top of parasequences in skeletal wackestone to packstone deposits (Facies C2) in the transgressive and highstand systems tract. Fossils include abundant reworked bivalves, common bivalve molds, crinoids, and rare gastropod molds. Bivalves are typically disarticulated and broken into 0.5-1.0 cm fragments and are therefore unidentifiable. The exception is *Myopholas*, which is sometimes complete enough to identify. Crinoids in the lower Sundance have been identified as *Chariocrinus* and are typically disarticulated. Large (2-3 cm) bivalve molds are only found at the Shell-Red Gulch Dinosaur Tracksite locality and small bivalve molds (~1 cm) were identified from the Dirty Annie's and Shell-Trapper Creek Road localities. These invertebrate fossils were deposited in deep

subtidal storm beds that would have reworked and abraded fossil material. The skeletal wackestone to packstone beds are also pervasively burrowed which, would have subsequently further reworked the skeletal material after deposition.

In the upper Sundance, invertebrate fossils occur along several flooding surfaces. Beds of the scallop, *Camptonectes*, and oyster shoals commonly occur in the upper Sundance in Facies S1 along flooding surfaces. *Camptonectes* occur in 0.1-0.3 m beds and are often broken and reworked. Rarely, belemnites occur within *Camptonectes* beds. Beds of *Camptonectes* represent the cap of a shallowing-upward cycle in the offshore mudstone deposits (Facies S1). Oyster shoals occur as discontinuous mounds along a horizon at the top of a shallowing-upward succession in offshore mudstone. These oyster shoals cap the top of a parasequence in the highstand systems tract in the upper Sundance. Abundant to common invertebrate fossils occur in fine-grained concretions within offshore mudstone deposits (Facies S1), along the maximum flooding surface. Invertebrate fossils found in the concretions include abundant bivalves such as *Astarte*, *Pleuromya*, and *Vaugonia*, common belemnites, as well as rare to common occurrences of the ammonite, *Cardioceras*. Invertebrate fossils found in the concretions of the upper Sundance are often recrystallized or occur as molds. These fossils, like the vertebrate fossils found in the concretions, accumulated during a period of stratigraphic condensation, which allowed for abundant fossils to accumulate without dilution by sediment.

In the lower Sundance, common *Gryphaea nebrascensis* and *Chariocrinus* occur above the sequence boundary in the ooid shoal deposits of the falling stage systems tract. *Gryphaea* are commonly coated with spongiostromate.

In the upper Sundance, recrystallized, disarticulated, and abraded bivalves, bivalve molds, and crinoids commonly occur in a channel lag deposit that marks the uppermost sequence boundary in the Sundance. Reworked crinoids, *Tancredia*, *Camptonectes*, *Ostrea*, and belemnites are common while *Quenstedtia* and *Ceratomya* occur rarely. Skeletal fragments range from coarse sand to pebble sized and are often too abraded to identify (Fig. 8, C). This material, like the vertebrate material, reflects the fossil assemblage of the underlying facies into which the channel is incising. Therefore, the variety of bivalves present is heterogeneous laterally among outcrops.

Within the offshore mudstone deposits of both the lower (Facies C1) and upper Sundance (Facies S1) there is a low diversity but high abundance of invertebrate fossils. In the lower Sundance, very abundant *Gryphaea nebrascensis* occur in the highstand systems tract in gray mudstone that is 5-25 m thick and thins to the south as it onlaps onto the Sheridan Arch. In the upper Sundance, very abundant belemnites occur in the gray mudstone deposits below the oyster shoals but decrease in abundance upsection. This decrease in abundance likely reflects the shallowing upward deposits. The abundance but low diversity in both of these offshore mudstone facies reflects favorable conditions and possibly a high preservation potential for *Gryphaea* in the lower Sundance and belemnites in the upper Sundance.

DISCUSSION

Relationship to Previous Stratigraphic Research on the Sundance

Although the facies in the Sundance have been previously described and interpreted (Imlay, 1956; Pipiringos, 1968; Wright, 1973; West, 1985; Uhlir et al., 1988;

Kilibarda and Loope, 1997; Kvale et al., 2001), this is the first study that documents that sequence stratigraphic framework of the Sundance Formation. This context clarifies several aspects of Sundance stratigraphy. First, this sequence stratigraphic framework aids in correlation among outcrops. Failure to recognize this framework in earlier stratigraphic research on the Sundance has resulted in difficulty correlating among outcrops (see West, 1985). Previously, isolated lenses of limestone and sand in the Sundance were documented (Wright, 1973; West, 1985). This study recognizes regionally extensive surfaces that define correlatable packages.

Second, this study's sequence stratigraphic interpretation clarifies facies interpretations. The third facies association is interpreted here as an incised valley fill of shallow tidal facies. Initially these deposits were described as offshore sands (Brenner and Davies, 1974; Brenner et al., 1985) but were reinterpreted to represent a complex of tidal facies (Uhlir et al., 1988). This sequence stratigraphic interpretation supports the tidal inlet interpretation.

Third, it explains the distribution of previously identified exposure surfaces. Bipedal tridactyl dinosaur trackways are preserved on a subaerial exposure surface atop the lower carbonate member (Kvale et al., 2001), which is interpreted in this study as the cap of a progradational parasequence set and a sequence boundary. Kvale et al. (2001) proposed that the surfaces of the underlying parasequences may also contain dinosaur trackways. However, this is not likely because the underlying parasequences do not shallow-upward to the extent of the last parasequence and therefore lack the subaerial exposure that is necessary for dinosaur trackways. This study also identifies the subaerial exposure of oolitic shoals to form eolianites (Kilibarda and Loope, 1997) as a sequence

boundary that marks a major reorganization from the predominately carbonate lower Sundance to the siliciclastic upper Sundance.

Occurrence of Fossils

Invertebrate distribution in the Sundance is consistent with previous studies of invertebrates elsewhere in the geologic record, which have found that abrupt changes in invertebrate community structure, and taxon abundance are often tied to sequence stratigraphic architecture (Brett, 1995; Holland 1995; Holland, 2000). First, changes in invertebrate assemblages occur at flooding surfaces in the transgressive systems tract in both the lower and upper Sundance. Second, fossil accumulation occurs along the maximum flooding surface of the upper Sundance that is represented by an interval of stratigraphic condensation, which resulted from sediment starvation (Holland, 2000). Finally, changes in invertebrate assemblages occur at the sequence boundary between the lower and the upper Sundance where major facies reorganization is indicated.

In contrast to previous studies, this study evaluates a study area where macroinvertebrates have a low diversity and in which individual taxa are typically restricted to a single facies (Brett, 1995; Holland, 1995; Holland, 2000). Most of the initial work on how sequence stratigraphic architecture affects invertebrate fossil occurrences has been done on carbonate Paleozoic rocks that exhibit a high diversity of taxa (Brett, 1995; Holland, 1995; Holland, 2000). Comparatively, the Jurassic mixed siliciclastic-carbonate Sundance contains a low taxonomic diversity in each facies. *Gryphaea*-bearing offshore mudstone of the lower Sundance (Facies C1) and belemnite-rich offshore mudstone of the upper Sundance (Facies S1) are both dominated by a single

taxon. Where previous work (Holland, 2000) has been able to track subtle changes in community structure based on the appearance and disappearance of a few taxa, in the Sundance abrupt changes in community structure occur resulting in no overlap of taxa between facies. Lack of macrofossil diversity in the Sundance could result in subtle ecological changes going unnoticed.

While fewer comparable analyses have been done on the effects of sequence stratigraphic architecture on preservation of marine vertebrates, some evidence suggests correlation between stratigraphic architecture and vertebrate fossil preservation (Rogers and Kidwell, 2000; Allulee and Holland, 2005; Peters et al., 2009). In terrestrial settings, vertebrate skeletal concentrations in lags track the skeletal abundances of fossil material in the underlying facies (Rogers and Kidwell, 2000).

Vertebrate remains in the upper Sundance are found along discrete stratigraphic surfaces and the systems tract of deposition affects quality of preservation as has been shown for other marine settings (Allulee and Holland, 2005; Peters et al., 2009). First, the partially articulated marine reptiles in the upper Sundance are found along the maximum flooding surface. At Wadi-Al Hitan, Egypt, partially to articulated Eocene marine mammals have a high preservation rate on marine flooding surfaces reflecting environmental and temporal condensation during periods of slow net sediment accumulation (Peters et al., 2009). Additionally, Ordovician fish plates from the Harding Sandstone occur most frequently on flooding surfaces where there is evidence of condensation (Allulee and Holland, 2005). Second, fragmented marine reptile fossil material can be found in a channel lag directly above the sequence boundary that overlies

the Redwater Shale in the Sundance, and in a channel lag that represents a sequence boundary in the Eocene deposits at Wadi Al-Hitan (Peters et al., 2009).

Vertebrate fossil occurrences in the Sundance vary from previous studies in several aspects. First, vertebrates preserved along the maximum flooding surface in the upper Sundance are contained in fine-grained concretions. While vertebrates were found along major flooding surfaces in both the Eocene deposits at Wadi Al-Hitan and in the Harding Sandstone, they were not encased in concretions (Allulee and Holland, 2005; Peters et al., 2009). Second, vertebrates in the Sundance are found within transgressive and highstand systems deposits in offshore and transition zone facies. Previous studies of vertebrate occurrences in a sequence stratigraphic context have not noted this facies control on vertebrates in the transgressive and highstand systems tract. At Wadi Al-Hitan, no vertebrates were found in highstand systems tract deposits and the fossils found in the transgressive systems tract were always associated with major flooding surfaces (Peters et al, 2009). Third, at Wadi Al-Hitan, the falling stage systems tract rarely to commonly preserves complete, articulated marine mammals (Peters et al., 2009). This excellent preservation is absent in the upper Sundance because the falling stage systems tract is not present, and high sedimentation rates are necessary to preserve articulated specimens (Peters et al., 2009). Finally, the vertebrate occurrences in the Sundance are considerably rarer compared to Wadi Al-Hitan or the Harding Sandstone (Allulee and Holland, 2005; Peters et al., 2009). This may reflect a difference in a variety of processes based on geologic setting such as, sedimentation rate, seawater chemistry, the rate of transgression and regression, or a fewer specimens initially to be input in to the fossil record.

While vertebrate occurrences in the Sundance are rare, sequence stratigraphy can be used as a method to predicting where prospecting would be most successful. The absence of a falling stage systems tract in the upper Sundance provides a potential explanation as to why the Sundance does not contain well-preserved vertebrates (pers. comm. R. O'Keefe, 2011). Instead, partially articulated vertebrates in the Sundance occur along the maximum flooding surfaces where sediment rates are much lower making, vertebrates more likely to either not undergo preservation or to become disarticulated before burial. As a result, articulated marine vertebrates are rarer and more difficult to discover in the Sundance of the Bighorn Basin than at Wadi-Al Hitan. However, excellent specimens have been discovered and are commonly preserved in concretions that represent the maximum flooding surface in the Sundance (O'Keefe et al., 2009). Because this maximum flooding surface is poorly exposed southward in the Bighorn Basin, future prospecting for vertebrates in the Sundance would likely be most successful in northern outcrops along this surface.

CONCLUSIONS

1. The Jurassic Sundance Formation is exposed along the eastern margin of the Bighorn Basin and this study identifies four depositional sequences within the Sundance. The lower two sequences are dominantly carbonate and the upper two sequences are entirely siliciclastic. The lower three sequences contain marine facies, whereas the uppermost sequence is represented by and estuarine incised valley fill, reflecting the receding Sundance Seaway and the transition to the overlying terrestrial deposits of the Morrison Formation.

2. The occurrence of fossils in the Sundance is partly related to facies. For example, bivalve and crinoid fragments are limited to the shelf carbonate facies and oolitic shoal facies, abundant *Gryphaea* are limited to offshore mudstone in the Stockade Beaver Shale, and abundant belemnites are found only in offshore mudstone of the Redwater Shale.

3. Sequence stratigraphic architecture also controls the preservation of fossils in the Sundance, such as flooding surfaces, surfaces of forced regression, and surfaces of forced regression. Reworked, microbally coated, and pyritized *Gryphaea* occur at the top of the Stockade Beaver Shale underneath the basal surface of forced regression. The most fossiliferous horizon in the Sundance Formation is the concretion unit that represents the maximum flooding surface in Facies Association S. Poorly preserved bivalves, belemnites, marine reptile bone, and plant material is found in a lag at the base of an incised valley fill, represented by the Windy Hill Member.

4. Vertebrate prospecting can be improved in the Sundance by concentrating in on concretions along the maximum flooding surface, in Sequence J5, in the Redwater Shale. Vertebrate prospecting efforts should also focus on offshore mudstone in the Redwater Shale directly below oyster shoals. Rare material of *Tatenectes laramiensis* may also be present in transition zone deposits in the Redwater Shale. While vertebrate material can be found in the channel lag at the base of the Windy Hill, it is often too abraded to contain any well-preserved specimens.

CHAPTER 3

CONCLUSIONS

The Jurassic Sundance Formation is exposed along the eastern margin of the Bighorn Basin and it contains four depositional sequences. The lower two sequences are dominantly carbonate and the upper two sequences are entirely siliciclastic. The lower three sequences contain marine facies, whereas the uppermost sequence is represented by and estuarine incised valley fill.

Fossil preservation in the Sundance is governed partly by facies.

Sequence stratigraphic architecture also controls the occurrence of fossils in the Sundance, such as flooding surfaces, surfaces of forced regression, and surfaces of forced regression. The most fossiliferous horizon in the Sundance Formation is the concretion unit that represents the maximum flooding surface in Facies Association S.

Vertebrate prospecting can be improved in the Sundance by concentrating in on concretions along the maximum flooding surface, in Sequence J5, in the Redwater Shale. Less well-preserved material may be found in offshore mudstone in the Redwater Shale. While vertebrate material can be found in the channel lag at the base of the Windy Hill, it is often too abraded to contain any well-preserved specimens.

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FIGURE 1—Locations of Jurassic outcrop belt (green) and measured sections in north-central Wyoming. Cross-section of Figure 5 is indicated.

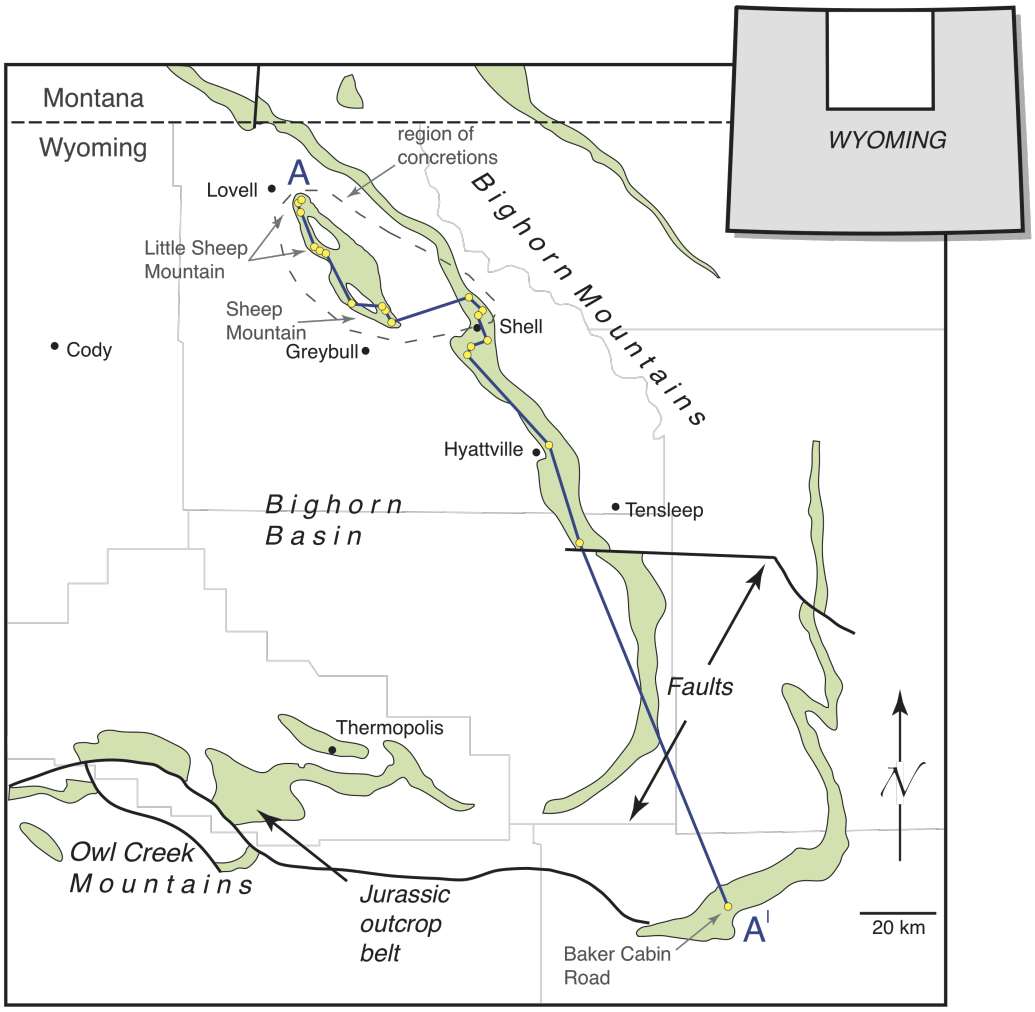

WYOMING
Montana
Wyoming
region of
concretions
A
Lovell
Little Sheep
Mountain
Sheep
Mountain
Greybull
Cody
Shell
Bighorn Mountains
Hyattville
Bighorn
Basin
Tensleep
Faults
Thermopolis
Owl Creek
Mountains
Jurassic
outcrop
belt
A'
Baker Cabin
Road
20 km

FIGURE 2—Stratigraphic nomenclature of the Sundance. Nomenclature from this study and other studies of the Sundance and the underlying and overlying formations including: Imlay (1947), Imlay (1956), Pipiringos (1968), West (1985), Kvale et al. (2001). Eustatic sea level change for the Bajocian to Tithonian (175-145 Ma) based on Hallam (1988). Marine cycles and unconformities (gray wavy lines) are based on Kvale et al. (2001).

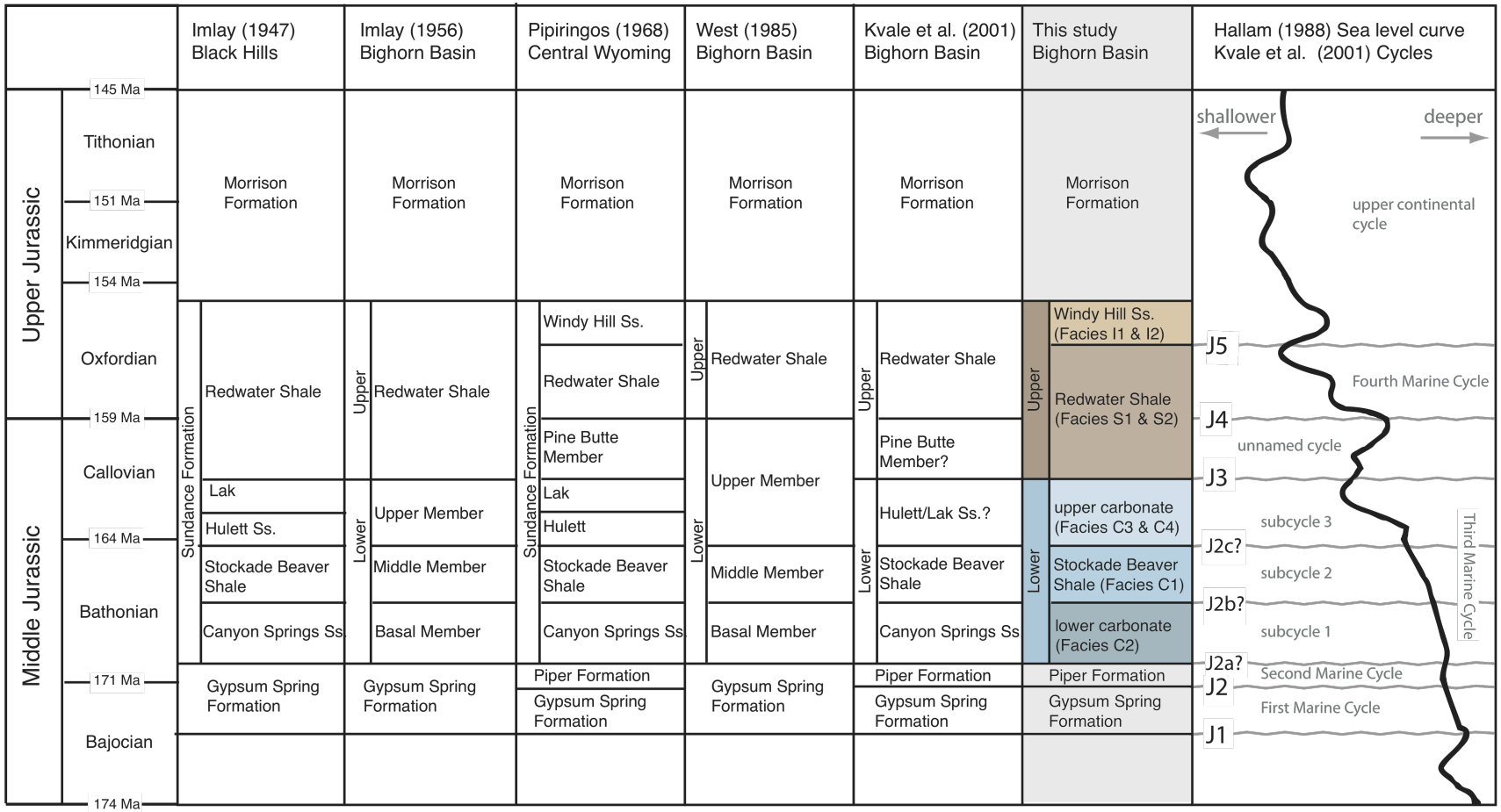

Imlay (1947) Black Hills
Imlay (1956) Bighorn Basin
Pipiringos (1968) Central Wyoming
West (1985) Bighorn Basin
Kvale et al. (2001) Bighorn Basin
This study Bighorn Basin
Hallam (1988) Sea level curve Kvale et al. (2001) Cycles
145 Ma
Tithonian
151 Ma
Kimmeridgian
154 Ma
Oxfordian
159 Ma
Callovian
164 Ma
Bathonian
171 Ma
Bajocian
174 Ma
Upper Jurassic
Middle Jurassic
Morrison Formation
Sundance Formation
Redwater Shale
Upper
Lower
Upper Member
Middle Member
Basal Member
Lak
Hulett Ss.
Stockade Beaver Shale
Canyon Springs Ss.
Windy Hill Ss.
Pine Butte Member
Hulett
Pine Butte Member?
Hulett/Lak Ss.?
Windy Hill Ss. (Facies I1 & I2)
Redwater Shale (Facies S1 & S2)
upper carbonate (Facies C3 & C4)
Stockade Beaver Shale (Facies C1)
lower carbonate (Facies C2)
Piper Formation
Gypsum Spring Formation
shallower
deeper
upper continental cycle
Fourth Marine Cycle
unnamed cycle
subcycle 3
subcycle 2
subcycle 1
Third Marine Cycle
Second Marine Cycle
First Marine Cycle
J5
J4
J3
J2c?
J2b?
J2a?
J2
J1

FIGURE 3—Paleogeographic reconstruction of the Western Interior Seaway during the deposition of the lower Sundance in the middle Bathonian stage of the Sundance, based on data from Wright (1973), Imlay (1980), West (1985), Brenner and Peterson (1994), Kvale et al. (2001), and this study. A-A^1 shows the location of the transect of outcrops used in this study (Figure 9).

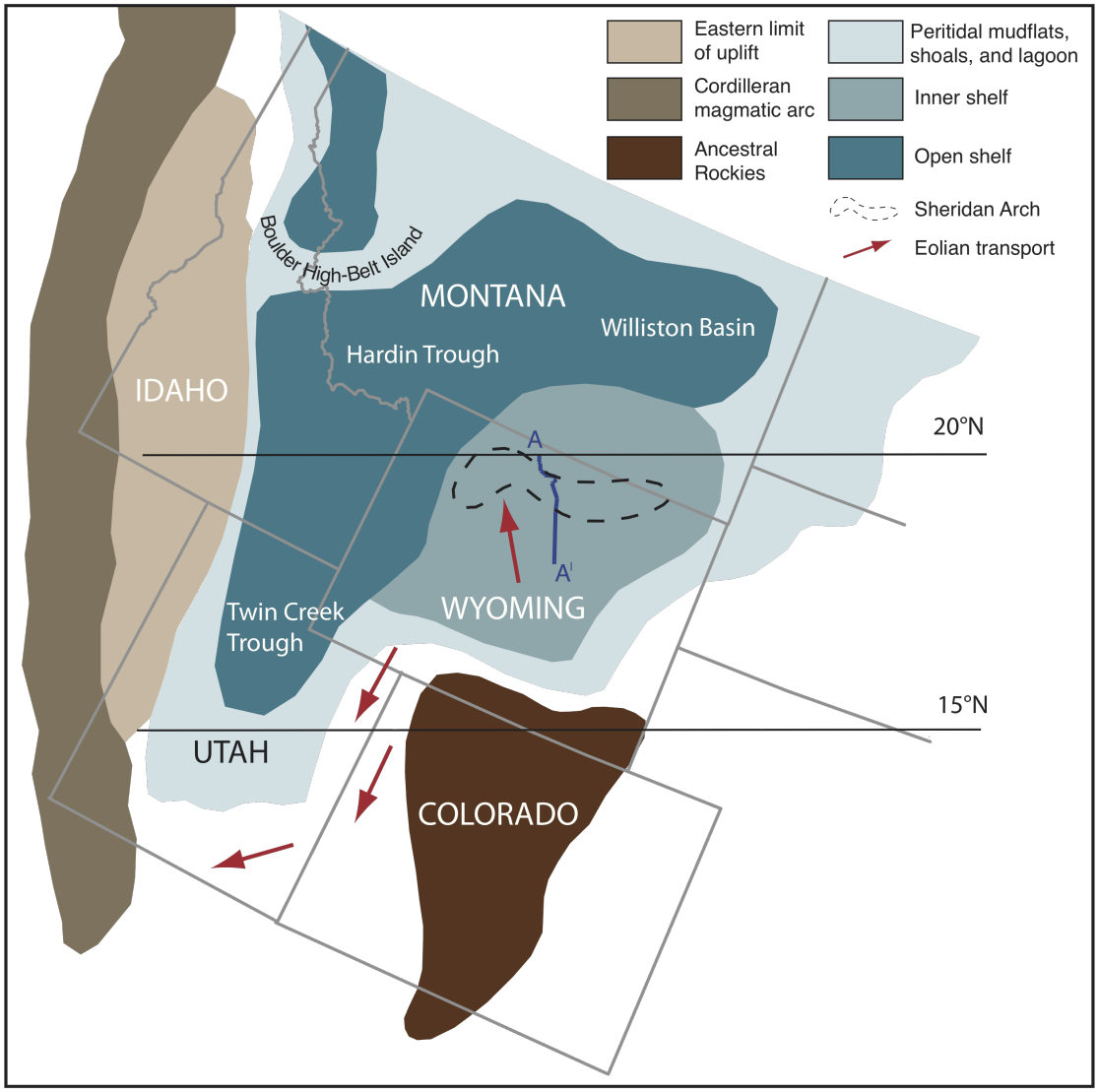
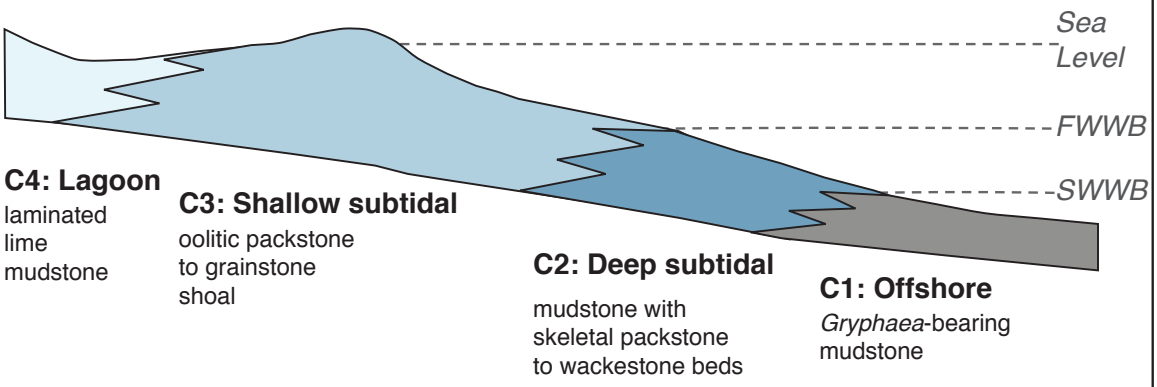
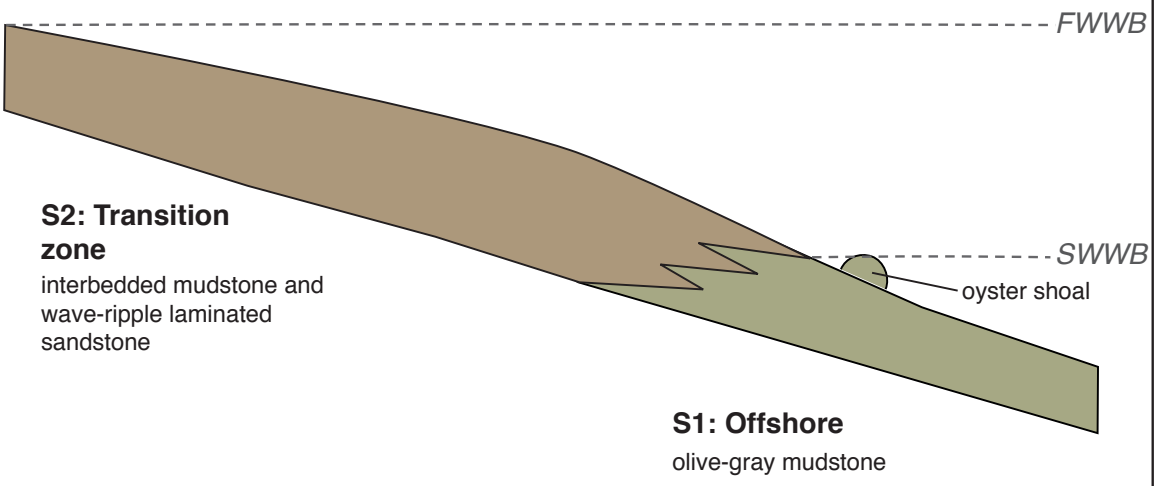

Eastern limit of uplift
Cordilleran magmatic arc
Ancestral Rockies
Peritidal mudflats, shoals, and lagoon
Inner shelf
Open shelf
Sheridan Arch
Eolian transport
Boulder High-Belt Island
MONTANA
Williston Basin
Hardin Trough
IDAHO
20°N
A
A'
WYOMING
Twin Creek Trough
15°N
UTAH
COLORADO

FIGURE 4—Facies models for the three facies associations: carbonate ramp (**top**), siliciclastic margin (**middle**), and incised valley fill (**bottom**). Colors correspond to units in Figure 5. Descriptions of facies are in Tables 1-3.

Lower Sundance Carbonate Ramp



Upper Sundance Wave-dominated Siliciclastic Margin



Upper Sundance Incised Valley Fill

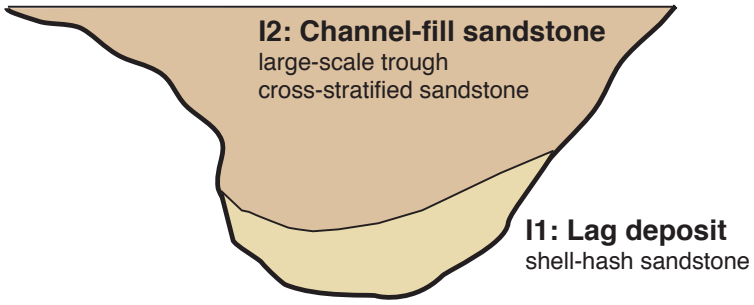


FIGURE 5— Outcrop photos of Facies Association C. (**A**) Exposure at Shell-Horse Creek Road of the lower Sundance sequence with the Piper Formation (PF) at the base, overlain by parasequences of deep subtidal mudstone interbedded with a skeletal wackestone to packstone (Facies C2). This is overlain by *Gryphaea*-bearing offshore mudstone (Facies C1). The shallow subtidal oolitic shoal facies (Facies C3) caps the top of the lower Sundance at this locality. White dashed lines indicate facies contacts. (**B**) Offshore mudstone facies (Facies C1) showing an abundance of *Gryphaea* weathering out of the mudstone parallel to beds at the Shell-Red Gulch Dinosaur Tracksite locality. Rock hammer height is 12 cm. (**C**) Exposure at Little Sheep Mountain C of three progradational parasequences of deep subtidal mudstone and skeletal wackestone to packstone deposits. Dashed white lines signify the tops of parasequences. Bushes are ~0.5 m high. (**D**) Exposure at Shell-Horse Creek Road of the shallow subtidal oolitic ooid shoal deposits overlain by ooid eolianites (Facies C3). Dashed white lines indicate the contact between the eolianite and shoal. Total exposure shown is ~10 m. (**E**) Oolitic shoal facies (Facies C3) with wave-ripple lamination (WRL) at the base transitioning into planar lamination (PL). Length of the pencil is 12 cm. (**F**) Exposure at Little Sheep Mountain C of laminated lagoonal mudstone facies (Facies C4). North arrow on card is 10 cm.

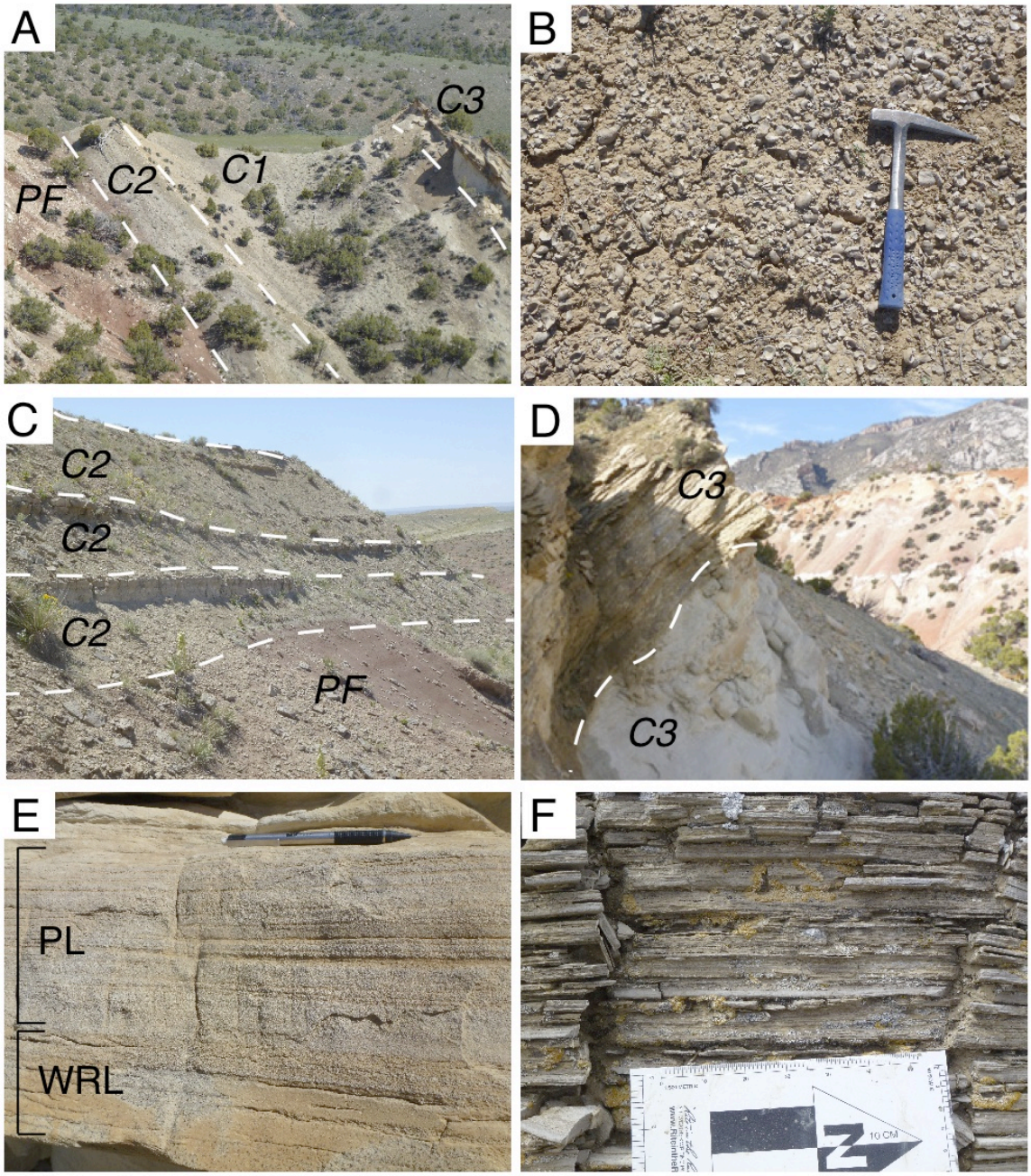

A
C3
C2
C1
PF
B
C
C2
C2
C2
PF
D
C3
C3
E
PL
WRL
F

FIGURE 6—Outcrop, fossil, and ichnofossil photos of Facies S1. (**A**) Exposure at Sheep Mountain-*Pantosaurus* Site of offshore mudstone deposits of the upper Sundance, Redwater Shale member (Facies S1). Two color-changes from gray to tan can be seen upsection. Dashed lines indicate the top of the tan beds that are also reflected in vegetation growing parallel to the horizon. The top dashed line marks the contact between Facies Association S and 3. Shrubs in the foreground are ~0.5 m. (**B**) Concretion containing partially articulated embryonic ichthyosaur vertebrae from the Redwater Shale (Facies S1) at the Sheep Mountain-*Pantosaurus* Site (O'Keefe et al., 2009). (**C**) Plesiosaur vertebrae preserved in a concretion from the offshore mudstone (Facies S1) of the upper Sundance near this study's Baker Cabin Road locality. Specimen was studied from the Wyoming Dinosaur Center collections in Thermopolis, Wyoming. Pencil length is 12 cm. (**D**) Articulated ichthyosaur in mudstone from the Redwater Shale near the Dirty Annie's locality. Rock hammer is 30 cm in length. (Photo Credit and Copyright: Shanan Peters) (**E**) *Planolites* from concretions from the offshore mudstone (Facies S1) of the upper Sundance at the Little Sheep Mountain D locality. North arrow on the card is 10 cm. (**F**) *Camptonectes* bed from the offshore mudstone (Facies S1) of the upper Sundance at the Dirty Annie's locality. Pencil length is 12 cm.

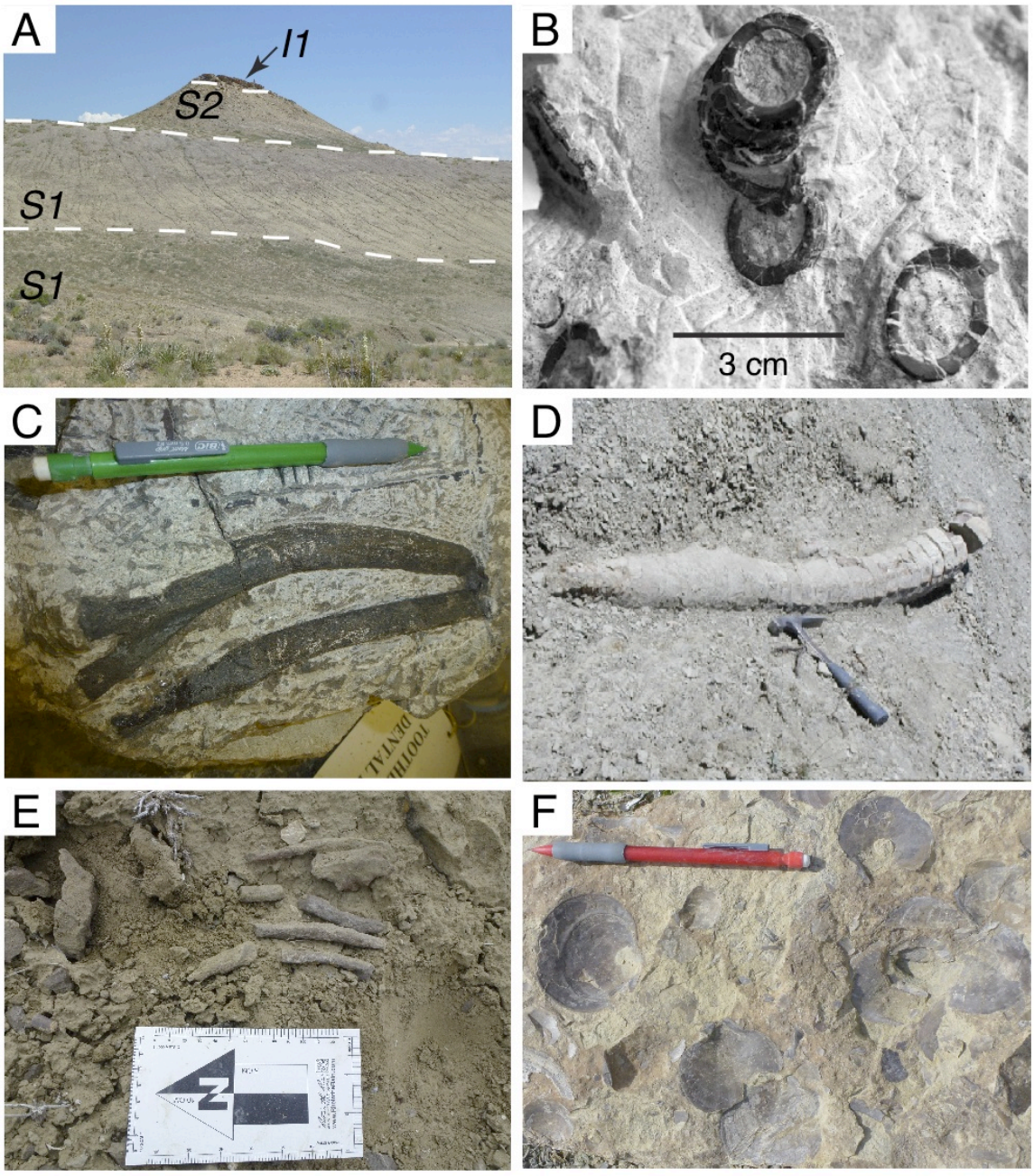

A
I1
S2
S1
S1
B
3 cm
C
D
E
F

FIGURE 7—Outcrop, fossil, and ichnofossil photos of Facies Association S and 3. (**A**) Regular echinoid plates found in the Redwater Shale (Facies S1) at Shell-Red Gulch Dinosaur Tracksite. Scale is in millimeters. (**B**) Disarticulated marine reptile metapodials found below an oyster shoal (Facies S1) at the Shell-Red Gulch Dinosaur Tracksite Supplemental locality. North arrow on card is 10 cm. (**C**) Erosive contact (dashed line) between the incised valley fill (Facies I1 and I2) of Facies Association I and the transition zone (Facies S2) of Facies Association S. (**D**) Interbedded wave-ripple laminated fine-grained sandstone and mudstone from the transition zone facies (Facies S2) at Shell-Trapper Creek Road. Height of pencil is 12 cm. (**E**) *Planolites* from the wave-ripple laminated sands of the transition zone facies (Facies S2) at Sheep Mountain. Pencil is 12 cm. (**F**) *Chondrites* on a surface of the wave-ripple laminated sands from the transition zone facies (S2) from Shell-Trapper Creek Road. Height of pencil is 12 cm.

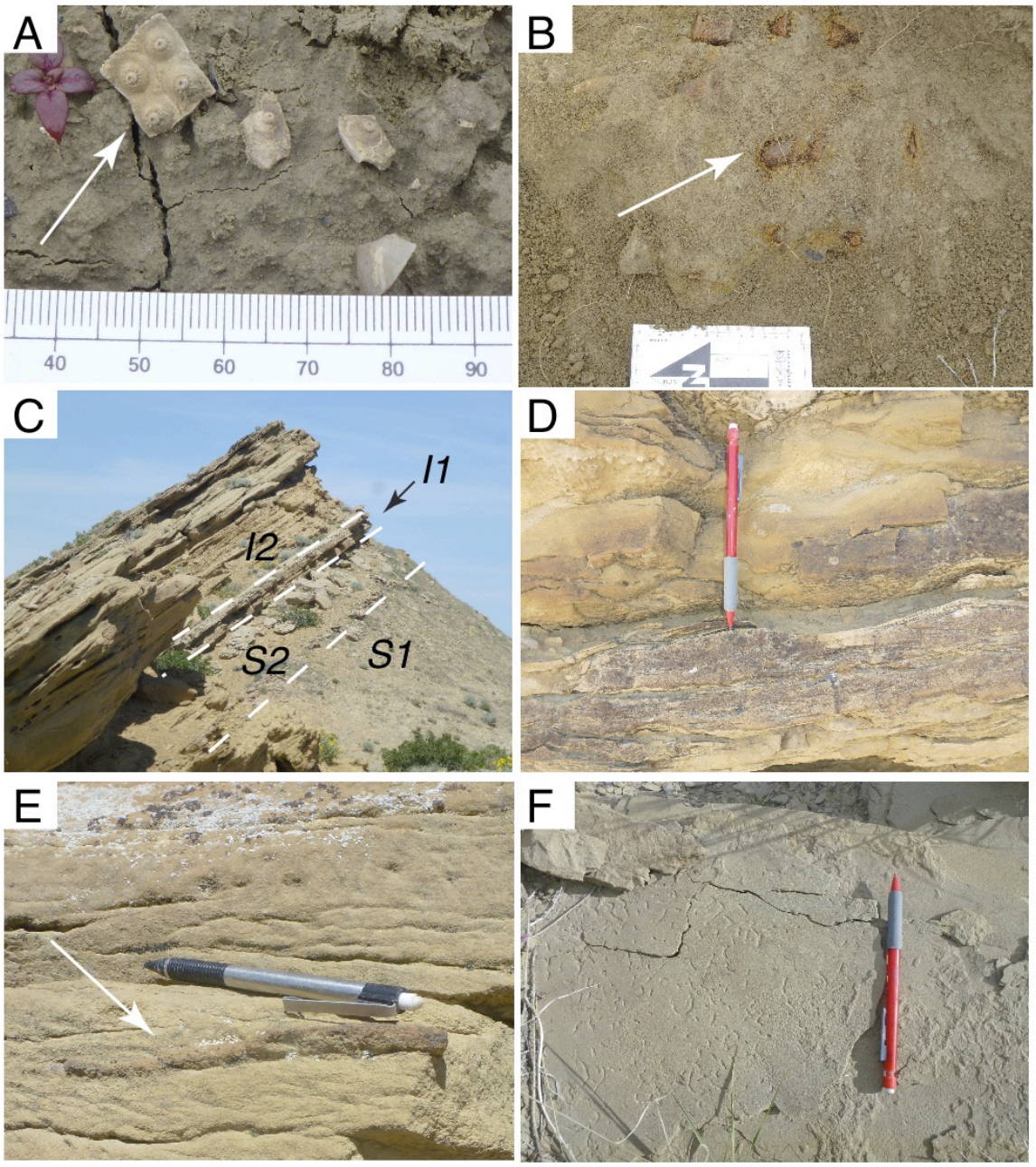

A
40
50
60
70
80
90
B
C
I1
I2
S2
S1
D
E
F

FIGURE 8—Outcrop, fossil, and ichnofossil photos of Facies Association S and 3. (**A**) A lined vertically curved burrow from the wave-ripple laminated transition zone facies (Facies S2) at Sheep Mountain. (**B**) Erosive contact between the tidal lag of Facies Association I (Facies I1) and the transition zone of Facies Association S (Facies S2) at Shell-Red Gulch Dinosaur Tracksite of transition zone (Facies S2). Lateral accretion surfaces that are ~1.5 m high. (**C**) Shell hash sandstone comprising a ~0.2 m thick lag deposit in Facies Association I at Dirty Annie's. (Facies I1) (**D**) Reworked marine reptile bone fragment from the shell hash sandstone lag in Facies Association I at Dirty Annie's. Scale is in millimeters. (**E**) Base of a bed of large-scale trough stratification from the incised valley fill (Facies I2) at Little Sheep Mountain B. Slab is ~3 m. (**F**) *Diplocraterion* preserved in the incised valley fill (Facies I2) at Sheep Mountain-County Road 1138. Pencil tip length is 1 cm.

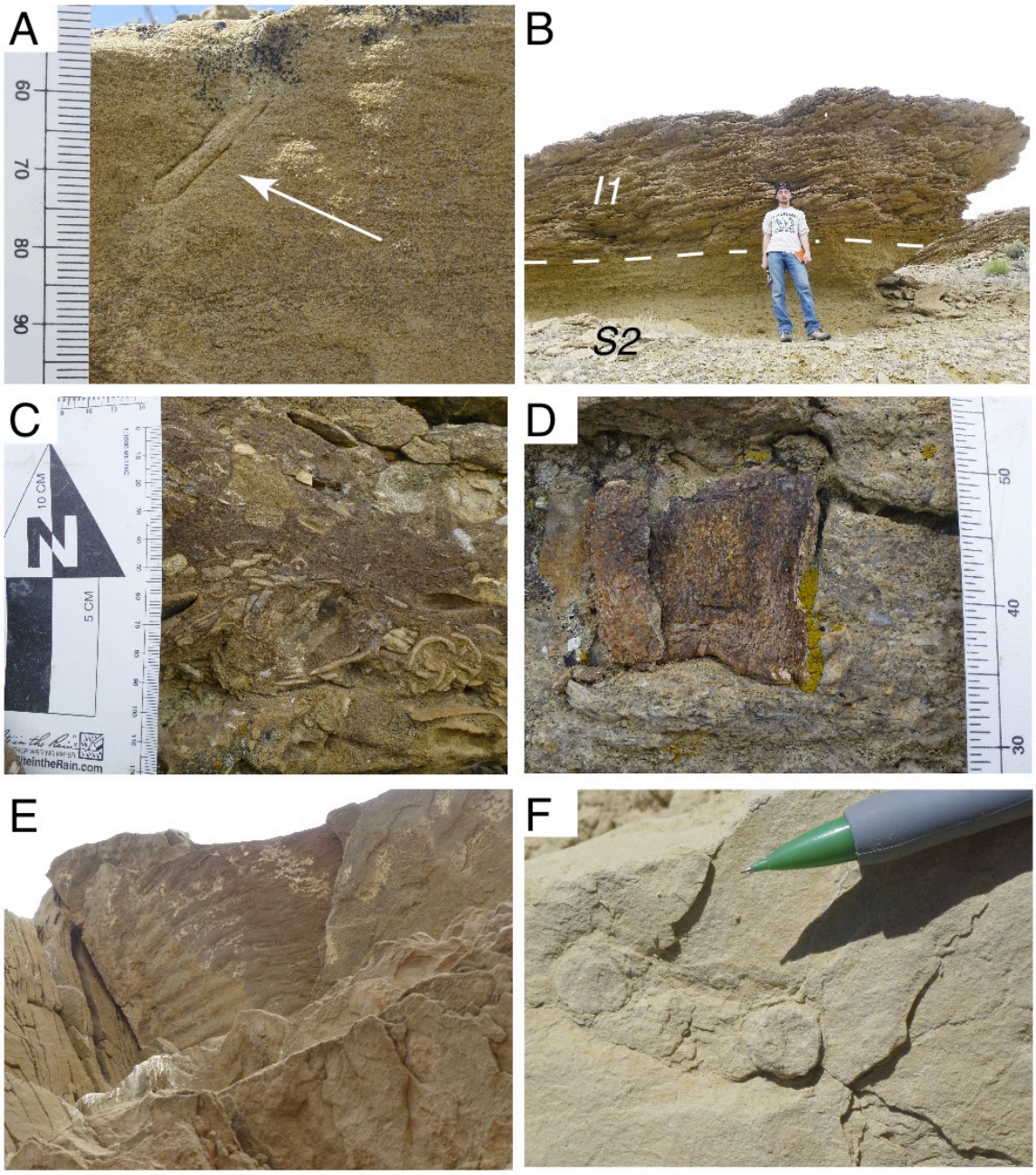

A
B
I1
S2
C
10 CM
5 CM
D
E
F

FIGURE 9— Stratigraphic cross-section and sequence stratigraphic interpretation of Sundance Formation along the eastern margin of the Bighorn Basin. mfs = maximum flooding surface; TST = transgressive systems tract; HST = highstand systems tract; bsfr = basal surface of forced regression; FSST = falling-stage systems tract; SB = sequence boundary; LST= lowstand systems tract; ts = transgressive surface. The datum is the underlying Piper Formation. Included as a fold-out.

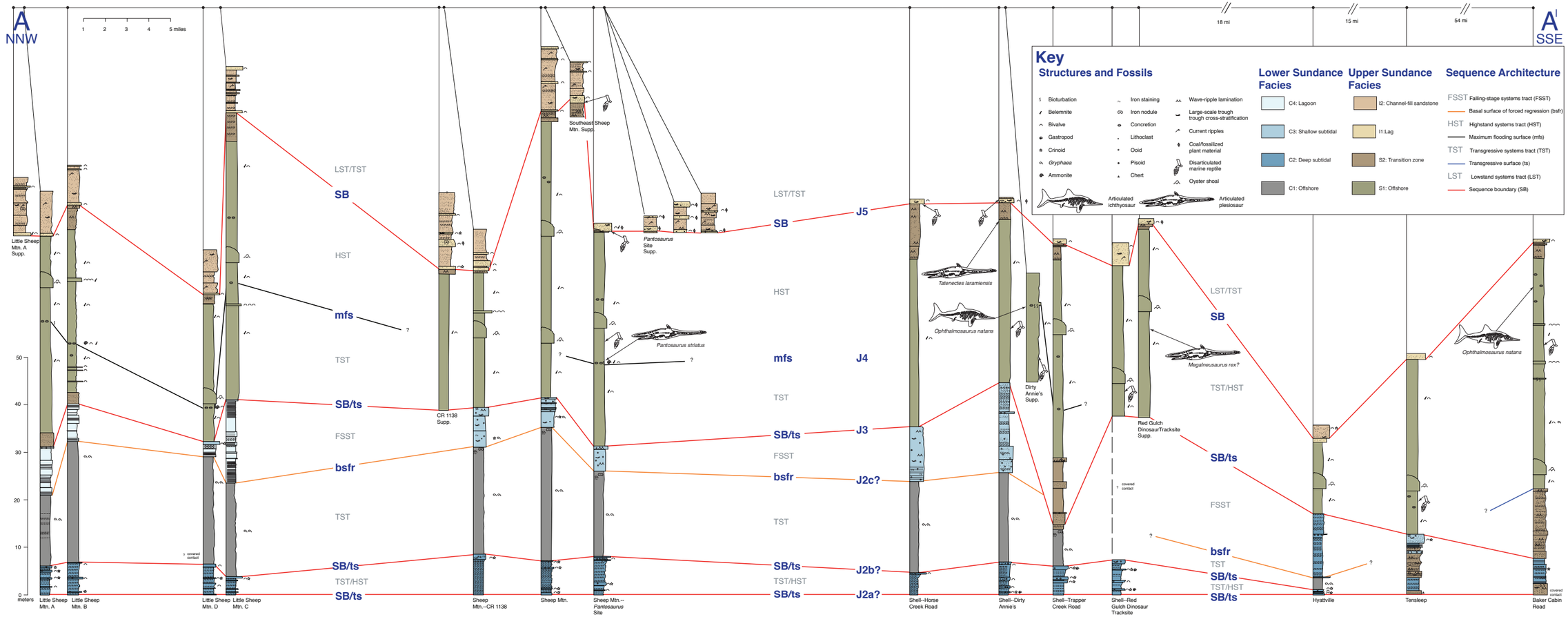

A
NNW
A'
SSE
1 2 3 4 5 miles
18 mi
15 mi
54 mi
meters
50
40
30
20
10
0
LST/TST
SB
HST
mfs
TST
SB/ts
FSST
bsfr
TST
SB/ts
TST/HST
SB/ts
J5
J4
J3
J2c?
J2b?
J2a?
Little Sheep Mtn. A Supp.
Southeast Sheep Mtn. Supp.
Panfosaurus Site Supp.
Pantosaurus striatus
CR 1138 Supp.
Tatenectes laramiensis
Ophthalmosaurus natans
Dirty Annie's Supp.
Megalneusaurus rex?
Red Gulch DinosaurTracksite Supp.
Ophthalmosaurus natans
covered contact
Little Sheep Mtn. A
Little Sheep Mtn. B
Little Sheep Mtn. D
Little Sheep Mtn. C
Sheep Mtn.–CR 1138
Sheep Mtn.
Sheep Mtn.–Pantosaurus Site
Shell–Horse Creek Road
Shell–Dirty Annie's
Shell–Trapper Creek Road
Shell–Red Gulch Dinosaur Tracksite
Hyattville
Tensleep
Baker Cabin Road
Key
Structures and Fossils
Bioturbation
Belemnite
Bivalve
Gastropod
Crinoid
Gryphaea
Ammonite
Iron staining
Iron nodule
Concretion
Lithoclast
Ooid
Pisoid
Chert
Wave-ripple lamination
Large-scale trough trough cross-stratification
Current ripples
Coal/fossilized plant material
Disarticulated marine reptile
Oyster shoal
Articulated ichthyosaur
Articulated plesiosaur
Lower Sundance Facies
C4: Lagoon
C3: Shallow subtidal
C2: Deep subtidal
C1: Offshore
Upper Sundance Facies
I2: Channel-fill sandstone
I1:Lag
S2: Transition zone
S1: Offshore
Sequence Architecture
FSST Falling-stage systems tract (FSST)
Basal surface of forced regression (bsfr)
HST Highstand systems tract (HST)
Maximum flooding surface (mfs)
TST Transgressive systems tract (TST)
Transgressive surface (ts)
LST Lowstand systems tract (LST)
Sequence boundary (SB)

FIGURE 10—Correlation of Little Sheep Mountain D and C to a spontaneous potential-resistivity well-log (20092). This well-log is located less than 1 km to the southwest of Little Sheep Mountain C. Key surfaces can be traced from outcrop to well-log. Some additional surfaces are also identifiable in well-log that cannot be observed in outcrop. Line color indicates the following surfaces: red = sequence boundaries, orange = basal surface of forced regression, and gray = other.

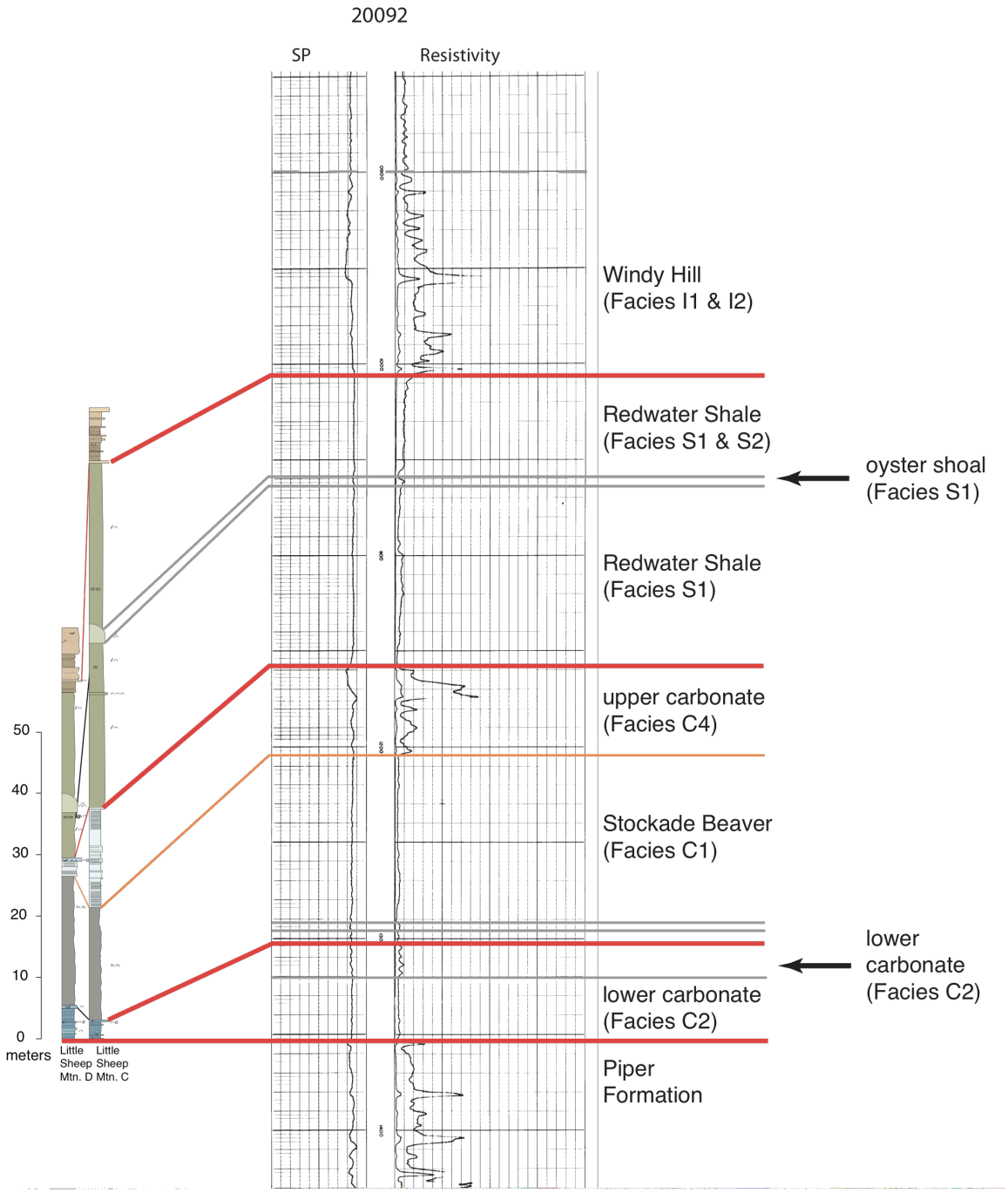
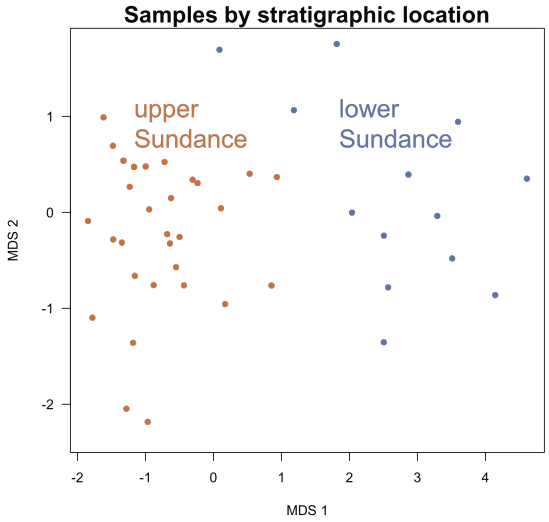
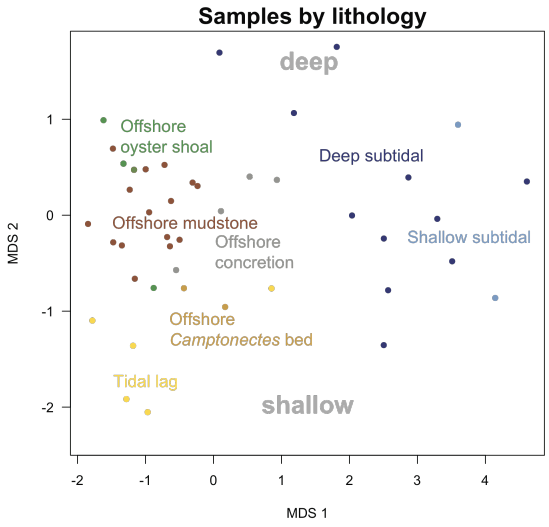

20092
SP
Resistivity
Windy Hill
(Facies I1 & I2)
Redwater Shale
(Facies S1 & S2)
oyster shoal
(Facies S1)
Redwater Shale
(Facies S1)
upper carbonate
(Facies C4)
Stockade Beaver
(Facies C1)
lower
carbonate
(Facies C2)
lower carbonate
(Facies C2)
Piper
Formation
50
40
30
20
10
0
meters
Little
Sheep
Mtn. D
Little
Sheep
Mtn. C

FIGURE 11—Non-metric multidimensional scaling of faunal censuses, with sample scores plotted by stratigraphic position (**top**), lithology (**middle**), and taxa (**bottom**). Taxa are labeled in blue with four-letter codes (see Table 2 for key to codes). Depth trends are noted on the lithology and upper Sundance lithology plots (bottom) in gray as "deep" and "shallow" gradients.


Samples by stratigraphic location
upper
Sundance
lower
Sundance
MDS 2
MDS 1


Samples by lithology
deep
Offshore
oyster shoal
Deep subtidal
Offshore mudstone
Offshore
concretion
Shallow subtidal
Offshore
Camptonectes bed
Tidal lag
shallow
MDS 2
MDS 1

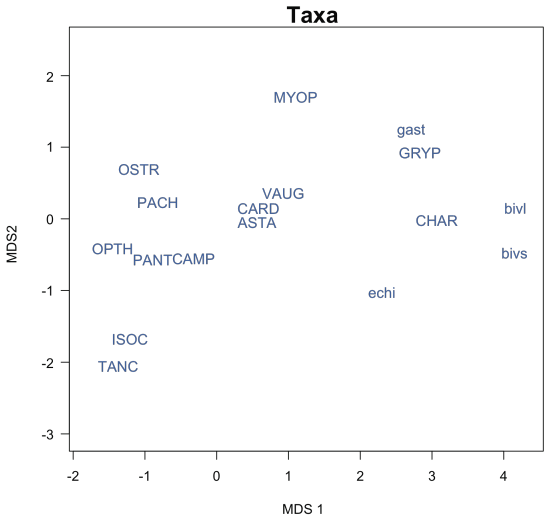

Taxa
MYOP
gast
GRYP
OSTR
VAUG
PACH
CARD
ASTA
CHAR
bivl
OPTH
PANTCAMP
bivs
echi
ISOC
TANC
MDS2
MDS 1

TABLE 1—Summary of facies present in Facies Association 1 (carbonate ramp) in the Sundance Formation exposed along the eastern margin of the Bighorn Basin, Wyoming.

Facies	Lithology and bedding	Sedimentary structures	Trace fossils	Body fossils
C1: Offshore	very thinly bedded tan to gray mudstone	none	none	abundant *Gryphaea nebrascensis*, foraminifera, echinoid spines, ostracods, fish teeth
C2: Deep subtidal	very-thinly bedded gray to brown calcareous mudstone to siltstone interbedded with a skeletal wackestone to packstone	mudstone: none; skeletal wackestone to packstone: wave-ripple lamination, planar lamination	none	mudstone: none; skeletal wackestone to packstone: bivalves, crinoids, and gastropods
C3: Shallow subtidal—ooid shoal	ooid packstone to grainstone	large-scale trough cross stratification, planar lamination, and wave-ripple lamination	none	reworked *Gryphaea nebrascensis*, bivalves, and crinoids
C4: Lagoon	gray lime mudstone	flaser to lenticular laminations	none	fish scales

TABLE 2—Summary of facies present in Facies Association S (wave-dominated shelf) in the Sundance Formation exposed along the eastern margin of the Bighorn Basin, Wyoming.

Facies	Lithology and bedding	Sedimentary structures	Trace fossils	Body fossils
S1: Offshore	glauconitic olive drab silty mudstone	none	*Planolites* and *Rhiozocorallium*	*Camptonectes bellistriatus*, *Astarte*, *Pleuromya, Cardioceras, Ostrea,* crinoids, belemnites, ichthyosaurs, plesiosaurs, and pliosaurs
S2: Transition zone	light tan fine- to medium-grained sublitharenite to litharenite	wave-ripple lamination	*Chondrites*, *Planolites*, and indistinguishable unbranching curved vertical burrows	none

TABLE 3—Summary of facies present in Facies Association I (incised valley fill) in the Sundance Formation exposed along the eastern margin of the Bighorn Basin, Wyoming.

Facies	Lithology and bedding	Sedimentary structures	Trace fossils	Body fossils
I1: Channel lag	calcite-cemented, fine to medium-grained sublitharenite	0.5-1.5 m high lateral accretion surfaces, and large-scale trough cross stratification	none	reworked neomorphosed bivalves, bivalve molds, *Tancredia*, belemnites, crinoids, and marine reptile bones
I2: Channel-fill sandstone	fine-grained sublitharenite	large-scale trough cross-bedding and lateral accretion surfaces	*Diplocraterion* and *Planolites*	none

TABLE 4—Four-letter taxon codes.

Code	Taxon	Higher Taxon
ASTA	*Astarte*	Bivalvia
bivl	Large bivalve	Mollusca
bivs	Small bivalve	Mollusca
CAMP	*Camptonectes bellistriatus*	Bivalvia
CARD	*Cardioceras*	Cephalopoda
CHAR	*Chariocrinus*	Echinoidea
ECHI	Echinoid fragments	Echinoidea
gast	Small gastropod	Mollusca
GRYP	*Gryphaea nebrascensis*	Bivalvia
ISOC	*Isocrinus*	Echinoidea
MYOP	*Myopholas*	Bivalvia
OPTH	*Ophtalmosaurus natans*	Reptilia
OSTR	*Ostrea striglecula*	Bivalvia
PACH	*Pachyteuthis densus*	Cephalopoda
PANT	*Pantosaurus striatus*	Reptilia
TANC	*Tancredia*	Bivaliva
VAUG	*Vaugonia*	Bivalvia

APPENDIX A

FIELD LOCALITIES

Little Sheep Mountain A Supplemental Sands:

44.822983° N, 108.306304° W

Little Sheep Mountain A:

44.815522° N, 108.306392° W

Little Sheep Mountain B:

44.787555° N, 108.298362° W

Little Sheep Mountain D:

44.701267° N, 108.268717° W

Little Sheep Mountain C:

44.694870° N, 108.254649° W

Sheep Mountain-County Road 1138 Supplemental:

44.586743° N, 108.142854° W

Sheep Mountain-County Road 1138:

44.587736° N, 108.141608° W

Sheep Mountain:

44.566666° N, 108.043818° W

Sheep Mountain Supplemental:

44.569537° N, 108.042308° W

Sheep Mountain-*Pantosaurus* Site:

44.536967° N, 108.030497° W

Shell-Horse Creek Road:

44.616712° N, 107.765743° W

Dirty Annie's upper Sundance:

44.555211° N, 107.771246° W

Dirty Annie's lower Sundance:

44.560331° N, 107.760228° W

Shell-Trapper Creek Road:

44.493416° N, 107.743082° W

Shell-Red Gulch Dinosaur Tracksite upper Sundance:

44.555211° N, 107.771246° W

Shell-Red Gulch Dinosaur Tracksite lower Sundance:

44.560331° N, 107.760228° W

Shell-Red Gulch Dinosaur Tracksite Supplemental:

44.482624° N, 107.796153° W

Hyattville:

44.267061° N, 107.574786° W

Tensleep:

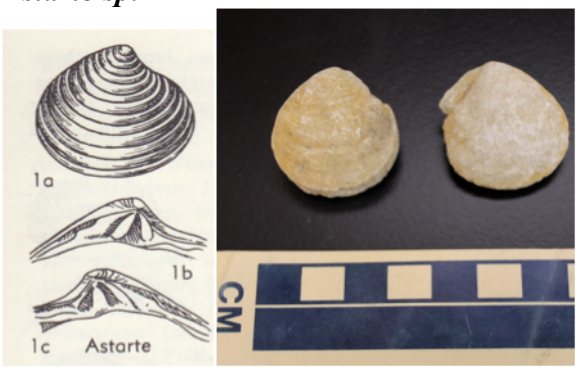
44.058645° N, 107.497770° W

Baker Cabin Road:

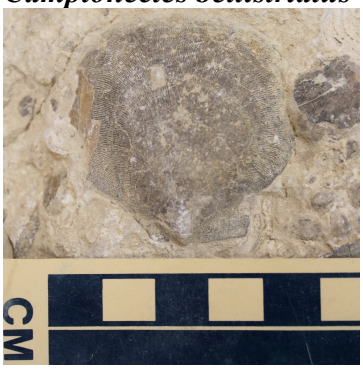
43.325217° N, 107.123533° W

APPENDIX B
INVERTEBRATE TAXA IDENTIFIED IN THIS STUDY

Astarte sp.



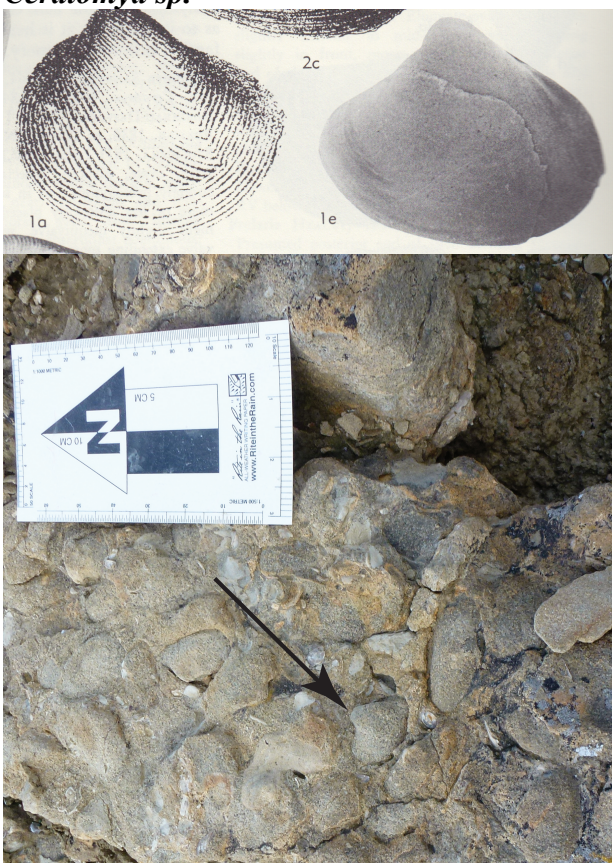
Camptonectes bellistriatus



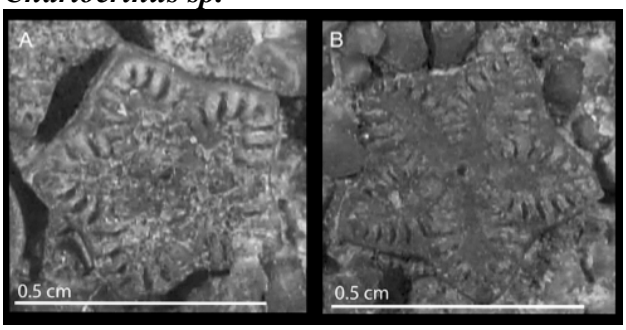
Cardioceras sp.



Ceratomya sp.



Chariocrinus sp.



Echinoid fragments



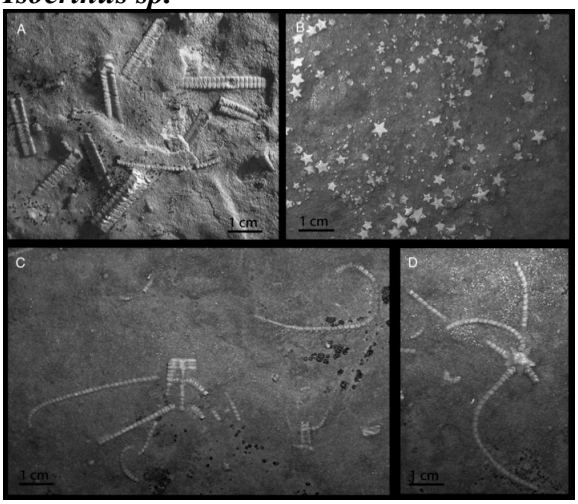
Gastropods (large)



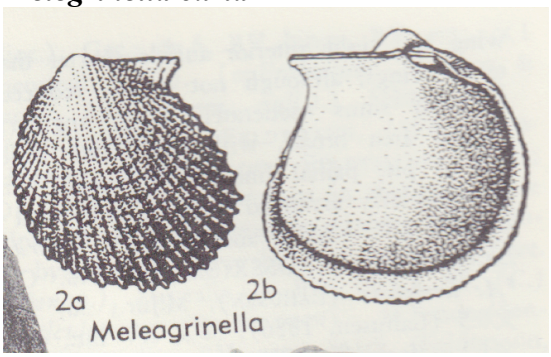
Gryphaea nebrascensis



Isocrinus sp.



Melegrinella curta



Myopholas sp.

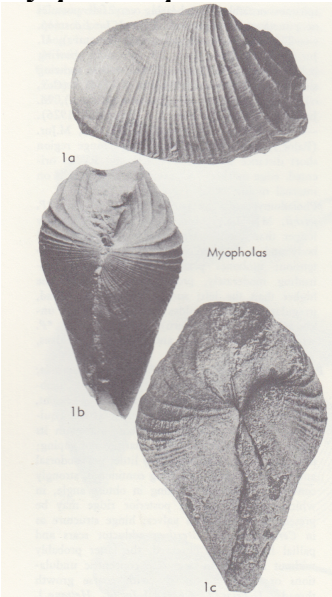
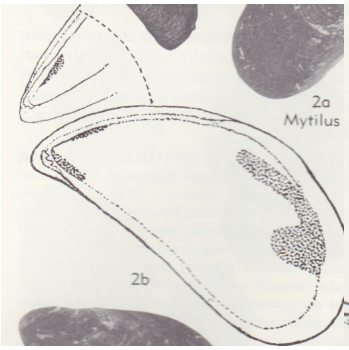
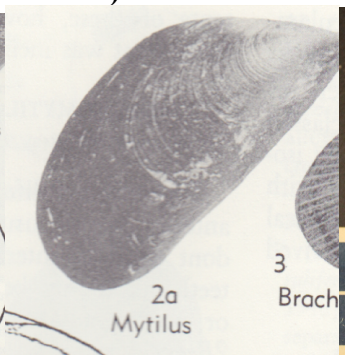


FIG. F20. Myopholadidae (p. N842).

Mytilidae (*Mytiloida* or *Modiolus*)







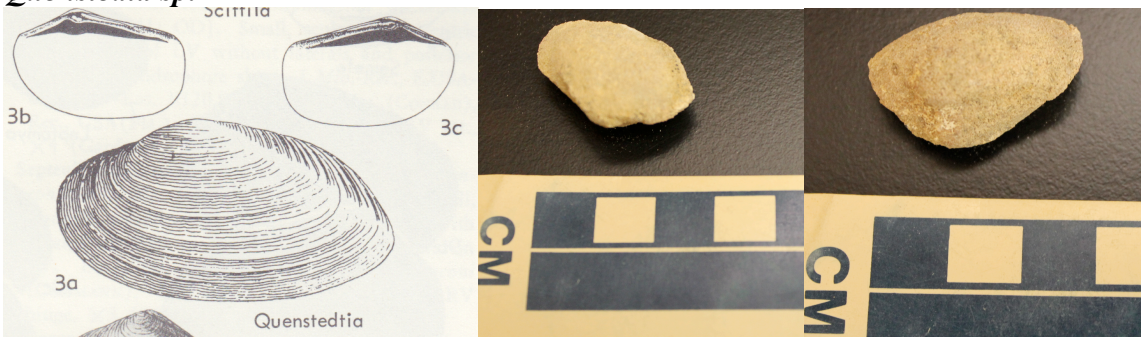
Ostrea sp.



Pachyteuthis densus



Quenstedia sp.



Tancredia sp.



Vaugonia sp.



APPENDIX C

FAUNAL CENSUSES

	Astarte sp.	Bivalve (<1cm)	Bivalves (>1cm)	*Camptonectes bellistriatus*	*Cardioceras sp.*	*Ceratomya sp.*	*Chariocrinus sp.*	Echinoid fragments	Gastropod (small)	Gastropods (large)	*Gryphaea nebrascensis*	*Isocrinus sp.*	*Melegrinella curta*	*Myopholas sp.*	*Myitilidae*	*Ophthalmosaurus natans*	*Ostrea sp.*	*Pachyteuthis densus*	*Pantosaurus striatus*	*Quenstedia sp.*	*Tancredia sp.*	*Vaugonia sp. (?)*
LSMA-C 100.6-101.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSMA-D 36.2-36.5	24	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
Pantosaurus 8.1-26.1	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0
LSMA-C 72.7-80.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	6	0	0	0	0
LSMA-B 60.8-65.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0
Pantosaurus 1.0-1.2	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sheep Mtn 77.4-78.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0
Hyattville 0.0-1.4	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSMA-A 71.0-71.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TCR 3.2-3.7	0	0	0	0	0	0	0	0	1	0	0	0	0	0	6	0	0	0	0	0	0	0
Sheep Mtn 7.1-35.0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0
LSMA-D 30.6-40.8	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	24	0	0	0	0
Horse Creek Rd 4.6-23.8	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0
LSMA-D 6.5-27.5	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0
TCR 17.0-17.1	0	24	0	0	0	0	6	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0
Tensleep 12.7-24.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	6	6	0	0	0	0
LSMA-B 0.7-0.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0
LSMA-C 71.7-72.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0
LSMA-B 47.2-52.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0
Sheep Mtn 77.4-99.1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0
LSMA-B 6.8-6.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TCR 73.7-74.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0
Hyattville 32.8-35.6	24	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
LSMA-B 66.1-66.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0
Dirty Annie's 3.3-3.8	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sheep Mtn 35.0-38.3	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CR1138 7.4-8.5	1	0	0	0	0	0	12	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
CR1138 59.5-67.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	6	0	0	0	0
TCR 2.8-3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	1	0	0	0	0	0
Baker Cabin Rd 22.1-25.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0
RGDT 1.0-1.3	0	0	0	0	0	0	12	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0
Tensleep 24.1-25.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	12	12	0	0	0	0
Baker Cabin Rd 47.5-.64.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0
LSMA-D 61.4-61.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Astarte sp.	Bivalve (<1cm)	Bivalves (>1cm)	*Camptonectes bellistriatus*	*Cardioceras sp.*	*Ceratomya sp.*	*Chariocrinus sp.*	Echinoid fragments	Gastropod (small)	Gastropods (large)	*Gryphaea nebrascensis*	*Isocrinus sp.*	*Melegrinella curta*	*Myopholas sp.*	*Mytilidae*	*Ophthalmosaurus natans*	*Ostrea sp.*	*Pachyteuthis densus*	*Pantosaurus striatus*	*Quenstedia sp.*	*Tancredia sp.*	*Vaugonia sp. (?)*
Pantosaurus 8.0-8.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tensleep 10.7-12.7	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSMA-C 60.5-71.7	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0
Sheep Mtn 99.1-99.8	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
LSMA-B 44.7-47.9(int)	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSMA-C 14.9-23.3	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0
Sheep Mtn 56.0-77.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0
Hyattville 1.4-3.4	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0
Dirty Annie's 1.6-2.0	0	0	6	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CR1138 30.9-34.2	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0
Dirty Annie's 19.5-25.7	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0
Sheep Mtn 1.2-7.1	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CR1138 8.5-30.9	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0
LSMA-A 17-40.8	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0
LSMA-D 2.3-2.5	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Horse Creek Rd 35.2-50.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0
Baker Cabin Rd 42.7-43.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TCR 5.9-13.7	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0
LSMA-C 80.6-80.8	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0
CR1138 55.8.0-56.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	6	0	0	0	0
LSMA-B 52.7-59.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0
LSMA-C 40.8-60.3	0	0	6	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dirty Annie's 45.5-57.5	0	0	0	6	0	6	0	0	0	0	0	0	0	0	0	6	12	24	1	6	0	0
Sheep Mtn 39.0-39.1	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hyattville 24.5-25.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	12	0	0	0	0
Dirty Annie's 0.6-0.9	0	0	24	0	0	0	24	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0
RGDT 38.2-43.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0
LSMA-A 80.4-86.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	12	0	0	0	0
LSMA-D 1.5-1.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dirty Annie's 61.5-86.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	12	0	0	0	0
Dirty Annie's 3.1-3.3	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hyattville 3.4-3.5	0	0	0	0	0	0	24	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0
Baker Cabin Rd 39.3-42.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0
LSMA-D 30.1-30.6	0	6	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pantosaurus 76.2-78.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0
RGDT 2.6-3.0	12	0	0	0	0	0	0	0	0	0	6	0	0	24	0	0	0	0	0	0	0	0
Baker Cabin Rd 25.0-26.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	24	0	0	0	0
Pantosaurus 7.3-7.5	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSMA-B 81.7-82.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Astarte sp.	Bivalve (<1cm)	Bivalves (>1cm)	*Camptonectes bellistriatus*	*Cardioceras sp.*	*Ceratomya sp.*	*Chariocrinus sp.*	Echinoid fragments	Gastropod (small)	Gastropods (large)	*Gryphaea nebrascensis*	*Isocrinus sp.*	*Melegrinella curta*	*Myopholas sp.*	*Mytilidae*	*Ophthalmosaurus natans*	*Ostrea sp.*	*Pachyteuthis densus*	*Pantosaurus striatus*	*Quenstedia sp.*	*Tancredia sp.*	*Vaugonia sp. (?)*
LSMA-D 3.6-3.7	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sheep Mtn 41.2-55.0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0
LSMA-B 59.8-60.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0
LSMA-A 4.7-5.1	0	0	0	0	0	0	12	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dirty Annie's 86.3-87.3	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	24	0
CR1138 39.2-55.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	24	0	0	0	0
TCR 5.5-5.9	0	24	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dirty Annie's 6.5-7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RGDT 7.9?-17.1	1	0	0	24	0	0	0	0	0	0	0	0	0	0	0	1	0	24	1	0	0	0
LSMA-D 5.9-6.5	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	6	0	0	0	0	0
Tensleep 25.1-38.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	12	0	0	0	0
TCR 35.2-35.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0
LSMA-D 0.0-0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0
Tensleep 10.0-10.1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pantosaurus 21.2-58.4	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	6	0	24	1	0	0	0
TCR 56.8-57.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0
Horse Creek Rd 82.1-82.8	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	1	0	1	0	0	0	0
RGDT 6.6-7.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Baker Cabin Rd 47.3-47.5	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSMA-C 80.8-100.6	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
Tensleep 9.3-10.0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CR1138 67.3-69.8	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0	0	24	0
TCR 73.1-73.3	0	12	1	0	0	0	0	0	0	0	0	6	0	0	0	0	0	6	0	0	24	0
LSMA-C 31.2-31.9	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0
LSMA-B 65.7-65.9	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dirty Annie's 57.5-59.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	12	0	0	0	0
Hyattville 17.0-24.5	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0
CR1138 59.1-59.5	0	0	0	24	0	0	0	6	0	0	0	0	0	0	0	0	0	1	0	0	0	0
LSMA-A 54.0-80.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0
Tensleep 19.3-50.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Baker Cabin Rd 42.4-42.7	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pantosaurus 59.4-76.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	6	0	0	0	0
Tensleep 10.3-10.5	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hyattville 25.5-32.0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0
Pantosaurus 58.4-59.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0
LSMA-C 3.4-3.7	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSMA-A 3.3-3.5	0	0	0	0	0	0	6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Astarte sp.	Bivalve (<1cm)	Bivalves (>1cm)	*Camptonectes bellistriatus*	*Cardioceras sp.*	*Ceratomya sp.*	*Chariocrinus sp.*	Echinoid fragments	Gastropod (small)	Gastropods (large)	*Gryphaea nebrascensis*	*Isocrinus sp.*	*Melegrinella curta*	*Myopholas sp.*	*Mytilidae*	*Ophthalmosaurus natans*	*Ostrea sp.*	*Pachyteuthis densus*	*Pantosaurus striatus*	*Quenstedia sp.*	*Tancredia sp.*	*Vaugonia sp. (?)*
LSMA-A 5.7-6.0	0	0	0	0	0	0	1	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RGDT 18.2-38.2	1	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0
Hyattville 12.7-12.9	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSMA-A 70.8-71.0	12	0	0	6	12	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0
Horse Creek Rd 4.3-4.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Baker Cabin Rd 42.7-47.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	24	0	0	0	0
LSMA-D 40.8-41.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	12	0	0	0	0
RGDT 5.2-5.4	0	0	0	0	0	0	0	0	0	6	0	0	0	24	0	0	0	0	0	0	0	0
Baker Cabin Rd 26.3-39.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0
LSMA-B 52.3-52.7	12	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	6
LSMA-B 6.9-32.3	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0
LSMA-B 3.5-3.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sheep Mtn 55.0-56.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0
Hyattville 10.7-12.7	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dirty Annie's 7.0-19.5	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0
RGDT 17.1-18.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	1	0	0	0	0
TCR 28.8-56.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	24	0	0	0	0
Dirty Annie's 59.5-61.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	12	0	0	0	0