Middle Jurassic (Bajocian and Bathonian) Dinosaur Megatracksites, Bighorn Basin, Wyoming, U.S.A.

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Two previously unknown rare Middle Jurassic dinosaur megatracksites are reported from the Bighorn Basin of northern Wyoming in the Western Interior of the United States. These trace fossils occur in carbonate units once thought to be totally marine in origin, and constitute the two most extensive Middle Jurassic dinosaur tracksites currently known in North America. The youngest of these occurs primarily along a single horizon at or near the top of the "basal member" of the "lower" Sundance Formation, is mid-Bathonian in age, and dates to ~167 ma. This discovery necessitates a major change in the paleogeographic reconstructions for Wyoming for this period. The older tracksites occur at multiple horizons within a 1 m interval in the middle part of the Gypsum Spring Formation. This interval is uppermost Bajocian in age and dates to ~170 ma.

Terrestrial tracks found, to date, have been all bipedal tridactyl dinosaur prints. At least some of these prints can be attributed to theropods. Possible swim tracks of bipedal dinosaurs are also present in the Gypsum Spring Formation. Digitigrade prints dominate the Sundance trackways, with both plantigrade and digitigrade prints being preserved in the Gypsum Spring trackways. The Sundance track-bearing surface locally covers 7.5 square kilometers in the vicinity of Shell, Wyoming. Other tracks occur apparently on the same horizon approximately 25 kilometers to the west, north of the town of Greybull. The Gypsum Spring megatracksite is locally preserved across the same 25 kilometer east-west expanse, with the Gypsum Spring megatracksite more extensive in a north-south direction with tracks occurring locally across a 100 kilometer extent. Conservative estimates for the trackway density based on regional mapping in the Sundance tracksite discovery area near Shell suggests that over 150,000 in situ *tracks may be preserved per square kilometer in the Sundance Formation in this area. Comparable estimates have not been made for other areas.*

Similarities between the two megatracksites include their formation and preservation in upper intertidal to supratidal sediments deposited under at least seasonally arid conditions. Microbial mat growth on the ancient tidal flats apparently initiated the preservation of these prints.

INTRODUCTION

Middle Jurassic dinosaur trackways and tracksites have been documented from marginal marine and eolian sediments of the Carmel, the Entrada Sandstone, and the Bell Ranch formations in Utah, Colorado, and Oklahoma, but, until recently, were unknown in age-equivalent Middle Jurassic Gypsum Spring, Piper, and Sundance formations of Wyoming and Montana (Lockley et al., 1996, 1998). The reason for this is, in part, the dominantly marine nature of the Middle Jurassic systems responsible for the deposition of these formations in Wyoming and Montana. However, potential dinosaur track-bearing nonmarine and marginal marine deposits do exist in the Gypsum Spring, Piper, and Sundance formations (Fig. 1). For example, eolian deposits have been identified in sandstones of the Bathonian-aged Canyon Springs Sandstone Member of the Sundance Formation in southernmost Wyoming (Blakey et al., 1988) and in the latest Bathonian to early Callovian eolian oolitic grainstones from the upper part of the "lower" Sundance in north-central Wyoming (Kilibarda and Loope, 1997). The common occurrence of gypsum and other evaporite-rich depositional facies throughout the Bajocian and Bathonian Gypsum Spring and Piper sequences indicate that periodically marine conditions shifted towards more terrestrial lagoonal and hypersaline sabkha-dominated environments throughout much of north-

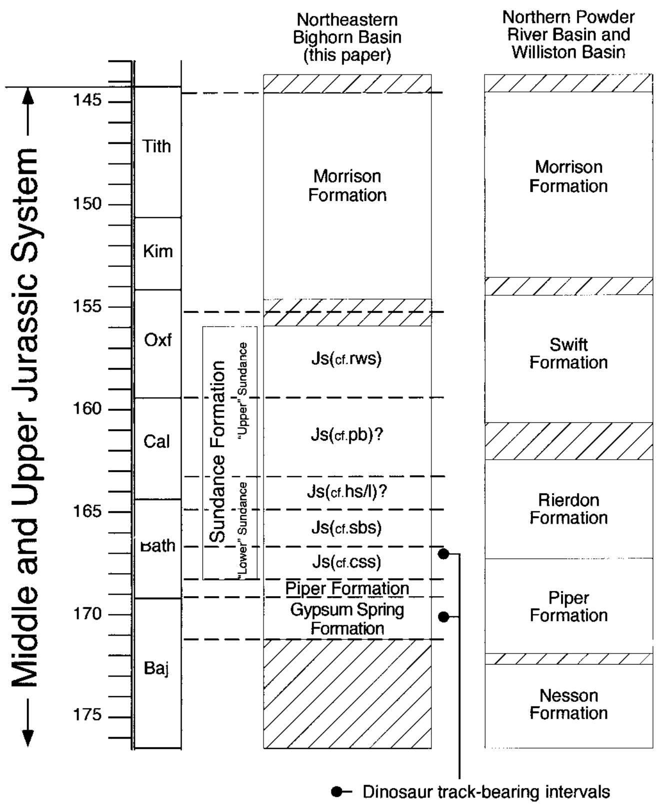

FIGURE 1—Generalized Jurassic stratigraphy of the northeastern Bighorn Basin and adjoining areas, Wyoming and Montana. Jurassic unconformities discussed in text are indicated (dashed lines). Position of unconformity intervals in the Powder River and Williston Basins (Johnson, 1992) remain unmodified from that source. Position of unconformity intervals within the "lower" Sundance of the Bighorn Basin are based on evidence discussed herein. Canyon Spring Sandstone Member (css), Stockade Beaver Shale Member (sbs), Hulett Sandstone Member and Lak Member (hs/l), Pine Butte Member (pb), and Redwater Shale Member (rws) commonly are recognized members in the Sundance Formation of the central and southern portions of the Powder River Basin

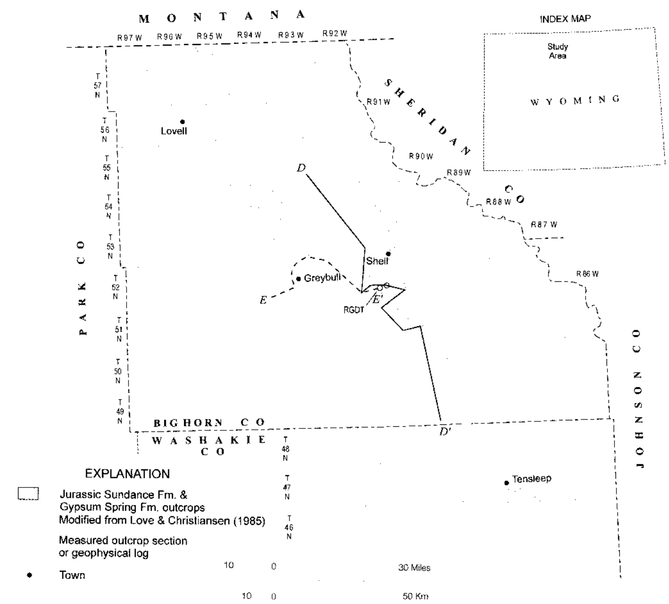

FIGURE 2—Map of the northeastern part of the Bighorn Basin, northern Wyoming, showing locations of the Red Gulch Dinosaur Tracksite (RGDT), regional cross-sections (see Figure 4), and the distribution of the Sundance and Gypsum Spring formations.

ern Wyoming during deposition of these strata (Wright, 1971). In addition, Imlay (1956) and subsequent researchers (e.g. Piperingos and O'Sullivan, 1978; Brenner and Peterson, 1994) documented regional unconformity bounded transgressive-regressive cycles between and within the Sundance, Piper, and Gypsum Spring formations of Wyoming and Montana. The presence of these cycles suggests the possibility of the preservation of low-stand or early transgressive, nonmarine or marginal marine facies within these units, both of which have the potential to be dinosaur track-bearing.

Two newly discovered Middle Jurassic dinosaur track-bearing horizons in the Bighorn Basin of northern Wyoming are reported herein (Fig. 2) from carbonate units once thought to be totally marine in origin. The older occurs within the middle part of the middle Jurassic Gypsum Spring Formation, and the slightly younger below a Middle Jurassic flooding surface that occurs near the base of the Sundance Formation. The former was discovered during the summer of 1999, and the latter in May of 1997. The occurrence of trackways at these stratigraphic intervals extends from outcrops some 25 kilometers to the north of the town of Greybull southward, approximately 100 kilometers, towards the town of Tensleep and eastward from Greybull, some 20 kilometers, to sites in the vicinity of the village of Shell (Fig. 2). The best exposures and some of the best-preserved trackways are those that occur near the base of the Sundance Formation in an area now referred to as "The Red Gulch Dinosaur Tracksite" (RGDT; Fig. 2). This site covers an area of some 15 hectares and preserves thousands of bipedal tridactyl dinosaur footprints on the upper surface of a coated-grain grainstone. This site is situated on federal lands administered by the U.S. Department of the Interior, Bureau of Land Management (BLM), and is easily accessible to the public.

With the exception of those rare instances in which dinosaur tracks associated with marine or lacustrine facies are thought to have been formed by buoyed and nearly swimming animals, the presence of dinosaur tracks is a clear indication of subaerial exposure. These tridactyl traces in the Sundance and Gypsum Spring formations, associated with intertidal and supratidal depositional facies, indicate the presence of subaerial exposure surfaces that were previously unknown from these sediments in the Bighorn Basin.

Middle Jurassic dinosaur remains of any type that are the age equivalent to the Sundance and Gypsum Spring formations are rare and largely unknown in North America. On-going studies of Jurassic stratigraphic successions and associated dinosaur fossils in the Western United States reveal that dinosaur ichnofaunas are facies related to some degree (Lockley, et al., 1994; Mickelson, unpublished data). In other words, certain types of faunal remains can be associated with specific depositional facies. To understand the paleoecology of this dinosaur fauna, it is first necessary to understand the depositional context in which the remains are found. The Gypsum Spring and the lowermost Sundance vertebrate trace fossils can be dated accurately biochronologically, and geochronologically, and through subsurface and outcrop correlation to other regions. As such, they can be put into a broad, regional context and will become very important to the understanding of Middle Jurassic dinosaurs. This paper reports the occurrence, stratigraphic position, depositional setting, climatic significance, morphologic elements, and ages of these dinosaur trackways. The linkage between microbial mat development on intertidal flats and track preservation also is discussed.

REGIONAL PALEOGEOGRAPHY

During the Jurassic, large portions of the Western Interior of North America were inundated by a shallow epicontinental seaway bounded on the west by a subduction-generated volcanic arc that extended northward from Mexico along the western margin of the United States into southwestern Canada. The seaway was bounded on the east by the North American craton (Fig. 3). This elongated seaway may have been less than 500 km wide in some areas, separated from the Gulf of Mexico by the Ancestral Rockies uplifts to the south, and restricted on the east by complex shoreline conditions extending into the present day Dakotas. As global eustatic sea levels fluctuated in response to tectonic controls, this shallow seaway spread southward from the Arctic to inundate the Western Interior in a series of at least four major pulses, consisting of transgressions in the Early Jurassic (Pliensbachian-Toarcian), twice in the Middle Jurassic (Bajocian-Early Callovian and Late Callovian), and again during the Late Jurassic in early Oxfordian time (Pipiringos and O'Sullivan, 1978). A Middle Jurassic foreland basin depocenter existed along the western margin of this inland sea where several thousand feet of sediments associated with the Twin Creek Trough were deposited in central Utah and westernmost Wyoming. The average depth of this shallow seaway to the East was less than 100m in which small variations in sea level could have produced shoaling sequences capped by associated eolian deposits in some localities (Imlay, 1956; Kilibarda and Loope, 1997). Several palinspastic/paleogeographic reconstructions have placed the Wyoming portion of the Western Interior of North America within 15^0 to 20^0 N latitude during this time period (e.g., Saleeby and Busby-Spera, 1992, plate 5).

MIDDLE JURASSIC STRATIGRAPHY IN THE BIGHORN BASIN

General Stratigraphy

The Middle Jurassic deposits of northern Wyoming are primarily marine in origin and record at least parts of four, and possibly five, major depositional cycles associated with regional transgressive-regressive events that affected much of the Western Interior region. Each of these major depositional cycles is bounded by unconformities of generally regional extent and have been termed the "First," "Second," "Third," and "Fourth" Marine cycles by Brenner and Peterson (1994). Additionally, a fifth, poorly characterized, unnamed cycle exists between the "Third" and "Fourth" Marine cycles (Fig. 4A). These cycles are significant because each has the potential to have preserved dinosaur tracks at the top of each cycle.

The relationships among the various Middle Jurassic lithostratigraphic units and marine cycles in the Bighorn Basin can be demonstrated with a combination of measured outcrop sections and subsurface geophysical logs (Fig. 4). In the Bighorn Basin of northern Wyoming, the lowest Middle Jurassic depositional cycle (First Marine cycle) is represented by the Gypsum Spring Formation. The Gypsum Spring is bounded by the J-1 unconformity at the base and the J-2 unconformity at the top (Piperingos and O'Sullivan, 1978). In the northeastern part of the Bighorn Basin, it consists of a stacked sequence of thin-bedded dolomitic and calcareous, often stromatolitic carbonates that are dominated by infaunal suspension feeding bivalves, and gypsiferous red and green-banded mudstones that overlie a locally thick gypsum bed. The formation thickens from East to West across the basin. The Gypsum Spring tracksites reported herein occur near the top of a 10 m thick coarsening-up cycle visible on geophysical logs, immediately above a ~1–3 meter thick gypsum bed (Fig. 4D, outcrop section 6 and geophysical log Tarheel 13X–5). The ammonites *Parachondroceras sp.* and *Sohlites sp.* have been reported from the middle part of the Gypsum Spring Formation on the western side of the Bighorn Basin. These species imply a probable age of late Bajocian (Calloman, 1982) for that part of the formation and the track-bearing interval.

A medial Middle Jurassic unit, the Piper Formation, has been recognized by some to occur above the Gypsum Spring Formation in the Bighorn Basin and, if present, represents the "Second Marine Cycle" (Brenner and Peterson, 1994; Piperingos and O'Sullivan, 1978). It is composed of reddish mudstones that contain thin irregular lenses or pods of gypsum, limestone, and reddish mudstone with greenish mudstone interbeds. In general, the Piper thins from West to East and North to South across the basin (Fig. 4). The thinning is attributed to onlap of the Piper onto the northwestern flank of the Sheridan Arch or the "Black Mountain High," a possible precursor to the Sheridan Arch (Piperingos and O'Sullivan, 1978; Brenner and Peterson, 1994; D. E. Schmude, pers. comm., 1999). The Sheridan Arch is a pre-Laramide topographic and structural high identified by previous workers on the basis of regional changes in ostracode assemblages, the thinning or truncation of "lower" Sundance deposits over the arch, and the localized preservation of ooid grainstone-dominated shoaling sequences (Peterson, 1954 a,b; Imlay, 1956; and West, 1984).

The overlying Sundance Formation of northern Wyoming is primarily a marine unit of middle to late Jurassic age (middle Bathonian to middle Oxfordian; Imlay, 1956) and includes at least two major unconformities (J-3, early to middle Callovian and J-4, late Callovian to early Oxfordian–Piperingos and O'Sullivan, 1978; Kilibarda and Loope, 1997) and the "Third" and "Fourth" marine cycles of Brenner and Peterson (1994; Fig. 4A). It is capped by the nonmarine upper Jurassic Morrison Formation (middle Oxfordian to Kimmeridgian; Uhlir et al., 1989).

Imlay (1956) proposed an informal division of the Sundance Formation for north-central Wyoming of a "lower" and an "upper" Sundance Formation. The "lower" Sundance is bounded by two unconformities and is considered

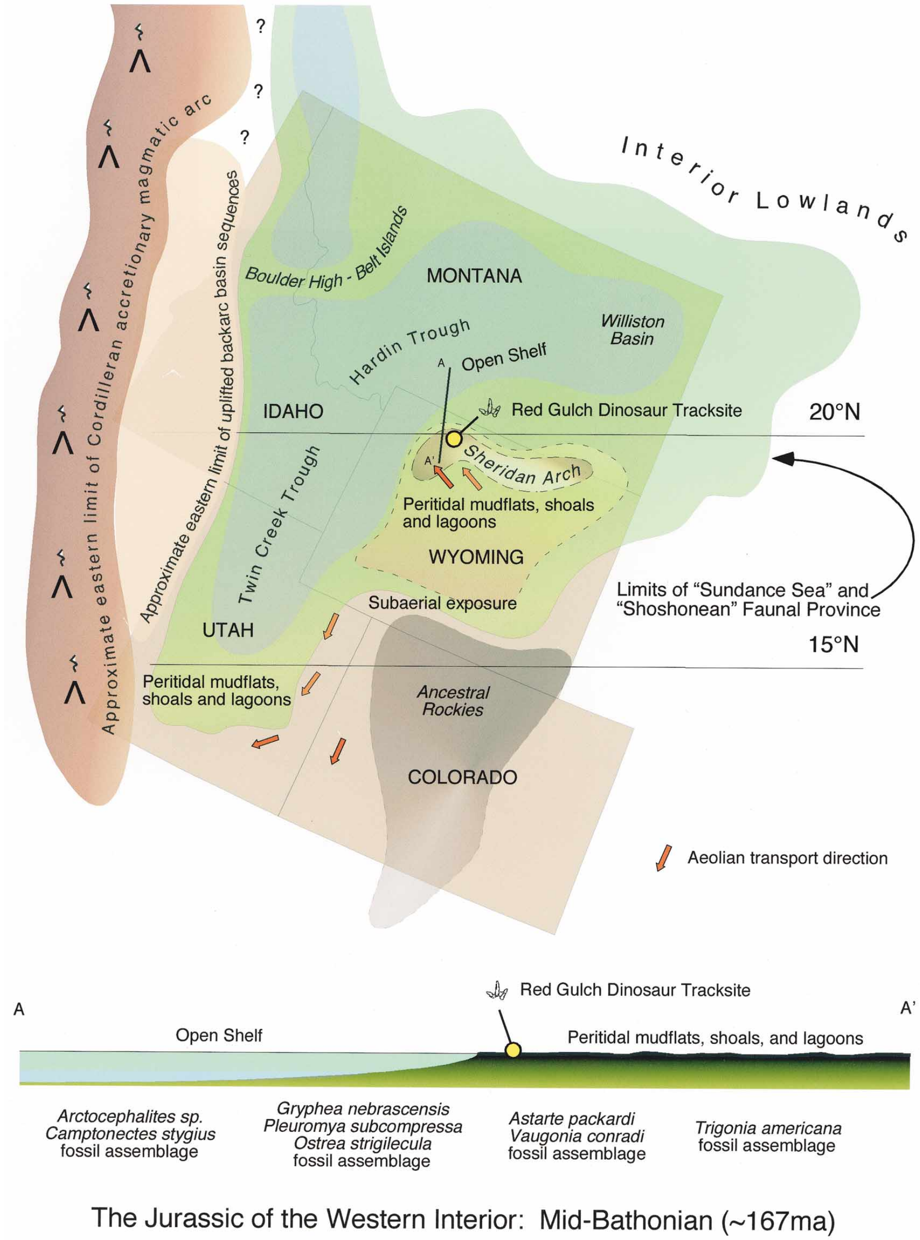

FIGURE 3—Paleogeographic reconstruction of the Western Interior Seaway during mid-Bathonian time. Compiled from the interpretations of Wright (1971), Imlay (1980), Kocurek and Dott (1983), Blakey et al. (1988), Brenner and Peterson (1994), and this research.

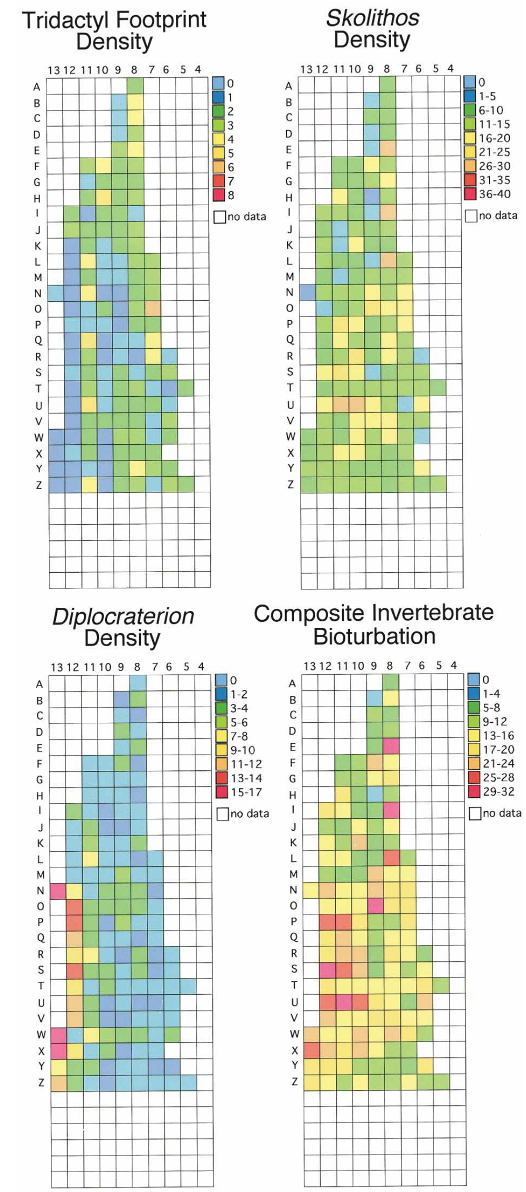

FIGURE 8—Index maps of 141 m² at the southern end the Red Gulch tracksite outcrop show spatial densities of ichnofossils (number per m²) across the outcrop. Grid represents 1 m units subdivided into 0.25 m quadrants. The maps are oriented with South at the top of the page. For the tridactyl footprint ($n = 247$) map, there is a significant decrease in mean densities by column from columns 5–13, $R^2 = 0.46$, $p<0.04$, one-way ANOVAs). The *Skolithos* ($n = 1721$) map shows a significant decrease by

distance of grid square from square Z5 ($p<0.0042$, linear one-way ANOVAs). *Diplocriterion* ($n = 418$) traces show a significant increase in mean densities by column from column 5–13 $p<0.007$, one-way ANOVAs) and a significant decrease in densities by distance of grid square from square Z13 ($p<0.0015$, one-way ANOVAs). Total invertebrate ichnofossil ($n = 2154$) density shows a significant increase by column from column 5–13 ($p<0.0024$, one-way ANOVAs), and a significant decrease by distance of grid square from square Z13 ($p<0.0001$, one-way ANOVAs).

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to be primarily marine (Imlay, 1956, 1980). The lower unconformity is regional and unnamed (referred to as J-2a herein, however) and was reported by Imlay (1956) to be marked by chert clasts, but the upper has been termed the J-3 unconformity by Pipiringos and O'Sullivan (1978; Fig. 4A). The "Third Marine Cycle" is bounded by these unconformities.

Imlay (1956) subdivided the "lower" Sundance into three primary lithologic units or "members" that can be correlated easily around the eastern margin of the Bighorn Basin and into the subsurface on geophysical logs (Fig. 4B). The present studies have shown that each of these "members" record marine transgressive-regressive cycles that are bounded at the base by a flooding event and capped by exposure surfaces. These flooding surfaces are designated in this report as J2a, J2b, J2c, and J3 from oldest to youngest.

Imlay's (1956) "basal member" consists of a 0.75 m to 8.0 m thick succession of sand-size siliciclastic and/or carbonate clastic deposits and interbedded calcareous yellowish to brownish grey mudstone that is apparently coeval with the eolian Canyon Springs Member of the Sundance Formation in southern Wyoming (Blakey, et al., 1988; Fig. 1). Imlay (1956) reports that the base of the "basal member" is marked by a regional unconformity (referred to as J2a, herein) that is erosive, irregular, and marked in many places by pebbles, most of which consist of chert. Imlay (1956, 1980) interpreted the "basal member" of the Sundance Formation as the initial deposits of a transgressing Sundance Sea. The Red Gulch Dinosaur Tracksite and laterally associated trackways constitute the exposure surface at, or very near, the top of the "basal member" of the "lower" Sundance just below the J2b flooding surface (Fig. 4). A laminate wackestone that locally directly overlies the tracksite and infills the tracks contains, among other microfossils, two dinoflagellates: *Mendicodinium groenlandicum* and *Nannoceratopsis deflandrei* subsp. *senex*. These forms indicate a Middle to Late Bathonian age for the wackestone (G. Thompson, pers. comm., March, 2000).

The "middle member" is a relatively thick, olive-green arenaceous wackestone that is typically 16-to-32 m thick and contains the oyster *Gryphaea nebrascensis* in abundance. The unit is coeval with the Stockade Beaver Shale Member of northeastern Wyoming. The occurrence of *Gryphea nebrascensis* at the base of the "middle member" of the "lower" Sundance implies an age of upper Bathonian (Calloman, 1982) for this interval. A specimen of *Cadoceras muelleri* (= *Paracephalites* sp.) was found at the base of the *G. nebrascensis*-bearing "middle member" during the course of this investigation. This ammonite also indicates an upper Bathonian age for the sediments just above the track-bearing interval (Calloman, 1982; Taylor et al, 1982).

One complete transgressive-regressive cycle and a portion of a second cycle can be identified within the "middle member." These cycles are recognized most easily on the east side of the Bighorn Basin in both outcrop and on geophysical logs. The lowest cycle in the "middle member" is bounded at the base by the J2b flooding surface, capped by a calcareous quartz-rich sandstone and oolitic grainstone that appears to be quite lenticular, and is present only in an area extending several miles south and west from the Red Gulch Dinosaur Tracksite. Mud-draped ripples within the oolitic grainstone facies have amplitudes up to 3 cm. The drapes show evidence of desiccation and periodic subaerial exposure through the preservation of well-developed polygonal mud-cracks that are filled with grainstone from the overlying ripple set. This evidence of exposure occurs immediately below the J2c flooding surface. The uppermost transgressive-regressive cycle in the "middle member" extends from the J2c flooding surface upwards to include the "upper member."

The "upper member" is dominated by glauconitic sandstones and/or oolitic grainstones, and is generally less than 8 m thick. The top of this unit is bounded by the J3 unconformity suggesting it is the equivalent to the dinosaur track-bearing interval in the upper part of the Entrada Sandstone of Utah. Kilibarda and Loope (1997) recognized the presence of isolated eolian sand dunes composed of cross-stratified marine oolites at the top of this "member" in the Sheep Mountain area north of Greybull (Fig. 4B, measured section 1). The eolian facies constitutes the subaerial deposits associated with the top of the last marine subcycle in the "lower" Sundance.

Above the J3 unconformity lies the upper half of the Sundance Formation. The transgressive facies of the first "upper" Sundance marine cycle includes a basal arenaceous mudstone that contains, among other fossils, the ammonite *Cardioceras* sp. This ammonite in association with the scallop *Camptonectes bellistriatus* in the initial deep water facies of the first "upper" Sundance depositional cycle imply a middle Callovian age (Calloman, 1982; Taylor et al., 1982).

Thus, within what Brenner and Peterson (1994) defined as the "Third Marine Cycle" in the "lower" Sundance are at least three sub-cycles of base-level fluctuation (Fig. 4) that resulted in subaerial exposure in the northeastern corner of the Bighorn Basin. Subcycle 1 culminates at the top of, or just above, the dinosaur-track bearing unit in the "basal member" (Fig. 4C, below J2b). Subcycle 2 terminates in the mud-cracked oolitic grainstone facies within the "middle member" (Fig. 4C, below J2c), and the end of subcycle 3 is marked by the occurrence of the eolian dune complex described by Kilibarda and Loope (1997) at the top of the "upper member" (Fig. 4C, below J3). Presently, no dinosaur track ichnites have been recognized from the second or third subcycles in Wyoming, although these subcycles certainly have the potential to preserve such fossils.

Of particular importance to this study is the presence of several bentonites occuring in positions critical to the assessment of the chronostratigraphy of the track-bearing intervals. These include a 10-cm thick bentonite from two meters above the Red Gulch tracklayer and occurring within the middle portion of "subcycle 2" of the "third ma-

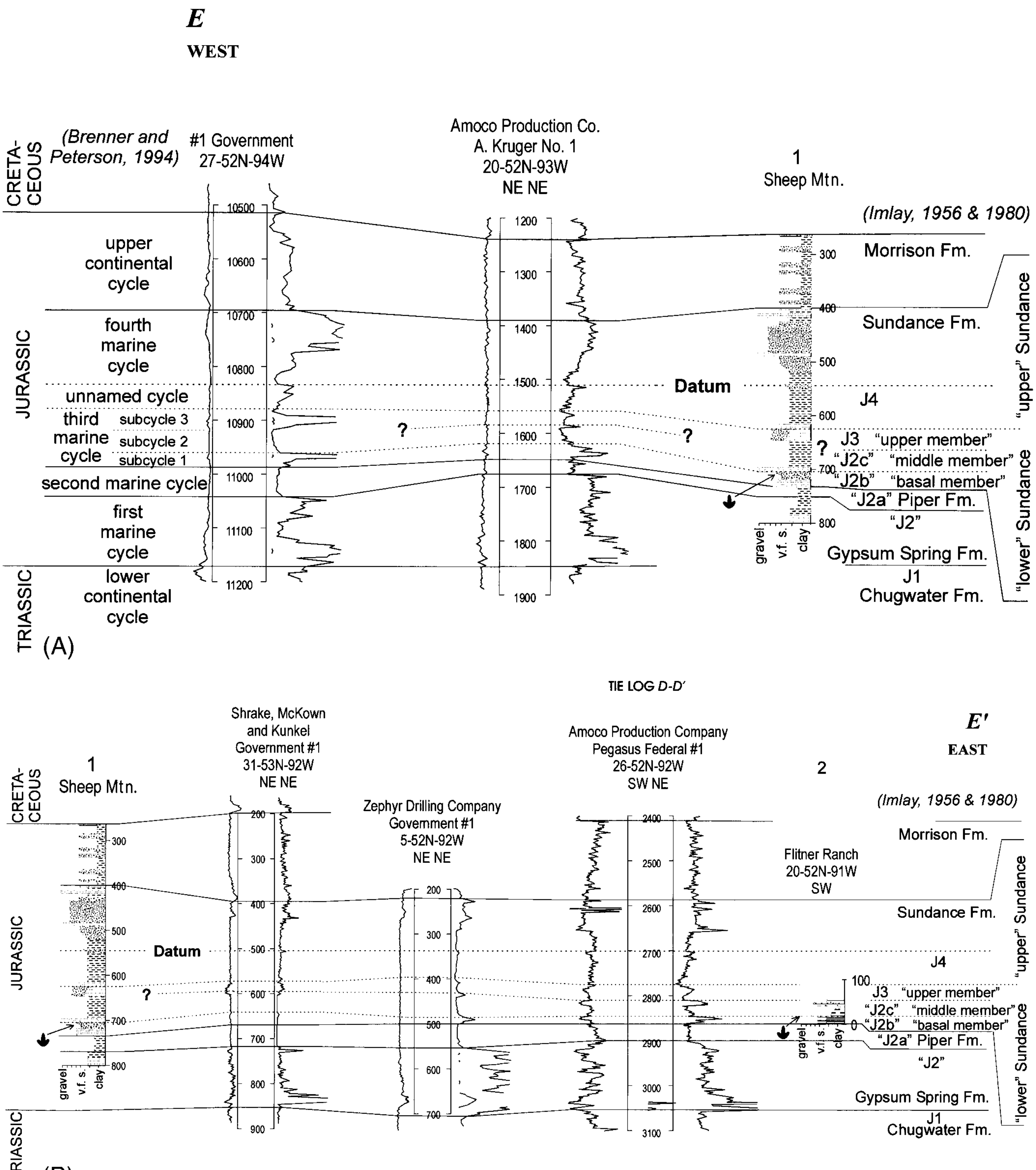


FIGURE 4—Regional cross-sections through the study area. Outcrop sections described in the course of this study (1, 2, 5, 6), a previously published measured section (Imlay Section 20), and correlated electrical (left trace) and resistivity (right trace) logs are shown. (A and B) E-E′ west-east cross-section. (C and D) D-D′ northwest-southeast cross-section. (E) Explanation of symbology. See Figure 2 for locations of the cross sections.

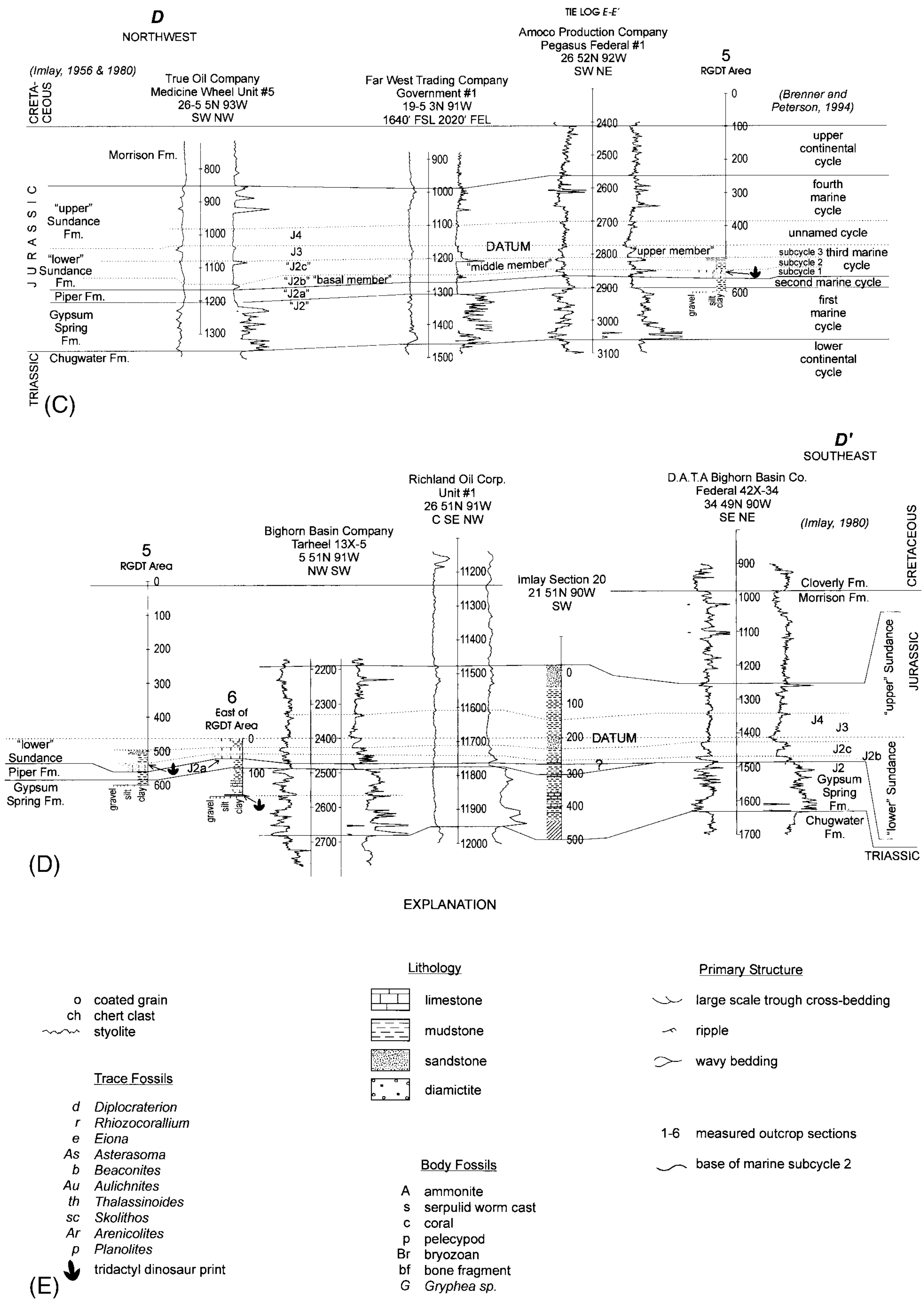


FIGURE 4—Continued.

TABLE 1—K-Ar ages of biotite microphenocrysts separated from bentonitic water-laid tephra of the Sundance and Morrison formations, northeastern Bighorn Basin, Wyoming. Stratigraphic occurrence of these bentonites as follows: **Jsa**, 2nd subcycle of the 3rd marine cycle, Sundance Formation; **Jsb**, 4th marine cycle, Sundance Formation; **Jm12**, Morrison Formation.

Sample#	^{40}Ar*/gm	%Radiogenic Ar	Wt % K_2O	Age (10^6 yr)	Average Age (10^6 yr)
Jm12 100/200	3.605×10^{-11}	62.5%	1.65%	151.5+/−4.0	151.5+/−4.0
Jsb 100/140	1.950×10^{-9}	94.2%	8.20%	158.1+/−3.6	
Jsb 140/200	1.942×10^{-9}	95.2%	8.16%	158.4+/−3.7	158.2+/−3.6
Jsa 100/140	2.040×10^{-9}	96.9%	8.15%	166.1+/−3.9	
Jsa 140/200	1.920×10^{-9}	96.3%	7.75%	164.4+/−3.8	165.2+/−3.8

Biotite analyses performed at Dartmouth College K-Ar Laboratory (J. Aronson and L. Amidon)

* Radiogenic 40Ar (10-9 moles)

rine cycle" of the Sundance, two 5-cm thick bentonites occuring some 10 cm apart in the lower third of the "fourth marine cycle" of the Sundance, and a 5-cm thick bentonite near the base of the overlying Morrison Formation. These altered tephra were identified and subsequently dated at the geochron lab at Dartmouth College (Table 1, Fig. 5). The occurrence of the bentonite immediately above the Red Gulch track-bearing stratum is especially significant as it yielded an age (Sample Jsa, K-Ar, biotite) of 165.2 ± 3.8 x10^6 yr, which confirms the mid-Bathonian age assigned to the track layer based on the above molluscan biochronology.

The J-2 Enigma

A great deal of the Middle Jurassic of Wyoming has remained largely unprospected for dinosaur ichnites. However, as noted above, there is the potential for such remains to be preserved in Wyoming and the surrounding states. To gain a broadly regional understanding of dinosaur track diversity of any one geologically contemporaneous surface or stratigraphic interval, one must be certain of the regional correlations. The recognition of widespread unconformities is an important component of establishing time-equivalent stratigraphic horizons over vast areas. The unconformity at the base of the Piper Formation and its relationship to the J2 unconformity is a bit of an enigma at this point. The J2 is reported in the literature to be marked with dark chert, which is considered to be one of the key features in the recognition of this unconfomity (Imlay, 1980; Piperingos and O'Sullivan, 1978; O'Sullivan and Piperingos, 1997). However, Imlay's (1956) sections imply that a major chert-bearing flooding surface also exists in the Bighorn Basin at the bottom of the "basal member" (Fig. 4D, J-2a in Imlay section 20) below the coated grain grainstone succession that contains the tracks associated with the Red Gulch Dinosaur Tracksite. A later publication by O'Sullivan and Piperingos (1997) seems to have placed Imlay's basal Sundance chert-bearing horizon at the base of the Piper Formation, a significant deviation from Imlay's (1956) stratigraphic interpretation.

Reconnaissance work has failed to show the presence of a chert-bearing horizon at either the lower contact of the "basal member" of the Sundance Formation or at the base of the Piper Formation in the northeastern part of the Bighorn Basin as defined by Imlay (1980). On the contrary, outcrop and subsurface evidence in the northeastern part of the Bighorn Basin clearly indicate that the most pronounced chert-bearing horizon in the "lower" Sundance occurs at the base of the "middle member" (J-2b) of the Sundance Formation above the "lower" Sundance track-bearing layer. It is possible that on the east side of the basin, the J-2 unconformity is not unique in that there exists multiple, dark chert-bearing unconformities (J-2, J-2a, and J-2b). However, the present investigators have found dark chert associated only with the J-2b unconformity at this time. It is possible that a miscorrelation exists between what traditionally has been referred to as the "basal member" of the "lower" Sundance in the eastern margin of the Bighorn Basin and what as been referred to as the "basal member" of the lower Sundance in the western margin of the Bighorn Basin. It will be important to clarify this issue to determine how the Red Gulch Dinosaur Tracksite compares chronostratigraphically to other Middle Jurassic track-bearing intervals in the Western Interior.

STRATIGRAPHY AND SEDIMENTOLOGY OF THE DINOSAUR TRACKSITES

Sundance Formation

To place the "lower" Sundance Formation tracksites in a stratigraphic and sedimentologic context, several detailed outcrop descriptions were made in the Red Gulch Dinosaur Tracksite (RGDT) area and several to the northwest in the vicinity of Sheep Mountain Anticline north of the town of Greybull (Fig. 2). Figure 6 shows the relationship between lithofacies of the lower part of the Sundance Formation a few meters above and below the position of the track-bearing interval. This cross section compares outcrop sections present in the Red Gulch Dinosaur Tracksite area, south of the town of Shell, and an outcrop in the Sheep Mountain area, north of Greybull. In general, the "basal member" of the Sundance becomes more arenaceous from the RGDT area westward towards Sheep Mountain.

In the vicinity of the RGDT, and immediately below the position of the track-bearing surface, is an approximately 3–8 m thick interval of interbedded fine-grained grainstones, wackestones, and calcareous mudstones and occasional arenaceous carbonates. The grainstone and wackestone beds are more resistant to weathering and often stand out in relief in scarp faces. In some cases, these resistant units can be correlated from 100's to 1000's of meters. This interval together comprises Imlay's (1956) "basal member" of the "lower" Sundance.

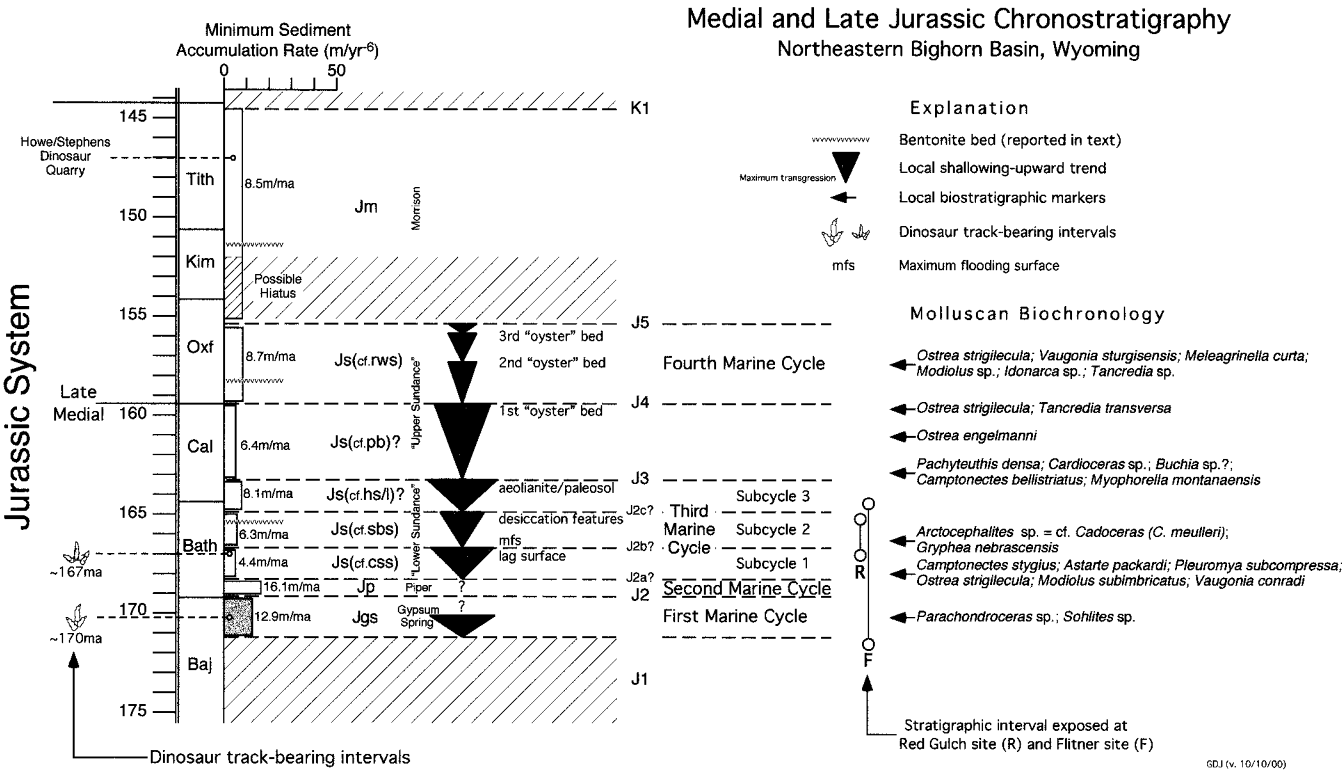


FIGURE 5—Medial and Late Jurassic chronostratigraphy for the northeastern Bighorn Basin, Wyoming. The chronometric position of the multiple marine shoaling-upwards cycles expressed in this portion of the "Sundance" seaway is constrained by a local molluscan biochronology and by the stratigraphic position and age (K-Ar, biotite) of several associated bentonites (see text). This sequence interpretation is based on the present work, the stratigraphic sections measured by Imlay (1957; 1982), Wright (1971), Doyle (1984), Meyer (1984), and the stratigraphically controlled fossil occurrences identified therein. This Bighorn Basin chronology is based upon several key elements in the local molluscan biostratigraphy:

(1) The occurrence of *Parachondroceras sp.* and *Sohlites sp.* in the middle Gypsum Spring Formation near Cody—implying a probable age of late Bajocian (Calloman, 1982).

(2) The occurrence of *Gryphea nebrascensis* at the base of the "middle member" (= Stockade Beaver shale member) of the "lower" Sundance—implying an age of upper Bathonian (Calloman, 1982).

(3) The occurrence of a complete specimen of *Cadoceras muelleri* (= *Paracephalites* sp.) at the base of the *G. nebrascensis*—bearing "middle member" of the "lower" Sundance—implying an age of upper Bathonian (Calloman, 1982; Taylor et al., 1982).

(4) The occurrence of *Cardioceras* sp. in association with *Camptonectes bellistriatus* in the initial deep water facies of the first "upper" Sundance depositional cycle—implying an age of middle Callovian (Calloman, 1982; Taylor et al., 1982).

Additionally, two dinoflagellates, recovered from the laminated wackestones lying 2 cm above the tracklayer at the Flitner site, suggest a Middle to Late Bathonian age for the interval: *Mendicodinium groenlandicum* (First Appearance Datum—Middle Bathonian in Pechora Basin on Russian Platform [in Arctic ammonite zone of *Arcticoceras eshmae* and *A. harlandi*]); and, *Nannoceratopsis deflandrei* subsp. *senex* (Last Appearance Datum—somewhere within the interval Upper Bajocian—Upper Bathonian in Arctic Canada [probably in Arctic ammonite zone of *Arcticoceras eshmae* and *A. kochi*], G. Thompson, pers. comm., March, 2000).

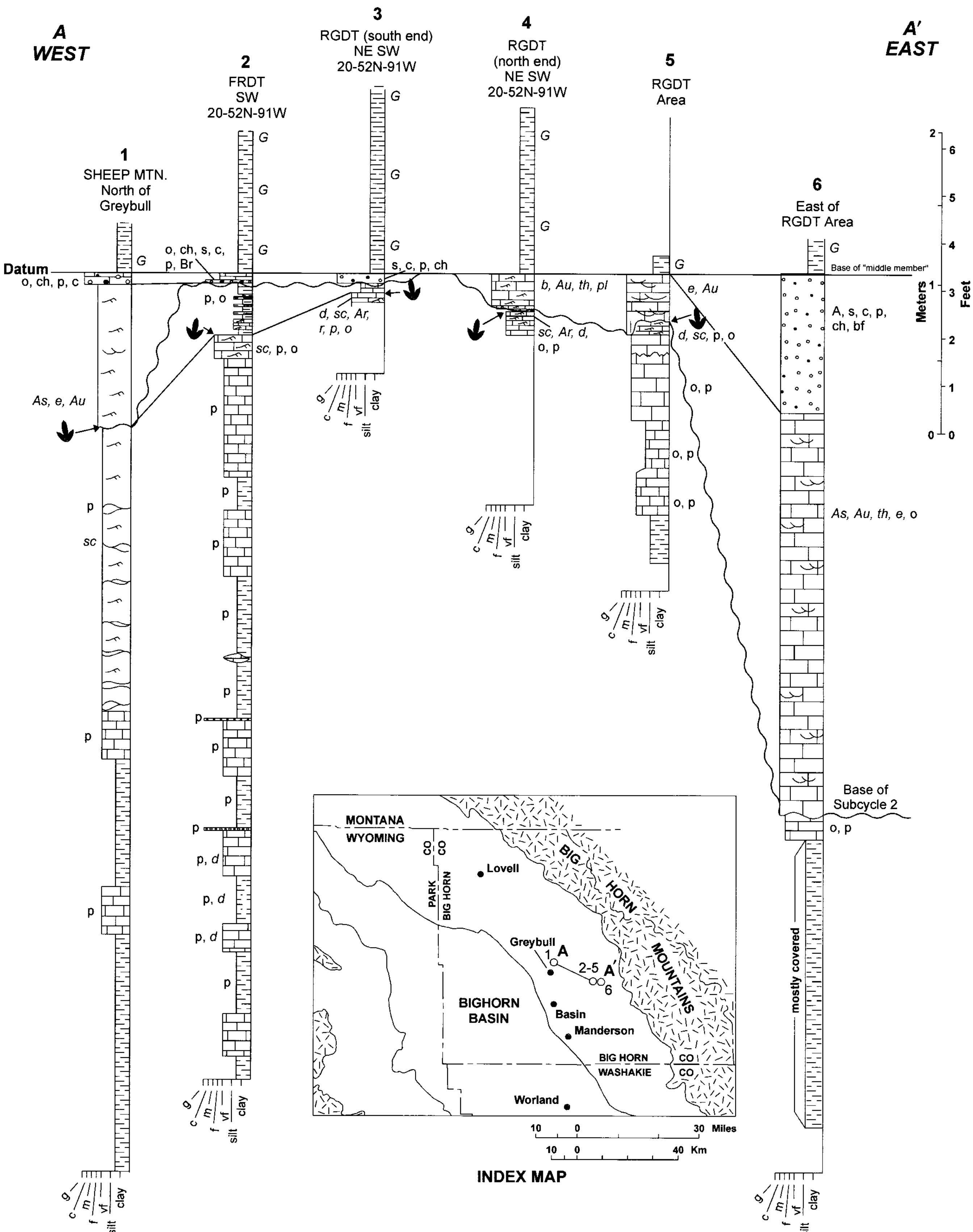
Therefore, the Red Gulch/Flitner tracksite is considered by us to be mid-Bathonian and probably dates to ~167ma. The older, Gypsum Spring tracksites are uppermost Bajocian and probably date to ~170ma. This biochronology is tied to the mid-Mesozoic timescale of Gradstein et al. (1994).

Abbreviations: Canyon Spring Sandstone Member (css), Stockade Beaver Shale Member (sbs), Hulett Sandstone Member and Lak Member (hs/l), Pine Butte Member (pb), and Redwater Shale Member (rws) of the Sundance Formation (Js); Piper Formation (Jp); Gypsum Spring Formation (Jgs).

Although mostly massive, preserved primary structures within the grainstones include faint parallel and ripple laminations. Large *Diplocraterion* traces, up to 20 cm in length and 8–10 cm wide as well as other traces, occur within this interval locally (see details below). Shell-lag deposits of bivalve fragments are concentrated in the upper 2 cm of some of the grainstone and wackestone beds. The RGDT dinosaur tracks occur on the uppermost surface of the youngest of these fine-grained grainstone beds.

Petrographically, the grainstones and wackestone clasts are dominated by coated grains and pellets with variable amounts of angular to sub-angular quartz sand. Most of the grainstone and wackestone units contain abundant evidence of microbial mat development with clotted, micritic masses common throughout. These often are associated with locally abundant oncolitic fabrics. Microfossils are present in most thin-sections with ostracods, codiacean algae, sponge spicules, and bivalve debris being the most abundant. In addition to very fine- to fine-sand sized pellets, coated grains, and microfossils, the grainstones contain a restricted fauna of small disarticulated thin-shelled bivalves.

The Red Gulch Dinosaur Tracksite and laterally equivalent track-bearing horizons in the vicinity of Shell formed on a coated-grain grainstone that exhibits a well-devel-


A
WEST
A′
EAST
1
SHEEP MTN.
North of
Greybull
2
FRDT
SW
20-52N-91W
3
RGDT (south end)
NE SW
20-52N-91W
4
RGDT
(north end)
NE SW
20-52N-91W
5
RGDT
Area
6
East of
RGDT Area
Datum
o, ch, p, c
o, ch, s, c,
p, Br
s, c, p, ch
d, sc, Ar,
r, p, o
b, Au, th, pl
sc, Ar, d,
o, p
e, Au
d, sc, p, o
A, s, c, p,
ch, bf
Base of "middle member"
As, e, Au
sc, p, o
As, Au, th, e, o
Base of
Subcycle 2
mostly covered
Meters
Feet
g
c
m
f
vf
silt
clay
MONTANA
WYOMING
PARK
BIG HORN
CO
Lovell
Greybull
BIG HORN MOUNTAINS
BIGHORN
BASIN
Basin
Manderson
WASHAKIE
Worland
10 0 30 Miles
10 0 40 Km
INDEX MAP

oped rippled surface. Thin sections reveal that the framework grains underwent an early rim cement phase in conjunction with a random dissolution (microbial micritization) of the carbonate grains. The rim cement is, in turn, followed by a cementation phase that exhibits a coarse calcite mosaic. The above evidence is strongly suggestive of meteoric conditions subsequently affecting this unit (and possibly the immediately underlying strata) for some period of time after an initial cementation phase.

The dinosaur trackways appear to be penecontemporaneous with the development of the rippled surface having been formed shortly after the rippling. The surfaces exhibit ripple indices of 9 to 12 suggesting either wave or current-generated ripples. However, their straight and flat-crested morphology combined with a slight asymmetry favors a wave genesis with formation in very shallow water.

The ripples are slightly asymmetric to the northeast in the Red Gulch Dinosaur Tracksite region. Their presence indicates submergence of the surface during ripple formation with modification to the crests during a falling-water stage and subsequent subaerial exposure during trackway generation. This short-term submergence and emergence may be related to wind or astronomically induced tidal variations in localized sea level associated with a very shallow-sloping intertidal shoreface.

Three hundred meters to the south of the Red Gulch Dinosaur Tracksite, on private land referred to as the Flitner Ranch Dinosaur Tracksite (FRDT), the same track-bearing coated-grain grainstone is overlain directly by a fine-grained shaley interval (Fig. 6, measured section 2). The interval consists of thinly interbedded organic-rich shales and pinstripe streaks of very fine-grained grainstone. Fresh samples of this unit exude a strong petroliferous odor. Petrographically, the matrix of the grainstone streaks is dominated by a laminated ostracod-bearing pelmicrite. The unit thins from 80 cm at the FRDT to 3 cm in the Ballroom section of the RGDT to zero at the Discovery section of the RGDT (Fig. 6).

In the vicinity of the RGDT, the dinosaur track-bearing coated-grain grainstone and thinly interbedded petroliferous shale is cut out by a poorly sorted, very coarse- to medium-grained highly fossiliferous grainstone (Fig. 6, measured section 6). This unit marks the base of marine subcycle 2 and is dominated by large-scale trough cross-bedding, which indicates paleoflow to the northwest. Petrographically, this overlying unit is a very fossiliferous, intraclastic oosparite with associated micritic clasts occurring throughout. This unit thins across the RGDT region from 2 m to less than 5 cm (Fig. 6). The unit appears to be channelized but, at present, only the southern margin across the RGDT area has been mapped.

Above the fossiliferous grainstone is a very lenticular arenaceous and argillaceous, poorly sorted diamictite that contains blade-shaped clasts of dark-chert up to 4 cm in diameter (Fig. 6, just below "datum"). Locally, the chert-bearing deposit also contains a poorly sorted broken and abraded accumulation of a diverse faunal assemblage including body fossils and/or internal casts of ammonites (cf. *Cadoceras*; up to 20 cm across), lucinoid pelecypods (cf. *Pachymya* sp.), oysters, including *Ostrea* sp. and *Gryphea* sp., fennestrate bryozoans, loosely coiled serpulid worm casings, bryozoans, clast-encrusting solitary corals, and rounded clasts (up to 5 cm across the long axis) derived from the underlying fossiliferous grainstones and wackestones. This unit appears massive with a total lack of internal bedding features. The poor sorting of the unit, the diverse assemblage of broken and abraded faunal remains, the presence of clasts derived from underlying deposits, and the absence of bedding indicates this unit is likely a storm deposit. Overlying this unit is a succession of arenaceous and fossiliferous wackestones that contains the pelecypod *Gryphea nebrascensis*, an important index fossil for the "middle member" of the "lower" Sundance.

To the west towards Sheep Mountain, the upper 2 m of the "basal member" of the "lower" Sundance becomes more arenaceous (Fig. 6). The track-bearing interval and the units immediately beneath it consist of interbedded calcareous mudstone and ripple- to wavy-bedded very fine-grained calcareous quartzose sandstones that grade easterly (in the direction of the RGDT) over several hundred meters into an arenaceous, fossiliferous, packed oosparite with common ostracode, bivalve, and codiacean algal debris that also is dominated by ripple to wavy bedding. Dolomitized fabric is common in the oosparite with partial to complete replacement locally abundant. Tridactyl dinosaur tracks occur in a thin shale near the top of this interval and are preserved on the underside of the overlying quartzose sandstone.

The dinosaur track-bearing sandstone layer is, in turn, overlain or cut out by a 1 m thick fine- to medium-grained fossiliferous coated grain-bearing, calcareous, quartz-rich, sandstone. The base of this unit marks the base of marine subcycle 2 in the Sheep Moutain area north of Greybull. The unit is characterized by large-scale trough-cross stratification (Fig. 6). The dominant paleoflow direction has not yet been determined for this unit. This unit is overlain, in turn, by a 6 cm thick, very poorly sorted fossiliferous and arenaceous coated-grain grainstone that contains large abraded oyster shell fragments. This unit occurs at the base of the *Gryphea nebrascensis*-bearing "middle member" and resembles a lag deposit.

The sandstone and grainstone units at both Sheep Mountain and the RGDT area, which cut out the track-bearing unit, exhibit a diverse normal marine trace fossil assemblage consistent with a *Cruziana* ichnofacies. These traces include, among others, *Eiona*, *Aulichnites*, *Asteriacites*, and *Beaconites*. Although Imlay (1956, 1980) included these marine trace fossil-bearing units within the "basal member" of the "lower" Sundance, the units actually

←

FIGURE 6—Detailed cross-section of the "basal member" of the 'lower" Sundance Formation in the vicinity of the Red Gulch Dinosaur Tracksite showing portions of measured outcrop sections. Refer to Figure 4E for explanation of symbols. The datum is the base of the "middle member" of the "lower" Sundance. Sections 1, 2, 5 and 6 in Figure 4 correspond in location to the partial sections illustrated in Figure 6. Note the very slight apparent relief on the track-bearing surface below the datum. The high area centered around section 3 is the area of most intense *Diplocraterion* bioturbation.

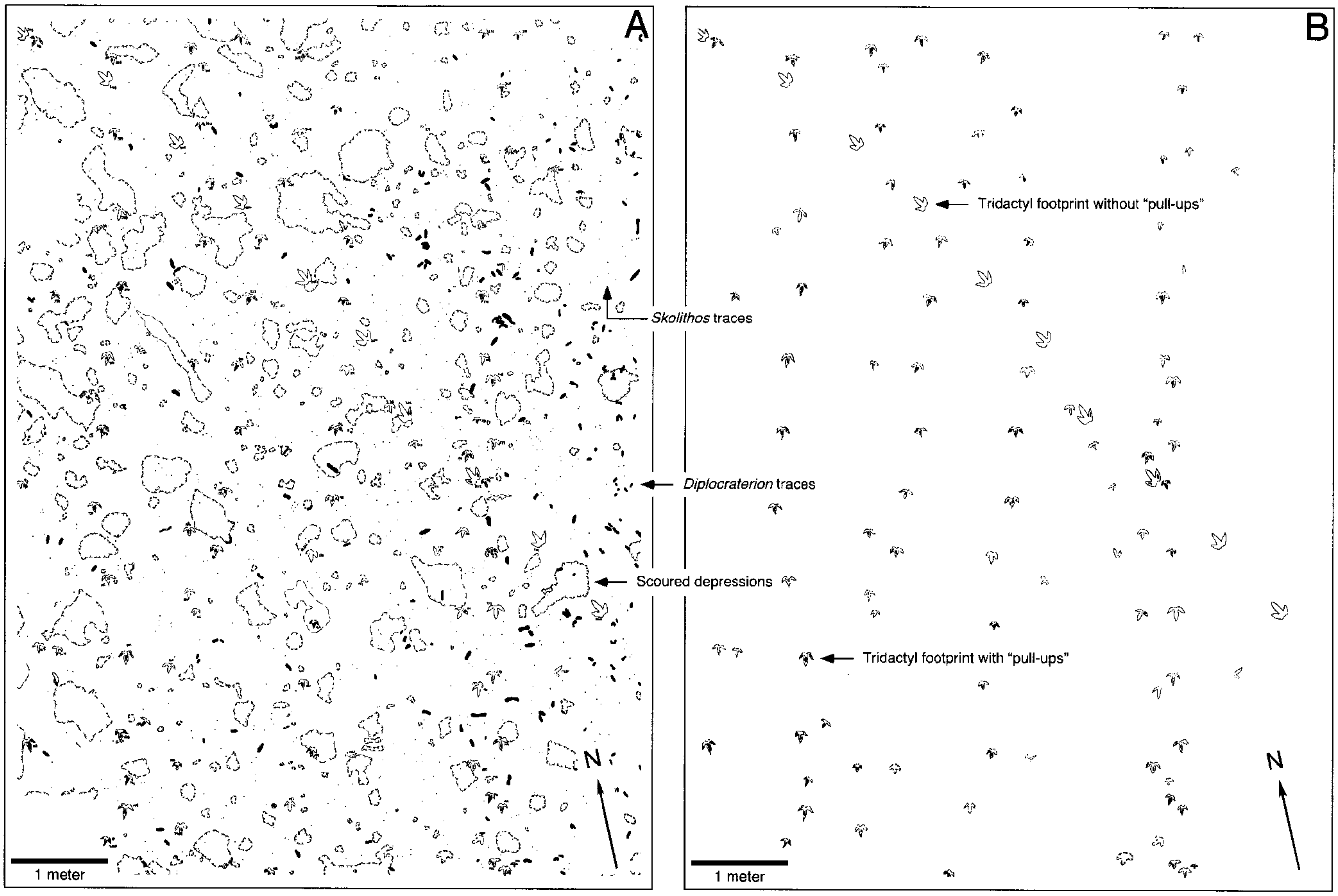


FIGURE 7—Ichnofossil maps created by Dartmouth College students of a 50m² portion of the 141m² area shown in Figure 8. Area is at the southern end of the Red Gulch Dinosaur Tracksite outcrop (see Figure 6, section 3). (A) Composite map of the surface was created by using a m² rectilinear mapping grid in conjunction with photographic documentation of the track-bearing surface. The map shows the size, shape, features, and orientation of tridactyl dinosaur tracks, invertebrate burrows, and the irregular biomediated erosional depressions discussed in the text. (B) Detail of same area as (A) illustrating only tridactyl dinosaur tracks and recognizable trackway associations.

mark the base of the marine subcycle 2 flooding event (Fig. 6).

At least two generations of invertebrate bioturbation can be recognized on the Red Gulch Dinosaur Tracksite track-bearing horizon: an older, more regionally distributed generation formed in soft ground conditions and contemporaneous with the vertebrate trackways; and a younger, more localized generation that formed in a subsequent, stratigraphically higher surface and penetrated downward into the buried tracklayer. To fully understand this relationship, a 140 m² test area at the Red Gulch Dinosaur Tracksite was mapped in detail with the help of third-year Earth science students from Dartmouth College. The surface was mapped in individual square meter sections at a scale of 1:8 (2.5cm = 20cm; Fig. 7). Vertebrate and invertebrate traces, as well as other surface features were drawn to scale in their positions within the square meter. Measurements were made of representative invertebrate traces of each type to assist in identification. The individual meter maps were compiled into a composite map of the area, from which ichnofossil and surface feature characteristics were identified and measured. Bioturbation density was then determined (Fig. 8).

The older generation of invertebrate traces can be classified as belonging to the *Skolithos* ichnofacies. The traces appear to have been formed contemporaneously with the generation of the dinosaur trackways and a soft-ground substrate. Their primary surficial expression is that of a vertical assemblage of *Skolithos*, a round vertical tube approximately 0.5 cm in diameter that is similar to those made by modern polychaete worms. Some of these tubes have what appear to be the preserved remains of feeding structures or excretion mounds that are occasionally paired, suggesting a "U" shaped *Arenicolites* morphology. Rare horizontal surficial traces that resemble poorly preserved gastropod trails are also present. Approximately 1700 *Skolithos*/*Arenicolites*, and 4 possible gastropod trails were identified in the map area. Acetate peels of the coated grain grainstone reveal that much of the sediment is massive and bioturbated. Infaunal burrows also include both *Planolites* and *Terebellina*. Also present in the mapped area are 25 bivalve molds (resembling *Astarte*) filled with grainstone (steinkerns). The traces and sedimentary structures are consistent with an intertidal onshore facies persistent during formation of the dinosaur trackway.

A second, younger generation of invertebrate faunal traces is also present on the RGDT surface. The traces

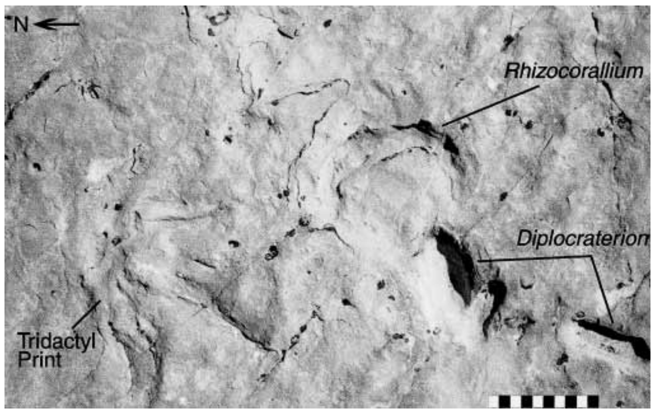


FIGURE 9—Photo of tridactyl print shown in proximity to *Diplocraterion* and *Rhizocorallium* traces. The bar scale is 10 cm long.

were initiated after the dinosaur track-bearing surface had been buried and had begun to de-water and form a firm to semilithified substrate. The younger traces consist of sharp walled, unlined and open (without spreite) *Diplocraterion* and *Rhizocorallium*—vertical to inclined "U"-shaped burrows ranging from 5 cm to greater than 12 cm in width, and 2 cm to 3 cm in diameter (Fig. 9). Such traces may reflect the burrowing of infaunal crustaceans or lugworms. These *Rhizocorallium* and *Diplocraterion* burrows were initiated on an overlying sedimentary layer that was removed subsequently by erosion and exhumed during transgression. This is shown by the shallowness of the *Diplocraterion* burrows on the dinosaur track-bearing surface with many burrows having nothing preserved but the rounded horizontal bottom of the characteristic "U"-shape tube. This trace assemblage clearly post-dates the dinosaur tracks as several examples of *Diplocraterion* traces intersecting preexisting dinosaur tracks are present on this surface. There is no evidence of infaunal boring into what would represent hardground fabric in this sequence. Approximately 420 *Diplocraterion,* and 20 *Rhizocorallium* were identified in the 140 m^2 test portion of the Red Gulch Dinosaur Tracksite map area. These are not uniformly distributed on the surface, with the density of burrows increasing to the north-northeast (Fig. 8). More regionally, the *Diplocraterion—Rhizocorallium* traces occur primarily within the approximately 15 hectare area of the Red Gulch Dinosaur Tracksite, and are not found with comparable density in outcrops of the track-bearing unit laterally from this site. This reflects a more localized, very slight, topographic high (relief of a few meters or less) in the Red Gulch Dinosaur Tracksite area that existed during initial marine transgression. This very slight high is apparent in Figure 6.

The *Diplocraterion—Rhizocorrallium* traces can be viewed as part of a *Glossifungites* ichnofacies. Such an ichnofacies can be formed in a variety of important sequence-stratigraphic horizons, including lowstand conditions, initial transgressive surfaces, wave or tidal ravinements, or maximum flooding surfaces (MacEachern, 1994). The very close stratigraphic association of both the overlying fossiliferous grainstone, which contains the *Cruziana* ichnofacies, and the dark chert-bearing storm deposits to the exhumed surface bearing the *Glossifungites* ichnofacies suggests that a moderate-energy ravinement formed during a transgressive stage of the Sundance Sea shortly after the creation of the dinosaur track-bearing interval.

Shallow (1–2 cm), irregularly shaped depressions from less than 5 cm to over 1 m in diameter also are present on the surface of the Red Gulch Dinosaur Tracksite mapped area (Fig. 7A). Similar depressions have been noted in other dinosaur track-bearing intervals in the rock record (e.g., Weimer and Land, 1972). The RGDT features appear to have formed through a combination of both biological and physical erosional processes. The depressions are very similar to features observed on modern intertidal flats that are stabilized by incipient and established microbial mat development (e.g., Reineck and Singh, 1980; Whitton and Potts, 1982; Keller et al., 2000; pers. observ.). In the modern setting, disruption of the stabilized tidal flat surface may occur at low tide through bioturbation (e.g., surface eruptions of burrows of infaunal organisms, browsing and grazing by epifaunal feeding, or bird or mammal locomotion across the surface). The result of this is the destruction or removal of a section of the microbial community. Thus, the underlying loose sediment that is not bound by the mat is eroded through a combination of current and wave action during a subsequent high tide, forming a shallow, irregular depression in the tidal flat surface. In many cases, depending on the wave energy, the eroded area can be much larger than the actual disruption and in most of the depressions, the sediments are rippled unlike the sediments outside the depressions that have been bounded by microbial mats for extended periods of time and have an attenuated rippled fabric (Fig. 10A).

The base of an erosional feature consists only of unconsolidated loose sediment until the microbial community has time to regrow over the depression. Such restabilization was observed to take place within hours to days (pers. observ.), but may take as long as several months (Whitton and Potts, 1982). The shape and depth of these modern depressions in microbial mats are very similar to the shapes and depths of the irregular depressions preserved in the Red Gulch Dinosaur Tracksite surface (Fig. 10A, B). Furthermore, a number of depressions in the Red Gulch track surface exhibit well-defined ripple structures while the area immediately surrounding the depressions does not bear ripples or bears ripple structures with less relief or definition than those inside the depression. This suggests that the sediments within these depressions were less consolidated or bound than those outside of the depressions, further supporting the idea of some microbial community coverage of the surface.

The microbial mat continued to develop after the formation of the erosional depressions and the creation of the well-defined tracks. This is shown in the preservation of a laminated micritic fabric that appears to mantle the well-defined tracks, including those tridactyl prints superimposed on the erosional depressions (Keller et al., 2000). Thus, the preservation of the well-defined tridactyl prints was initiated by the stabilization of the track-disrupted tidal flat by the microbial binding of the carbonate grains. Petrographic examination of samples from the RGDT and FRDT sites shows that, following the microbial stabilization phase, early cementation, in the form of an aragonitic rimming cement, was initiated. This was followed by a lat-

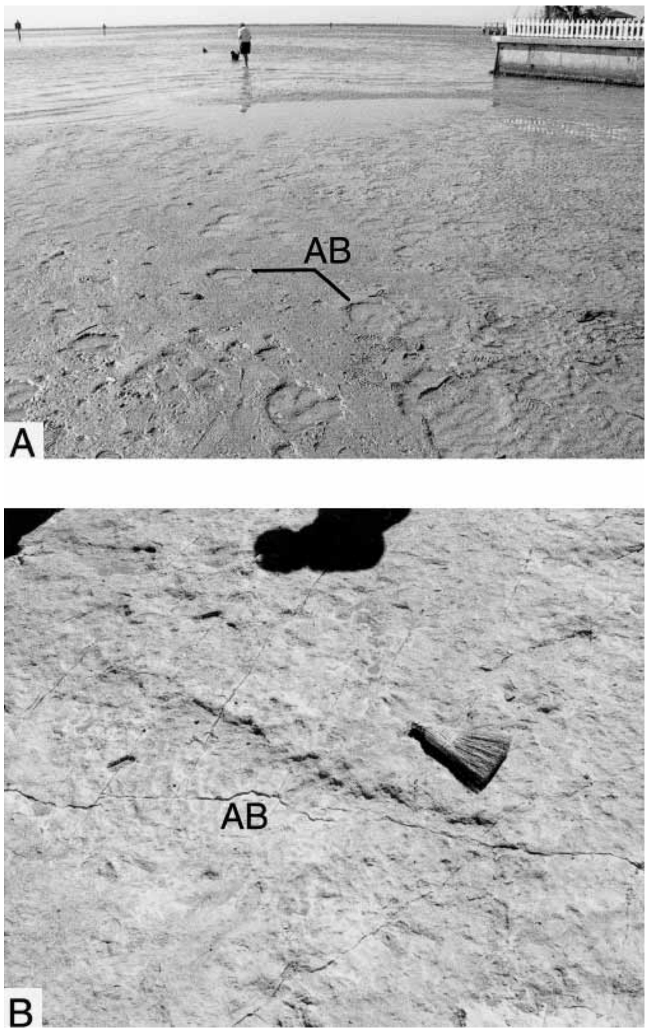


FIGURE 10—Modern and ancient examples of microbial mat-stabilized surfaces. (A) Modern intertidal zone adjoining Pine Island (Cape Coral), Florida, showing a surface stabilized by microbial mat development. Note the erosional depressions (labeled "AB"). These depressions formed after the mat surface was penetrated by walking animals or infaunal burrowing and then eroded during a subsequent high tide. These depressions have well-developed ripples within them. (B) An erosional depression in the Red Gulch Dinosaur Tracksite Ballroom section (below and to the left of the ~25 cm long broom). Note the presence of the ripple forms within the depression.

er phase cement ensuring a complete stabilization of the tracks.

The Red Gulch Dinosaur Tracksite and correlative track-bearing surfaces in the vicinity of Shell show desiccation features in the form of cubic salt crystal casts. The salt crystal casts usually are 1–4 cm wide. Many protrude from the surface, showing a three-dimensional corner of the cubic cast (Fig. 11). The salt casts tend to occur in groups of two or more and are locally abundant.

The presence of the salt-crystal casts implies significant climatic aridity (at least seasonally) where evaporation exceeded precipitation. Kinsman (1976) reported that a relative humidity of $<$ 76% is necessary to evaporate brines relative to halite. Maximum humidity during a day/night cycle could not have been higher than this for the halite

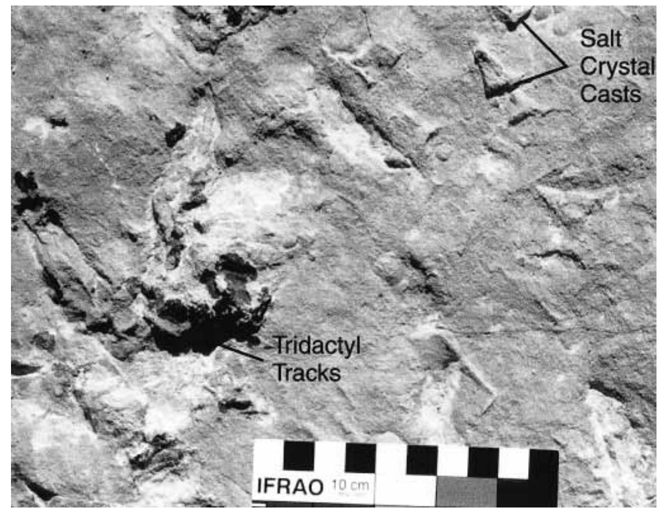


FIGURE 11—Salt crystal casts to the right of a tridactyl print. Photo taken in the vicinity of the Red Gulch Dinosaur Tracksite.

crystals to have formed (Kendall and Harwood, 1996). The halite crystals likely formed as the sediment was de-watering as a result of evaporation but prior to bioturbation indicated by the *Diplocraterion* and *Rhizocorallium* traces. The crystals also imply that the track-bearing horizon formed no lower than a high intertidal position that was inundated only during seasonally high tides.

Gypsum Spring Formation

The Gypsum Spring Formation dinosaur tracksites occur in a medial position within the Gypsum Spring Formation several meters above a thick gypsum deposit, the base of which marks the base of the formation in the northeastern part of the Bighorn Basin (Fig. 4D). The track-bearing horizon caps a 10-meter-thick upward-coarsening succession that is identifiable on geophysical logs from nearby oil and gas wells.

The lower part of this succession has not been examined in detail; however, the top of the succession is composed of a 3-m interval of interbedded mudstones, micritic limestone, and calcareous shale. The micritic beds range in thickness from 5 cm to 18 cm and locally show a wavy and "crinkled" stromatolitic fabric. In the vicinity of the town of Shell, at least four distinct track-bearing horizons can be identified within the lower 1 m of the micritic interval. Nodular gypsum up to 12 cm thick grew displacively within both the limestone and mudstone beds resulting in a slight heaving or disruption of the mostly parallel bedding causing the limestone beds to drape the nodules.

Above the track-bearing interval is a 2 m continuation of the thin-bedded micritic "crinkled" stromatolitic limestones and interbedded mudstones which, in turn, is overlain by a 2-m thick, pedogenic (?), massive, red mottled calcareous mudstone that contains nodular gypsum arranged in a vertisolic-like fabric.

The dinosaur track-bearing surfaces contain *Skolithos* and *Arenicolites* traces similar to those found in the Red Gulch Dinosaur track-bearing layer. The actual track-bearing surfaces in the Gypsum Spring Formation localities are degraded relative to the preservation of the youn-

TABLE 2—Summary of morphologic measurements taken from select Sundance (Js) and Gypsum Spring (Jgs) formation tridactyl prints. See text for locations of sites.

Site	Formation		Digit III Length (cm)	Digit III Width (cm)	Footprint Width (cm)	Footprint Length (cm) (Back of Heel to tip of Digit III)	Inter-Digital Angle II-IV (degrees)	Pace Angulation (degrees)
BM1	Jgs							
		N	2	2	2		2	
		Mean	5.3	0.35	5.8		86.5	
		Minimum	5	0.3	5.4		81	
		Maximum	5.6	0.4	6.2		92	
BM2	Jgs							
		N	3	3	2	2	2	1
		Mean	11.4	2.7	16.7	20	63	173
		Minimum	10.2	2.1	16.5	19.4	56	173
		Maximum	13.3	3	17	20.6	70	173
BM3	Jgs							
		N	6	6	6	4	6	9
		Mean	13.2	3.3	16.8	23.8	80.8	164.9
		Minimum	11	2.8	14	22	67	150
		Maximum	15.9	3.7	18.3	26	90	180
GS3	Jgs							
		N	2	2	2		2	
		Mean	13.1	3	18.2		86	
		Minimum	12.6	3	16.9		83	
		Maximum	13.5	3	19.5		89	
WSS1	Jgs							
		N	9	9	9	9	9	2
		Mean	13.8	2.8	18.2	22.8	97.2	171.5
		Minimum	8.9	1.5	12	13	80	168
		Maximum	18.3	5	21.5	26.6	115	175
FRDT	Js							
		N	20	20	20		20	12
		Mean	16	4.6	23.6		112.9	167.5
		Minimum	12.5	2.2	18.4		91	147
		Maximum	21	8.1	28.3		139	183
S3	Js							
		N	10	10	10	4	10	1
		Mean	11.5	2.3	14.2	14.6	85.6	174
		Minimum	7.1	1	7.2	10.4	60	174
		Maximum	19.1	4.5	26.4	16.8	118	174
S4	Js							
		N	3	2	2	2	2	
		Mean	5.9	1.6	6.7	11	58	
		Minimum	5	1.4	5.3	9.2	56	
		Maximum	7.5	1.7	8	12.8	60	

ger "lower" Sundance Formation trackways. This degradation and disruption of the track-bearing surface appears to have been caused, in part, by anhydrite heaving penecontemporaneously with deposition. The penecontemporaneous growth of the gypsum with the formation of the dinosaur tracks indicates the existence of, at least seasonally, a strongly arid climate during track formation. The Gypsum Springs tracks themselves are also deeper and less well preserved than the "lower" Sundance tracks even though they appear comparable in size, suggesting a wetter substrate during formation of the Gypsum Spring tracks.

Fenestral fabric, discrete, 10-cm diameter and smaller hemispheroidal stromatolites and oncolites, and laminated micritic mudstones and grainstones in the Gypsum Spring track-bearing strata all imply the importance of microbial communities in providing initial fabric stabilization. As is evident in the track-bearing unit of the Sundance Formation (discussed above), track preservation in the Gypsum Spring Formation was enabled similarly by this initial condition of microbial mediation.

DINOSAUR TRACKSITES

To characterize the dinosaur ichnites and their interplay with various substrate properties in this study, the best preserved Gypsum Spring and Sundance Formation track sites were described in detail. Measurements made on selected trackways and individual footprints, include digit III length, digit III width, footprint width, interdigital angles between digits II and IV, and pace angulations (after Leonardi, 1987; Thulborn, 1990; Farlow and Galton, 2000; Farlow, pers. comm., 1997). In addition, a footprint length was measured from the tip of digit III to the posterior end of a functional heel, when a functional heel was present. These results are summarized in Table 2. In addition, other measurements taken include stride lengths and trackway orientations. Field numbers were assigned to each of these trackways and individual footprints for identification. Mapping and photographing of footprints were done in low-angle light. A record of selected footprints was generated at the Flitner Ranch Dinosaur Tracksite by making latex molds and, from them, plaster casts. A field map of the Flitner Ranch Dinosaur Tracksite was made using a geodometer by T. Naus, South Dakota School of Mines and Technology, and D. Mickelson.

The sizes of the tracks from the Gypsum Spring and Sundance intervals are quite comparable both in print widths and digit III lengths, and were generated by small- to medium-sized bipedal dinosaurs. Tracks from both the Sundance and Gypsum Spring formations appear to have theropod affinities as determined by a characteristic tridactyl, nearly symmetrical footprint with tapering digits, a slight positive rotation, and a slightly "S" shaped digit III which is convex to the exterior of the foot (Figs. 12A, B; Langston, 1974; Farlow, 1987; Pittman, 1989; Thulborn, 1990). However, not all tracks exhibit these features and should not be assigned definitively a theropod origin. The values of the pace angulations of the trackways vary from 147 ° to 183 ° degrees, indicating that the animal placed one foot essentially in front of the other during locomotion. These values are comparable to those in other trackways of bipedal dinosaurs (Farlow, 1987; Thulborn, 1990). Tracks in the Sundance Formation typically are not impressed as deeply as those in the Gypsum Spring Formation (generally $<$ 1cm vs. $>$ 1 cm, respectively).

Tracks within the "basal member" of the "lower" Sundance Formation occur at multiple geographic localities in the northeastern Bighorn Basin, but are most concentrated in the area southwest of the town of Shell. Three geographically dispersed tracksites within the Sundance Formation (FDRT, S3, and S4) are summarized in Table 2. The Flitner Ranch and S3 sites are in the Shell area. The S4 site is located to the west at Sheep Mountain, just north of the town of Greybull. Hundreds of individual dinosaur tracks comprising tens of identifiable trackways have been mapped at the Red Gulch Dinosaur Tracksite. Details of the RGDT prints will be forthcoming in a subsequent publication.

There appears to be primarily a single Sundance Formation track-bearing surface in the Shell and Greybull areas, although locally in the Shell area as many as two stacked beds or ripple sets with a total thickness of 4 cm bear identifiable tracks. The tracks are all tridactyl with primarily digitigrade gaits. Most of the footprints are preserved on natural and excavated surfaces as concave epirelief impressions (after Leonardi, 1987). The exception to this are the tracks preserved at the S4 site in the Sheep Mountain area that are preserved as convex hyporelief (casts) tracks, one of which shows a clear functional heel impression (Fig. 12C). The footprint casts are preserved on the underside of a flat bedded fine-grained calcareous sandstone.

The vast majority of the Sundance footprints, including those preserved on the very well exposed RGDT surface, are represented only by digit impressions, typical of a digitigrade stance (Fig. 12D). As such, heels are not preserved as part of the footprint except in rare instances such as the track preserved at the S4 site (Fig. 12C). Estimates of heel

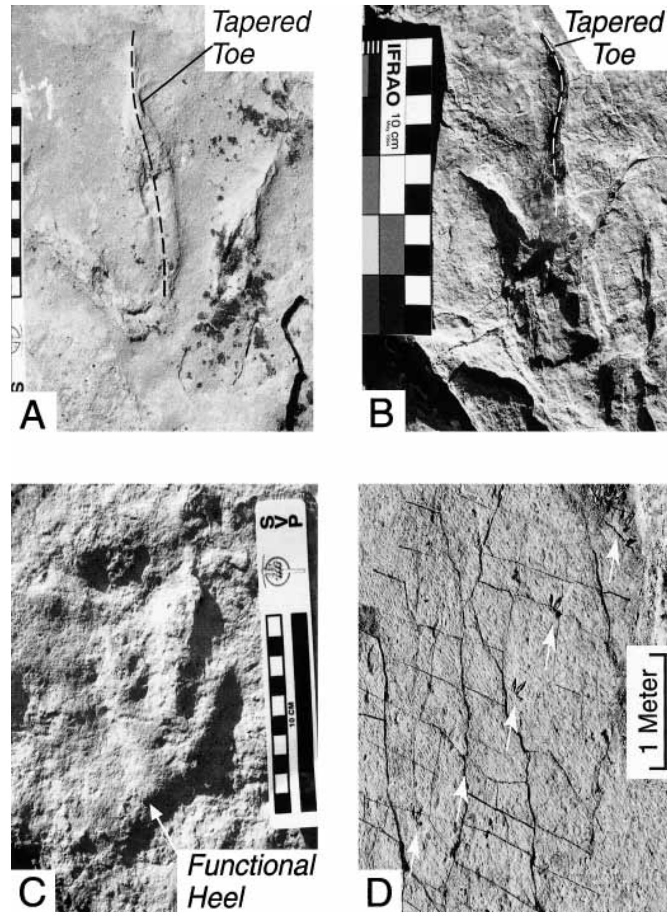


FIGURE 12—Sundance and Gypsum Spring formation tracks. (A) Site S3 tridactyl right footprint. Preserved as a concave epirelief impression, this track is one of several hundred at this locality. Note the sinuous curvature of digit III, the long slender tapering digits, and the near symmetrical appearance of the track. Such characteristics suggest a theropod origin. Scale is in centimeters. (B) Site GS1 tridactyl right footprint. The footprint is preserved as a concave epirelief impression. Like the track in Figure 12 A, this print also shows theropod-like features. (C) Site S4 tridactyl right footprint from Sheep Mountain. The footprint, preserved as a cast from a single block of calcareous sandstone, is that of a small gracile-like dinosaur. This track differs from the vast majority of the Sundance prints in that it preserves a heel-like impression. (D) Tridactyl trackway (arrows) preserved at the Flitner Ranch Dinosaur Tracksite. Note the absence of heel-like impressions. The trackway is oriented towards the southwest.

points using techniques, such as finding the intersection point of the lines created from the posterior projections of digits II and IV, are not reported herein. There is wide variability of such projections from tracks in a single trackway sequence. In addition, there was no way of confirming the validity of such projections because the tracks can not be assigned to any specific dinosaur species. Therefore, the lack of heel impressions or accurate estimates of heel positions negate estimates of hip heights and speeds using Alexander's (1976) mathematical relationships. The azimuth ("walking") directions of the Sundance Formation trackways in the vicinity of Shell are primarily to the south to southwest (Figs. 7B and 13).

"Pull-up" features and "impact" or "displacement" rims associated with most of the Sundance Formation impres-

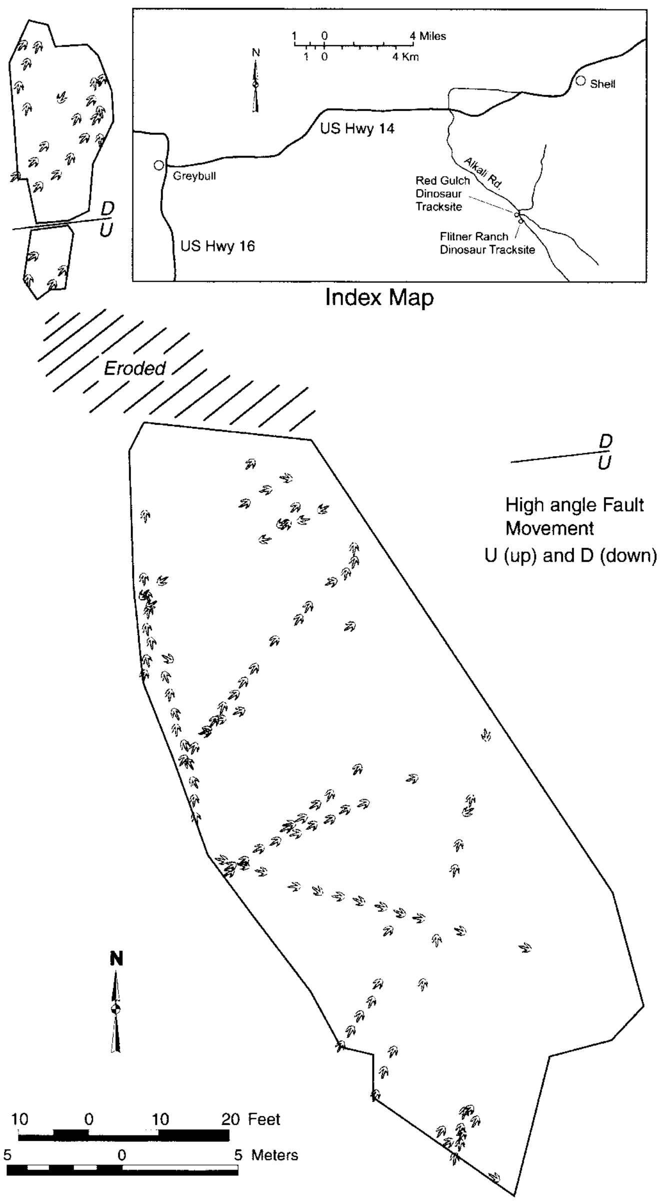


FIGURE 13—Map of the Flitner Ranch Dinosaur Tracksite. The map shows the location, but not relative size, of the tridactyl impressions made by bipedal dinosaurs. The tracks were surveyed and oriented using a geodometer; 21 trackways and 15 isolated prints were identified.

sions indicate that the majority of the tracks are primary surface tracks and not underprints. "Pull-up" features are formed when the substrate is suctioned to an animal's foot and then pulls up to form a convex feature when the foot is removed. "Impact or "displacement" rims form by the displacement of sediment from beneath the foot of an animal as its weight loads the sediment. The presence of "pull-ups" and "displacement" rims associated with the Sundance tracks indicates that the substrate was damp when the tracks were made.

Gypsum Spring tracks are primarily tridactyl and are preserved within a track-bearing interval that is even more extensive than the "lower" Sundance surface. Tracks have been identified within the middle part of the Gypsum Spring Formation from north of Greybull to as far south as the town of Tensleep. All of the tracks appear to have formed in what was originally micritic mud. Track preservation is generally not as good as in the younger Sundance Formation tracks, which likely reflects the differences in the original substrate lithology and consistency. Several sites reported herein are in the vicinity of Shell (Table 2, BM1, BM2, BM3, WSS1), and the third is north of the town of Greybull at Sheep Mountain (Table 2, GS3). Two additional localities exhibit linear traces of two to three subparallel "toe" impressions that resemble features that are interpreted as possibly have been made by swimming bipedal animals. One of these localities is in the vicinity of Shell and the second several kilometers north of the Gypsum Spring tridactyl prints at Sheep Mountain. Studies of all of these sites are on-going.

The best preserved and best exposed Gypsum Spring tracks are those in the vicinity of Shell. They are preserved as concave epirelief impressions (Fig. 12B). Unlike the Sundance tracks, a significant number of the Gypsum Spring tracks at sites BM3 and WSS1 preserve functional heel morphologies. As a result, the Alexander equation (Alexander, 1976) was used to estimate dinosaur speeds for several trackways (Table 3). Calculated speeds for the Gypsum Spring dinosaurs ranged from approximately 5.5 Km/h to 9.2 Km/h.

Within the Gypsum Spring footprint assemblage, the BM3 site preserves a rather unusual trackway. Within this trackway, distinctive elongated markings representing the proximal (heel) end of several footprint impressions are preserved (Fig. 14). Footprint symmetries indicate the trackway begins and ends with a right footprint. Several prints feature a proximal narrow rectilinear groove, tapered with an elongated rounded end projecting from the posterior margin of digit III. Comparison of each

TABLE 3—Summary of data used to calculate dinosaur speeds from select Gypsum Spring Formation trackways.

Site	Formation	Trackway Number	Number of Tracks in trackway	Average Footprint Length (cm) (Back of Heel to tip of Digit III)	Hip Height (cm) (4X Footprint Length)	Stride Length (cm)	Speed (kph)
BM3	Jgs						
		2	3	25.25	101	157.4	5.94
		3	3	22.25	89	137.4	5.49
WSS1	Jgs						
		1	3	25.1	100.5	161.6	6.24
		2	3	23.4	93.6	193.9	9.2

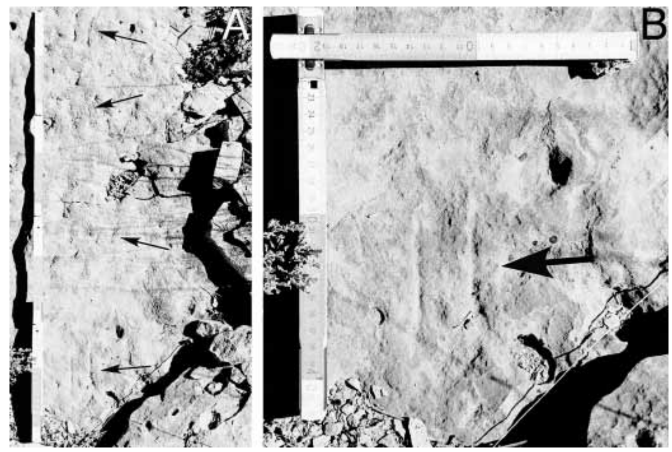


FIGURE 15—Possible "swim" traces associated with the middle track-bearing stratum of the Gypsum Spring Formation at locality GS4, 25 km north of Greybull, Wyoming. (A) Overview of track-bearing surface showing multiple, paired-groove swim traces. Two of these (near base and at top of photo) appear related, and may define a possible ~65 cm pace dimension for this track set. (B) Detail of one groove set from this same locality. Scales are calibrated in centimeters. Rulers are segmented in 10 cm intervals.

footprint reveals diverse morphologies in lengths and widths. Such random variations in morphology would seem to indicate slipping of the animal on a soft substrate. Such random variations do not allow for animal speed calculations.

Other unusual tracks in the Gypsum Spring Formation can be found at sites GS4 and GS5. Site GS4 occurs 25 kilometers north of Greybull and site GS5 occurs 8 kilometers southwest of Shell. Both the GS4 and GS5 sites preserve hundreds of unusual markings not found in other Gypsum Spring Formation tracksites (Fig. 15). The traces are deep, inclined, subparallel scrape marks that occur either in pairs or (rarely) in threes. Lateral spacing between the subparallel marks are typically a few centimeters. Many of the traces at GS4 are preserved at high angles to the general trend of the local ripple mark crests, a relationship that enabled easy recognition of these features. Of the several occurrences of these traces in the Gypsum Spring Formation, the most common forms are characterized by two parallel 1-cm wide grooves, spaced approximately 3.5 cm apart. Each groove set is approximately 8 cm long. The GS4 outcrops are extensive enough to show that these groove sets repeat again (pace?) every 65–70 cm along the outcrop surface. These traces are interpreted to represent toe scratch marks made by a buoyed animal briefly touching bottom while swimming over a muddy carbonate substrate. These interpretations are based on previous publications describing similar markings as swim marks and the interpreted and observed swimming behavior of theropods and large modern flightless birds (Bakker, 1971; Coombs, 1980; Bird, 1985; Pienkowski and Gierlinski, 1987; Gierlinski and Potemska, 1987; McAllister, 1989; Ishigaki,1989).

FIGURE 14—Line drawing of a long BM3 trackway. Track symmetries begin with a right (R) and end with a right (R) footprint. The animal was moving in a south to southeasterly direction. Distinctive elongated markings representing the proximal (heel) end of several footprint im-

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pressions are preserved. Such prints appear to indicate an animal slipping on a wet substrate.

DISCUSSION

The Middle Jurassic dinosaur record is considered sparse worldwide with relatively little known about dinosaurs from this period (Lockley and Hunt, 1995). Biostratigraphic analysis in combination with the absolute age reported herein leads to the conclusion that the Red Gulch/Flitner Ranch tracksites are mid-Bathonian and probably date to ~167ma. The older, Gypsum Spring tracksites are uppermost Bajocian and probably date to ~170ma. These dates are tied to the mid-Mesozoic timescale of Gradstein et al. (1994).

Dinosaur groups existing worldwide during this time included theropods and sauropods, but only theropods had been reported from the western U.S. For the Middle Jurassic of the U.S., the reptilian discoveries had been restricted to Utah. These include: (1) one terrestrial vertebrate fossil skeleton, a small and primitive crocodyliform *Entradasuchus* from the lower part of the Entrada Formation (Hunt and Lockley, 1995), a unit equivalent to the "upper member" of the "lower" Sundance; (2) dinosaur tracks in the slightly younger Moab Tongue of the Entrada Sandstone just below the basal contact of the overlying Summerville Formation (Mickelson, unpublished data); and finally, (3) a few small dinosaur tracks from the Carmel Formation (Lockley et al., 1998). The Carmel Formation appears to be age equivalent to the Piper Formation,"basal member", and all or part of the "middle member" of the "lower" Sundance. Therefore, the existence of abundant dinosaur tracks within the Bajocian Gypsum Spring Formation and Bathonian "lower" Sundance Formation contributes significantly to the knowledge concerning the geographic distribution of dinosaurs in North America during this time.

Mapping of the track-bearing units has allowed for the examination of several thousand tracks. Although specific measurements were made on only a fraction of these tracks, some tracks from the Gypsum Spring and Sundance formations appear to represent theropods, as determined by a characteristic tridactyl, nearly symmetrical footprint with tapering digits, a slight positive rotation, and a slightly "S" shaped digit III which is convex to the exterior of the foot (Langston, 1974; Farlow, 1987; Pittman, 1989; Thulborn, 1990). However, not all tridactyl prints exhibit these features and, as a result, can only be assigned definitely a bipedal origin.

The above raises the question of why a bipedal tridactyl-dominated community is represented in the Gypsum Spring and Sundance formations megatracksite faunas and why there are no preserved sauropod tracks in these formations. At least three possibilities exist. First, the climate that existed during Gypsum Spring and Sundance times in the northern Wyoming might have excluded sauropods; there simply wasn't enough for them to eat or it was too dry or too hot for them. Secondly, sauropods may not have existed in North America at that time. True sauropods first appear in the Early and Middle Jurassic in Europe. The first occurrence of North American sauropod skeletal and ichnological evidence doesn't appear in the Western Interior of North America until the end of the Jurassic when sauropod remains begin to show up in the Tidwell Member of the Morrison Formation (Hunt, et al., 1994; Lockley et al., 1994; Gierlinski and Sawicki, 1998; Gillette, 1996; Mickelson, unpublished data). Finally, one also must consider that the Middle Jurassic rock record of North America has not been examined in enough detail for one to be definitive about the absence of sauropods during this time period.

Both the "lower" Sundance and Gypsum Spring dinosaur footprints are preserved in what is interpreted to be coastal marine (tidal flat) sediments. Interestingly, recent observations on Upper Cretaceous deposits and associated egg clutches in the Tremp Formation of Spain suggest a periaquatic tidal flat ecology for the dinosaur taxa of that setting (López-Martínez et al., 2000). While providing strong evidence on tidal flat nesting habitats, the Tremp Formation example perhaps allows some insight into possible dinosaurian behavior relevant to the Sundance and Gypsum Spring ichnos within similar marginal marine settings.

Both the Sundance and Gypsum Springs ichnites were created under at least seasonally arid conditions. The presence of extensive deposits of displacively-grown gypsum within the Gypsum Spring track-bearing horizon may indicate a more persistently arid environment during Gypsum Spring time than in the slightly younger "lower" Sundance interval.

The large number of similar trackways in the Sundance Formation that trend in the same south-southwesterly direction (Figs. 7B and 13) may indicate gregarious animal behavior, the presence of a physically constrained pathway (such as a tidal flat adjacent to an open body of water), or frequent, repetitive visitation by a small number of individuals over a period of several days or weeks. The crest orientations of the ripples associated with the RGDT surface over a broad area near the town of Shell trend northwest—southeast with a slight asymmetry to the northeast, indicating that open water conditions existed to the southwest. As such, the southerly trend to the majority of the trackways in the vicinity of Shell indicates that the animals were moving towards the local shoreline and not parallel to it. This implies that the pathways may not have been constrained physically. If the animals were moving towards the water as indicated by the ripples then this suggests, but certainly does not confirm, that these animals may have been swimmers or waders.

A swimming behavior for the Gypsum Spring dinosaurs is suggested by the possible swim tracks preserved in that formation. The inferred swim tracks in the Gypsum Spring Formation (Fig. 15) are of a size and spacing that is consistent with the terrestrial tracks found elsewhere in the Gypsum Spring suggesting that they were made by animals of a comparable size. Their presence indicates deeper water conditions existed either locally or subsequent to the formation of the terrestrial tracks. To date, swim and terrestrial tracks have not been found in the same exact stratum for any single site. However, it does appear that the swim tracks occur laterally along the same stratum as the terrestrial tracks and in supra-adjacent strata indicating local changes in the paleogeography existent during formation of the Gypsum Spring track-bearing horizon. Further field work is needed to confirm this interpretation. If there are bipedal dinosaur swim tracks, then they provide direct evidence of the swimming ability of the Gypsum Spring dinosaurs in water depths approximately equivalent to the hip heights of the dinosaurs.

There is relatively little statistical variability between the dinosaur ichnites present in the "lower" Sundance and those in the Gypsum Spring. While the median size of the tridactyl impressions from both the Gypsum Spring and Sundance horizons are similar indicating a similar average size of the dinosaur faunas, the impressions are generally deeper in the Gypsum Spring than in the Sundance. Tracks, in regards to overall morphology, are better preserved in the Sundance Formation and less deformed than those in the Gypsum Spring Formation suggesting more saturated substrate conditions were existent during formation of the Gypsum Spring tracks. The presence of irregular elongated heel-like impressions in some of the Gypsum Spring trackways also suggest wet, slippery conditions of a saturated substrate. The composition of the substrates of the two formations likely had an impact on the sure-footedness of the dinosaurs. The Gypsum Spring tracks were formed in what was originally a micritic mud, whereas the Sundance tracks were formed in very fine- to fine-grained carbonate sand. The latter would have been a much less slippery substrate. In contrast to the Sundance tracks, the presence of heel impressions within the Gypsum Spring ichnites allows for the calculation of dinosaur speeds using Alexander's (1976) equation. Calculated speeds for the Gypsum Spring tracks range from 5.5 kph to 9.2 kph.

Conservative estimates for the regional trackway density within the 7.5 km^2 track-bearing area near Shell, based on track density from the Sundance Flitner Ranch Dinosaur Tracksite and the Red Gulch Dinosaur Tracksite, suggests that over 150,000 *in situ* tracks are preserved per square kilometer in the Sundance Formation in this area. Comparable estimates have not been made for other areas or for the Gypsum Spring Formation.

CONCLUSIONS

The "basal member" of the "lower" Sundance Formation and the older Gypsum Spring Formation contain rare Middle Jurassic dinosaur megatracksites. These track-bearing intervals are approximately 167 ma (Bathonian) and 170 ma (Bajocian), respectively. Both intervals occur in previously unrecognized intertidal to supratidal carbonate units once thought to be totally marine in origin, and both contain potentially tens of thousands to hundreds of thousands of tridactyl dinosaur tracks over a cumulative surface area of hundreds of square kilometers. The discovery of the Bathonian prints necessitates a major northwest shift in the paleogeographic shoreline reconstructions for Wyoming for this period.

The prints can be attributed to small- to medium-size bipedal dinosaurs. Some of these prints appear to be theropod in origin. The Sundance tracks primarily are represented by digit impressions, whereas both digit and heel impressions are preserved in some of the Gypsum Spring prints. Possible swim tracks of tridactyl dinosaurs also are preserved in the Gypsum Spring and may represent an offshore ichnofauna of swimming bipedal dinosaurs.

Both track-bearing intervals formed in at least seasonally arid climates. Track preservation was initiated by the formation of penecontemporaneous microbial mats that stabilized the tracks and prevented the initial reworking of the track-bearing surface by wind- or water-driven currents.

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