Available online at www.sciencedirect.com

SCIENCE DIRECT®

Sedimentary Geology 177 (2005) 175–194

Sedimentary Geology

www.elsevier.com/locate/sedgeo

Mixed sediment deposition in a retro-arc foreland basin: Lower Ellis Group (M. Jurassic), Wyoming and Montana, U.S.A.

William C. Parcell*, Monica K. Williams

Department of Geology, Wichita State University, 1845 Fairmount, Box 27, Wichita, KS 67260-0027, USA

Received 28 January 2004; received in revised form 17 January 2005; accepted 25 February 2005

Abstract

The "lower" Ellis Group (M. Jurassic) of northern Wyoming and southern Montana affords an excellent opportunity to examine the influence of tectonics, sea-level change, and incipient topography on facies dynamics and the evolution of mixed sediment ramp deposits. The Sawtooth, Piper, and Gypsum Spring formations (Bajocian to Callovian) represent sedimentation along the forebulge of a retro-arc foreland basin. The "lower" Ellis Group records deposition during two transgressive–regressive cycles, (1) a Bajocian-age cycle dominated by evaporites and red shales, and (2) a Bathonian-age cycle characterized by carbonates, evaporites, and red shales. These cycles are capped by a Callovian-age cycle distinguished by carbonates and red shales that is represented by the "lower" Sundance and Rierdon Formations. Transgressive episodes favored intensified chemical sediment production resulting in thick units deposited in subtidal to peritidal environments. Regressive periods are characterized by supratidal redbed progradation and subsequent shallowing–upward cycles. The depositional cycles in the lower Ellis Group developed due the interplay between sea-level change and tectonic subsidence related to the evolution of a retro-arc foreland basin. Differential subsidence before, during, and after deposition created paleohighs that locally influenced accommodation space and, thereby, complicated depositional and erosional patterns. This paper provides a regional framework for further analysis of the depositional history of the lower Ellis Group by addressing the stratigraphic relationships between the Sawtooth, Piper, and Gypsum Spring Formations.

Keywords: Clastic; Carbonate; Evaporite; Sequence stratigraphy; Jurassic

1. Introduction

Mixed siliciclastic and chemical deposits in ramp settings have been shown to respond to sea-level changes in a relatively predicable manner (Burchette and Wright, 1992; Azeredo et al., 2002). Although the controls on depositional facies patterns in passive systems are well documented, there are few published studies of the effects of local tectonic movements on mixed sediment depositional systems. However, this situation is recorded during the Middle Jurassic in the Western Interior of the United States where local

* Corresponding author.
E-mail address: william.parcell@wichita.edu (W.C. Parcell).

0037-0738/$ - see front matter
doi:10.1016/j.sedgeo.2005.02.007

tectonic movements related to the evolution of a retro-arc foreland basin influenced depositional and erosional patterns in a restricted ramp setting.

This paper presents a depositional model to examine the influence of tectonics, sea-level change, and incipient topography on facies dynamics and evolution of the mixed sediment Sawtooth, Piper, and Gypsum Spring formations. This is achieved using lithofacies distribution, bounding surfaces, and biostratigraphic zones within a sequence stratigraphic framework.

2. Geologic setting

The early Mesozoic was a time of great change for western North America as the continental margin evolved from largely passive depositional systems during most of the Paleozoic to tectonically-active basins in the early Mesozoic. A major shift in plate motions resulted in highly oblique convergence between the ancestral Pacific plates and the North American plate (Fig. 1). This intersection resulted in complex compressional, tensional, and transtensional forces, which produced a wide variety of depositional settings across the western North American plate including passive margin coastal plains to active margin mountains, arcs, and tectonic basins (Blakey, 1997). The Middle and Upper Jurassic deposits of Wyoming and Montana record at least four major transgressive–regressive marine inundations related to the development of a retro-arc foreland basin that was connected to the proto-Pacific Ocean (Fig. 1) (Peterson, 1954; Brenner and Peterson, 1994). With the onset of thrust faulting during the Middle Jurassic, a foredeep developed in present-day Utah and eastern Idaho depositing the Twin Creek Formation. To the east of this trough, the foreland basin was characterized by a ramp margin along the western edge of a cratonic forebulge (Fig. 2).

Sediments deposited on this forebulge are represented in northern Wyoming by the Gypsum Spring Formation, "lower" Sundance Formation, and "upper" Sundance Formation. In southern Montana, the cycles correspond to the Sawtooth Formation, Piper Formation, Rierdon Formation, and Swift Formation (Fig. 3). Early interpretations by Cobban (1945) and Peterson (1955) emphasized the shallow marine character of the Middle Jurassic section. However, Kilbarda and Loope (1997) and Kvale et al. (2001) have recently demonstrated that certain beds within the Sundance and Gypsum Spring Formations are also lagoonal to terrestrial in origin owing to the identification of aeolian limestone and dinosaur tracks.

Lithologies in the lower units of the Ellis Group vary widely depending on location in the basin and their position relative to paleostructures. The Sawtooth Formation in western Montana varies between limestone, dolomite, shale, siltstone, and sandstone. Cobban (1945) divided the Sawtooth Formation into three units: (1) a basal sandstone/siltstone unit, (2) a middle limestone/shale unit, and (3) an upper shale/siltstone unit. Lithologies in southern and eastern Montana are dominated by carbonates and evaporites. For these reasons, Imlay et al. (1948) defined the Piper Formation from exposures near Lewiston, Montana. The Piper is divided into three units (this time given formal member status): (1) Tampico Shale Member, (2) Firemoon Limestone Member, and (3) Bowes Member (Nordquist, 1955). The Gypsum Spring Formation of Wyoming is also informally divided into three major lithologic units based on lithology and regional continuity of strata. The basal unit contains predominantly white, massive gypsum or anhydrite with interbedded noncalcareous red shale and siltstone. The middle unit contains interbedded green–gray to varicolored shales and gray, black, and brown limestones. The informal upper unit contains primarily red to gray shale and siltstone.

2.1. The correlation quandary

Before discussion of the depositional evolution of the "lower" Ellis Group, the enduring problem of stratigraphic correlation of these units must be addressed. Two fundamental challenges persist. First, there is inconsistent use of the names "Gypsum Spring Formation" and "Piper Formation" because their formal type sections are recognized as incomplete and not representative of the units across much of Wyoming and Montana (Rayl, 1956; Meyer, 1984; Williams, 2003). The type section of the Piper Formation near Lewiston, Montana, as defined by Imlay (1948) represents only the upper third of the units that are commonly referred to as the Piper Formation elsewhere in Montana (Rayl, 1956). The

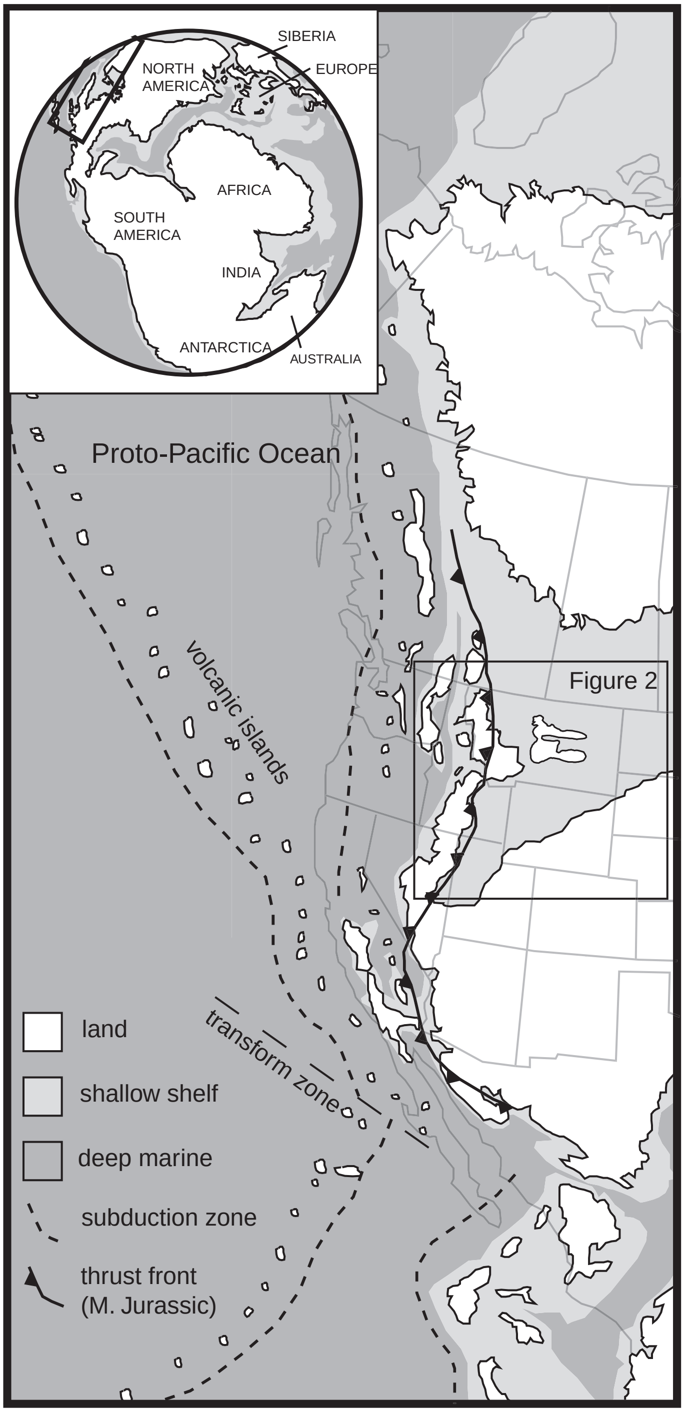

Fig. 1. Regional Middle Jurassic paleogeography of the western North America. The early Mesozoic convergence between the ancestral Pacific plates and the North American plate produced a wide variety of depositional settings across the western North American plate including passive margin coastal plains to active margin mountains, arcs, and tectonic basins. The "lower" Ellis Group was deposited in an epicontinental sea related to the development of a retro-arc foreland basin (modified from Blakey and Umhoefer, 2003; Allen et al., 2000).

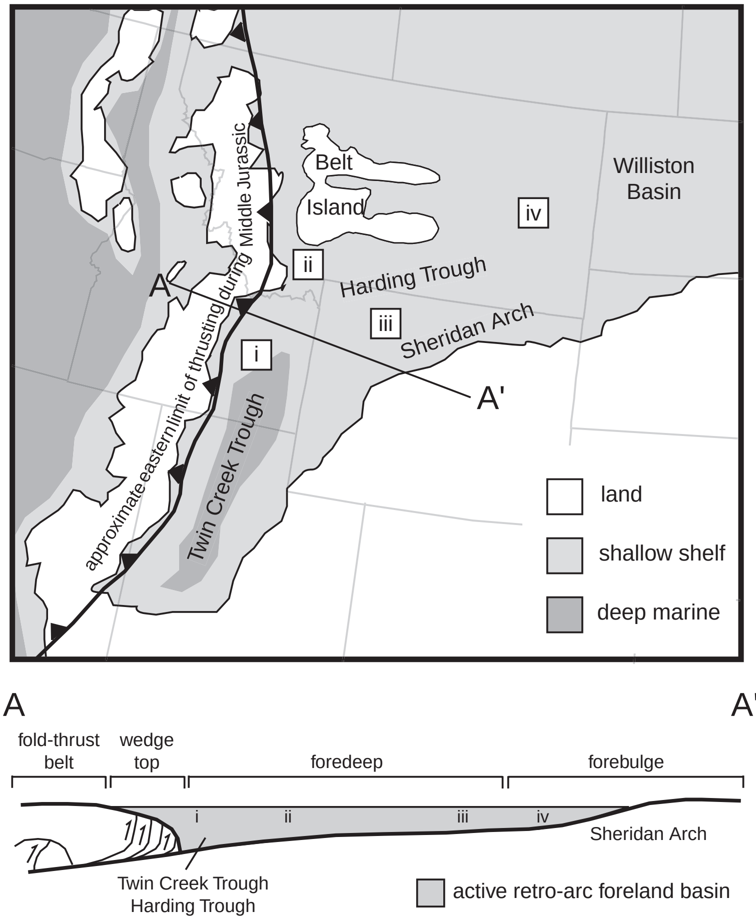

Fig. 2. Paleogeography of study area with generalized cross-section across retro-arc foreland basin (A–A'). Twin Creek Formation (i) was deposited within the western foredeep and the Sawtooth Formation (ii), Gypsum Spring Formation (iii), and Piper Formation (iv) represent deposition across the shallow foredeep and forebulge. Stratigraphic comparison of these formations is examined in Fig. 3.

type section of the Gypsum Spring at Red Creek in the Owl Creek Mountains, as defined by Love (1939, 1945), is also incomplete. The Red Creek section represents only the lower third of the section that is commonly identified as the Gypsum Spring throughout central and northern Wyoming.

Another problem with the type sections is that they include major erosional surfaces. Recognizing these unconformities is the second challenge for correlation of the Middle Jurassic units. Unconformities provide an important element in establishing isochronous units and relative timing of depositional events. Identifying unconformities in the Sawtooth, Piper, and Gypsum Spring formations have been largely based on the presence of a dark chert lag. Piperingos and O'Sullivan (1978) and O'Sullivan and Piperingos (1997) recognized regional unconformities by these chert lags and named them J-0, J-1, J-2, J-3, and J-4 (Fig. 1). These horizons have been widely reported throughout the Western Interior and used with much success in the southwest United States for constructing the depositional history of the Carmel and Entrada formations (Blakey and Parnell, 1995). However, there is no consensus in the literature as to where exactly these horizons occur in the "lower" Ellis Group. Imlay (1956) recognized a chert lag at the base of the Sundance Formation, while O'Sullivan and Piperingos (1997) seem to have placed this chert-bearing horizon at the base of the Piper Formation, and Kvale et al. (2001) recognize the most pro-

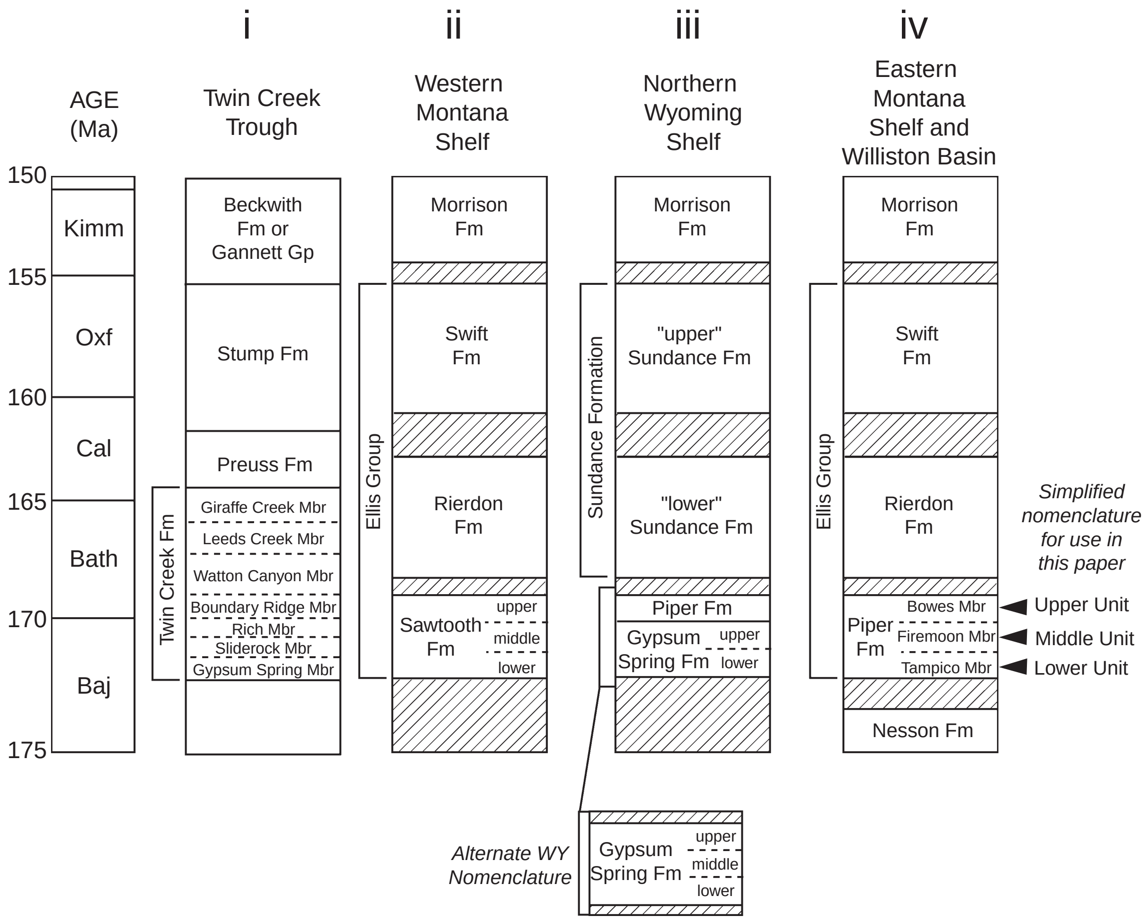

Fig. 3. Stratigraphy of the Middle Jurassic section across eastern Idaho (i), western Montana (ii), northern Wyoming (iii), and western Montana (iv). The Twin Creek Formation of eastern Idaho was deposited within the trough of the foreland basin. The Sawtooth, Piper, and Gypsum Spring formations represent increasingly restrictive environments towards the tectonic forebulge.

nounced chert-bearing horizon at the base of the "middle" member of the Sundance Formation and no unconformities at the base of the Piper or Sundance Formations. Meyer (1984) and Williams (2003) have concluded that the chert-bearing horizons are discontinuous features in the study area and may not necessarily mark unconformable relationships.

Incompleteness of type sections and inconsistent identification of unconformities have led to confusion over the stratigraphic relationships between the Piper and Gypsum Spring formations. Some consider these units to be at least partially equivalent (Imlay, 1956), while others recognize that the Piper Formation occurs above an unconformity that separates it from the Gypsum Spring Formation below (Schmude, 2000). Lithostratigraphic and biostratigraphic relationships indicate that all three formations record two equivalent T–R cycles and that there is no evidence for a regional unconformity separating one formation from another. Therefore, for simplicity of discussion, the following informal terms will be used throughout this paper: (1) Lower Unit (includes basal sandstone/siltstone unit of Sawtooth Formation, Tampico Member of Piper Formation, and lower unit of Gypsum Spring Formation), (2) Middle Unit (includes middle limestone/shale unit of Sawtooth Formation, Firemoon Member of Piper Formation, and upper limestone and shale member of Gypsum Spring Formation), and (3) Upper Unit (includes upper shale/siltstone unit of Sawtooth Formation, Bowes

Member of Piper Formation in Montana, the Piper Formation as commonly denoted in Wyoming, and the informal upper member of the Gypsum Spring Formation).

3. Methods and procedures

Outcrop and subsurface data were collected over five field seasons. Eight outcrops were examined in northern Wyoming and ten outcrops were studied in southern Montana (Fig. 4). In northern Wyoming, the outcrops are (1) Clark's Fork Canyon, State Route 294, (2) Indian Pass, Cody, (3) Chief Joseph Highway, State Route 296, (4) Shoshone River, Cody (Imlay, 1956), (5) Trail Creek, Cody, (6) Little Sheep Mountain, Lovell, (7) Sheep Mountain, Greybull, and (8) Red Gulch, Shell. In southern and southwestern Montana, outcrops include (1) Benbow Mill Road, Limestone, (2) Bridger Creek, Bozeman (Gardner et al., 1946), (3) Crooked Creek, (4) Devil's Slide, Gardiner, (5) Eustis anticline, Manhattan, (6) Fairy Lake, Bridger Mountains, Bozeman, (7) Fraser Lake, Bridger Mountains, Bozeman, (8) Indian Creek,

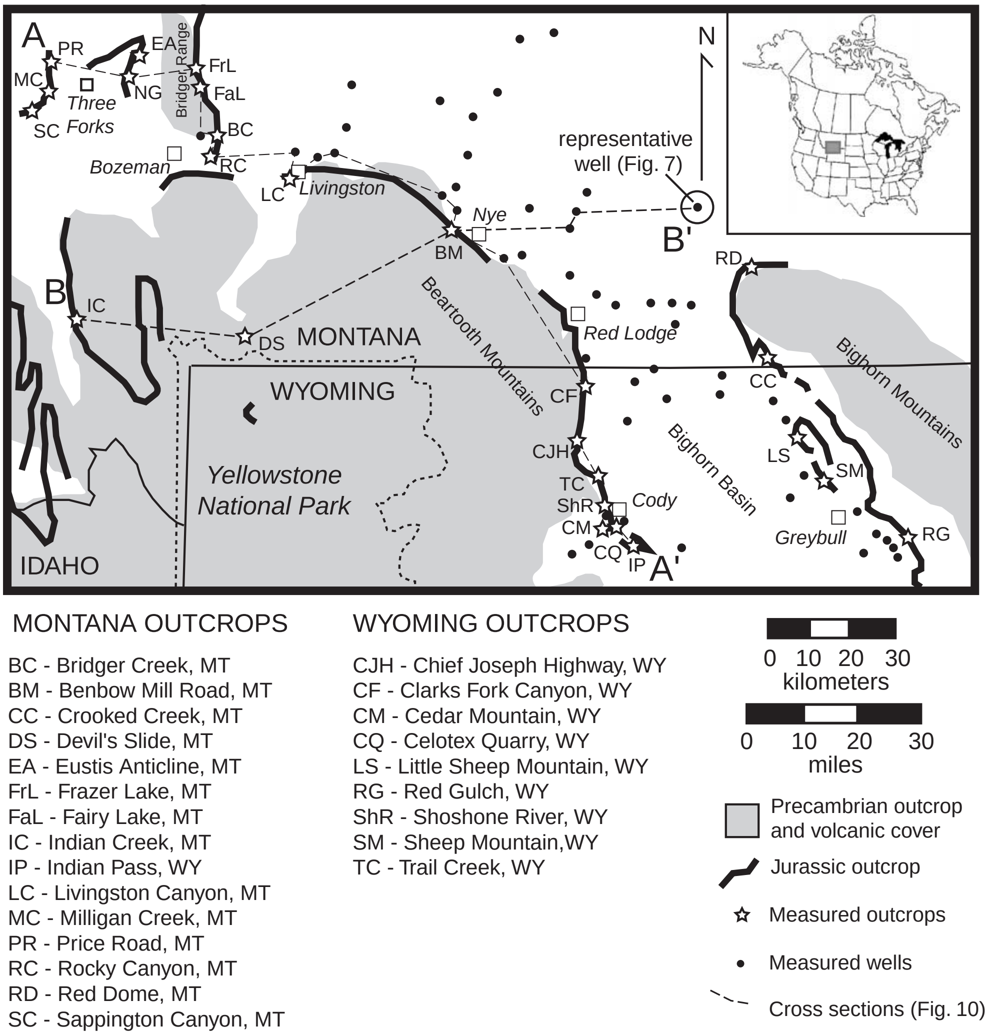

Fig. 4. Map of study area showing outcrop and well locations referred to in text. Cross-sections *A–A′* and *B–B′* are displayed in Fig. 10.

Madison County (Gardner et al., 1946), (9) Livingston Canyon, Park County, (10) Milligan Canyon, Three Forks, (11) Nixon Gulch, Manhattan, (12) Price Road, Three Forks, (13) Red Dome, (14) Rocky Canyon, Bozeman, (15) Sappington Canyon, Three Forks, and (16) Crooked Creek.

Field descriptions included the notation of color, lithology, grain or fossil fragment size/sorting, mineralogy, bedding relationships, sedimentary structures, macrofossils, and bioturbation. Thin sections were prepared, point-counted, and described; hand samples were analyzed; and macrofossils, microfossils, and trace fossils were noted. In areas where outcrops did not exist, well logs were tied-in to establish lithofacies geometries.

Biostratigraphic control was compiled from outcrop measurements in Crickmay (1936), Stanton (1899), Imlay (1948), Lalicker (1950), Peterson (1954), and Swain and Peterson (1951, 1953). Microfossil identification was supported by descriptions and classifications in Lalicker (1950), Peterson (1954), Swain and Peterson (1951, 1953), and Wall (1958).

4. Sawtooth and Piper lithofacies

Seven lithofacies are defined for the Sawtooth, Piper, and Gypsum Spring Formations: (I) red shale and mudstone, (II) gypsum and dolomite, (III) carbonate mudstone to packstone, (IV) oolitic packstone and grainstone, (V) fossiliferous wackestone to grainstone, (VI) dark, carbonate mudstone, and (VII) microbial buildups (Fig. 5). A regional depositional model integrating these seven lithofacies is shown in Fig. 6.

4.1. Lithofacies I: reddish brown shale

Lithofacies (LF) I is characterized by thick sections of reddish brown shales. These shales generally dominate the upper part of the Middle Unit and the entire Upper Unit. They are, by and large, noncalcareous, although locally may grade from greenish gray calcareous or noncalcareous shale at the base of the sections. Upsection, calcareous cement gradually decreases and fissile, silty shale dominates. LF I is characterized on gamma ray logs by an upsection increase in radioactivity (Fig. 7). Due partly to bad exposures and well-developed fissility and fracturing, no characteristic fossils were observed. Thin units of gypsum or gypsum nodules (usually <0.5 m, but may be up to 1.5 m) are found interbedded with the shales throughout each section, However, gypsum units and nodules generally decrease in abundance upsection. Contacts between the shale and gypsum often have a popcorn-like, intergranular texture.

4.1.1. Environmental Interpretation for Lithofacies I (supratidal)

LF I formed in terrestrial to supratidal conditions in an arid, oxidizing climate. The basal interbedded gypsum–mudstone was deposited during waning evaporative, supratidal conditions. The brick to pale red color of the mudstones and shales is interpreted to have formed as soils through in-situ oxidation of hydrated iron-bearing minerals during a hot, arid climate in both supratidal and terrestrial environments. The occurrence of basal interbedded and intergranular gypsum and the upsection increase in shale content across the basin suggests a gradual transition from evaporative, supratidal regions to shallow marine, open water.

4.2. Lithofacies II: gypsum and anhydrite

Massively bedded, cliff-forming, white gypsum or anhydrite dominates the Lower Unit in many locations. Individual beds average 1.5–2.0 m but some thicker beds (up to ~10 m) are present. Locally, the basal gypsum is absent with chert nodules, dolomite, or a siliceous limestone breccia occurring in its place. The gypsum and anhydrite are often interbedded with a variety of lithologies including moderate brown, noncalcareous shale; greenish gray, noncalcareous shale; greenish gray siltstone; grayish red-purple shale; light brown, calcareous shale; and laminated dolomite. Gypsum nodules or thin layers or lenses of gypsum are often interbedded with or intergrown with the shale sediments. Most of the large beds units can be correlated across the study area, but thin, interbedded units are often discontinuous. Well logs and outcrops indicate that the basal evaporite sequences are thin in southern Montana and increase in thickness towards northern Wyoming.

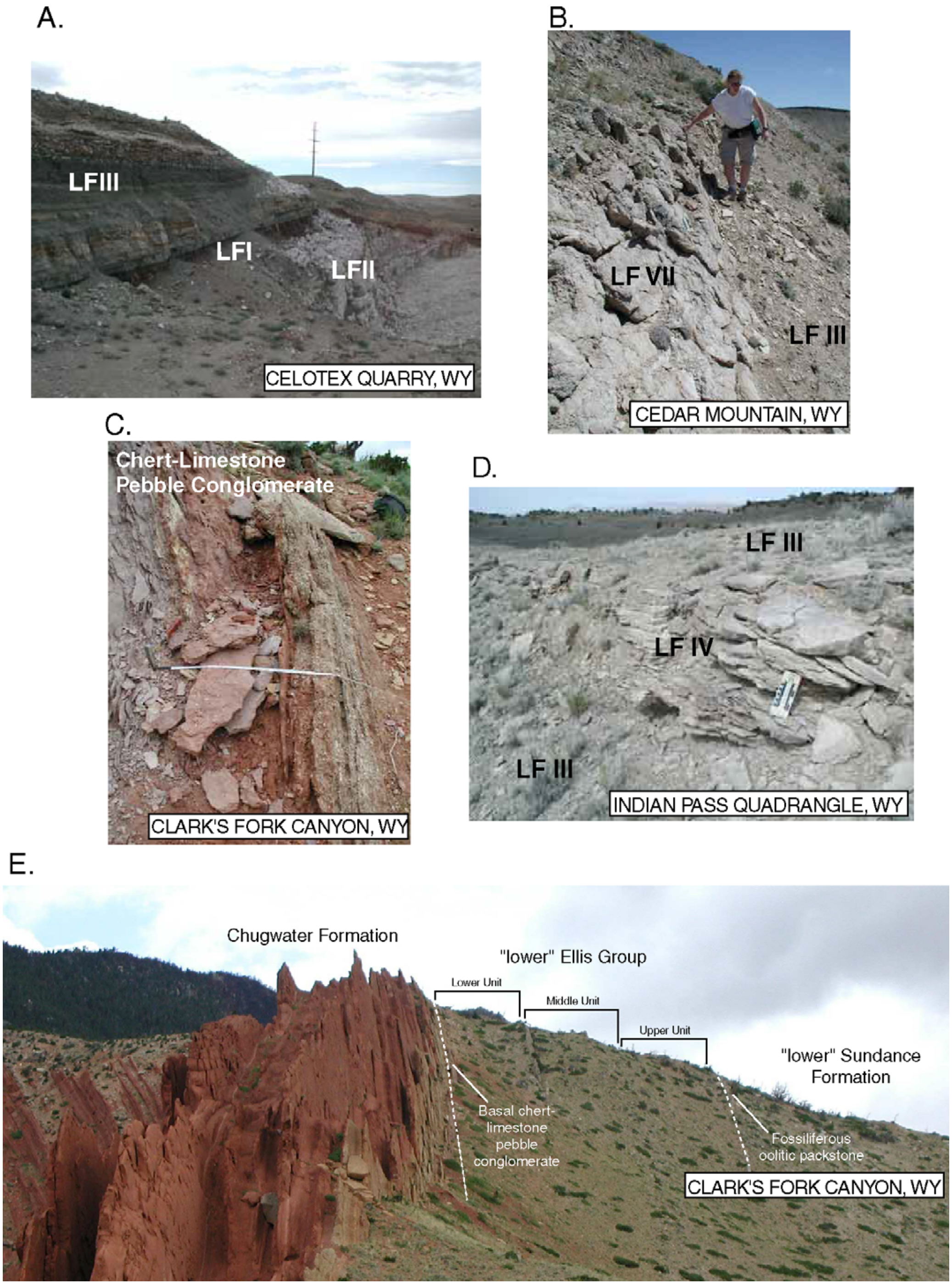

Fig. 5. Outcrop photos of Lithofacies I, II, and III from Celotex Quarry, Cody, Wyoming (A), Lithofacies III and VII from Cedar Mountain, Wyoming (B), chert–limestone pebble conglomerate at the base of the Piper Formation at Clark's Fork Canyon, Wyoming (C), Lithofacies III and IV from Indian Pass Quadrangle, Wyoming (D). Panel (E) is a photo of Clark's Fork Canyon showing the Piper Formation and internal members.

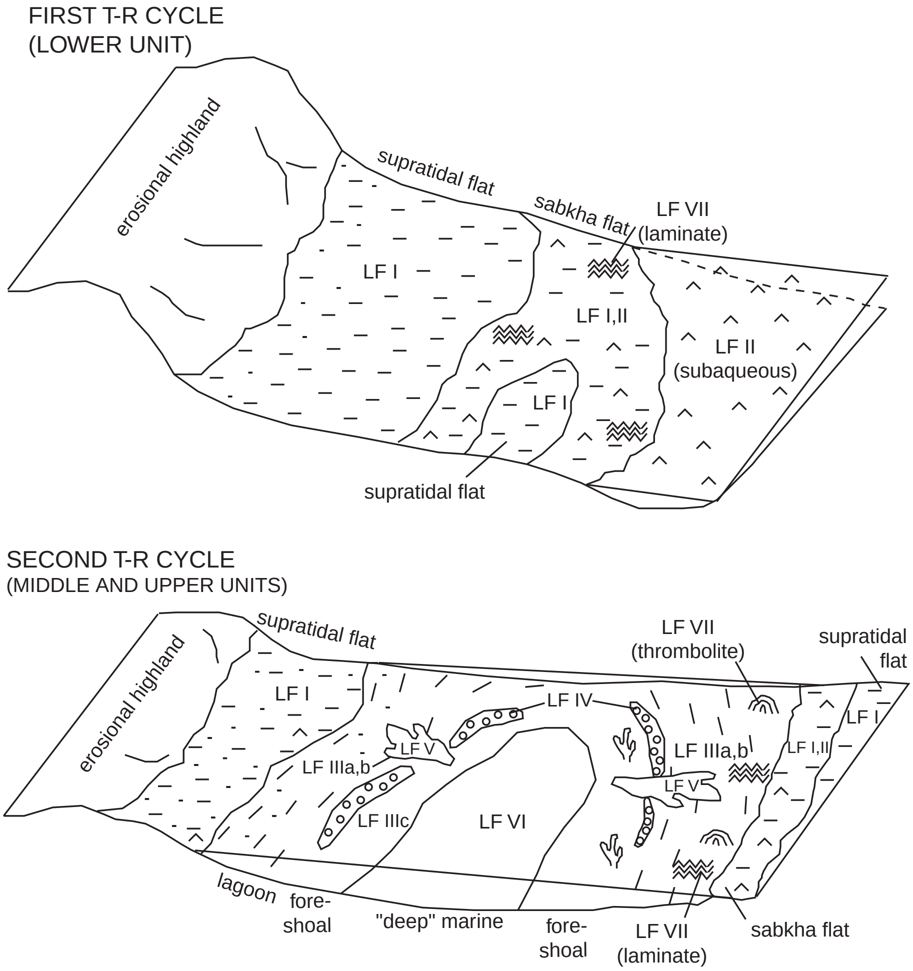

Fig. 6. Depositional model for the two major depositional cycles represented by the "lower" Ellis Group formations. The first cycle is dominated by restricted marine conditions as recorded by lithofacies I and II. The second cycle was characterized by a wider range of marine environments including deposition of Lithofacies I to VII. Transgressive episodes favored intensified chemical sediment production resulting in thick units deposited in subtidal to peritidal environments. Regressive periods are characterized by supratidal redbed progradation and subsequent shallowing–upward cycles.

4.2.1. *Environmental interpretation for Lithofacies II (restricted inner ramp)*

Lithofacies II (LF II) was deposited in restricted and evaporative, shallow water (<10 m), inner ramp settings bordering the southern margin of the study area. Gypsum probably precipitated in the water column and deposited as clastic sediment by low-energy currents. Low and wide symmetrical rippling of gypsum and dolomite in the basal evaporite unit suggest low-energy, shoaling conditions. Schreiber et al. (1973) suggested that such structures represent precipitation in current-swept waters in the photic to sub-photic zone.

4.3. *Lithofacies III: carbonate mudstone to packstone*

Three rock types in the Middle Unit are grouped in Lithofacies III (LF III): (a) green–gray, shaly, bioturbated mudstone, (b) tan-gray, silty mudstone, and (c) peloidal packstone. The green–gray mudstone unit (IIIa) is typified by thinly laminated, rippled, homogeneous, carbonate mud and interbed-

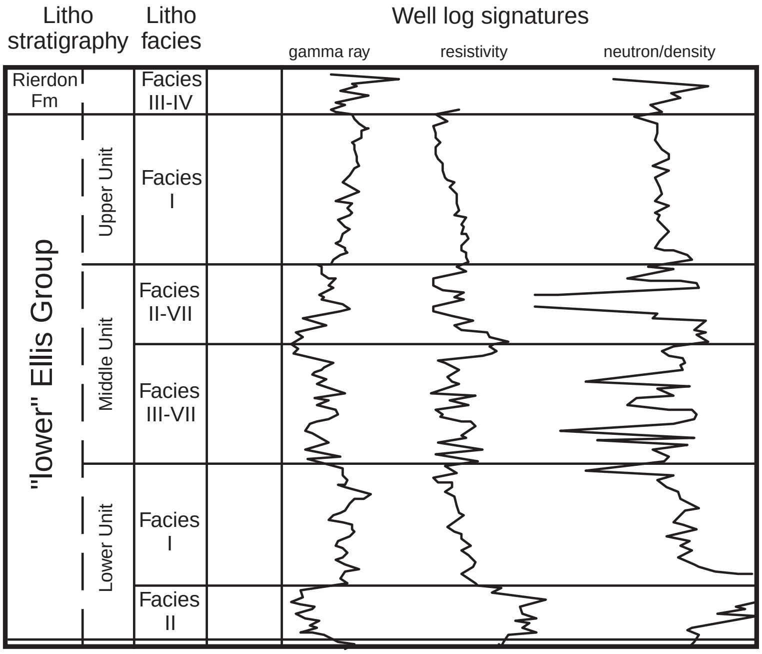

Fig. 7. Representative well Langstaff 2-K showing representative log signatures of the three units described in text.

ded, shaly mudstone. The laminations in the carbonate mud are often disturbed by *Cruziana* ichnofacies. LF IIIb is characterized by tan-gray, silty mudstones, which are thin to massively bedded (1 cm to 2 m thick) and contain a variety of bivalve species. These bivalves are representative of Wright's (1974) *Pleuromya subcompressa* assemblage from the Twin Creek Formation in western Wyoming. The peloidal packstone (LF IIIc) is characterized by small (~0.05–0.75 mm), elliptical to round, dark peloids. Packstones can occur with either a high ratio of fossil fragments and quartz silt to peloids, or with very few fossil fragments or quartz silt.

4.3.1. Environmental interpretation for Lithofacies III (subtidal to intertidal)

LF IIIa was deposited in moderately circulated, shallow, subtidal to intertidal waters within mid-ramp settings. The Benbow Mill Road section displays the characteristic Lithofacies IIIa (green–gray, shaly, bioturbated mudstone). Ripple marks in these green mudstones may imply low- to moderate-energy currents. Ripples, *Cruziana* ichnofacies, and the absence of desiccation cracks suggest subtidal conditions in either lagoons or shallow shelves.

LF IIIb (tan-gray, silty mudstone) formed in shallow water conditions below wave base. Moderate-energy currents dominated during deposition, as indicated by the associated bivalves species. Bivalves in LF IIIa–d coincide with Wright's (1974) *P. subcompressa* assemblage. Both epifaunal and infaunal suspension-feeding bivalves are present. A scleractinian coral, *Coenastraea hyatti* Wells, was also observed in growth position in Lithofacies IIIb at Trail Creek, Wyoming (this study), and Shoshone River, Wyoming (Imlay, 1956). Apparently, currents must have been strong enough to carry nutrients to epifaunal suspension feeders but not too strong to obstruct infaunal suspension feeding. However, lithofacies analysis indicates that the substrate was lime mud, which would disrupt infaunal suspension feeders and favor infaunal deposit feeders. Wright also noted this apparent contradiction in ecological environments in the *Pleuromya compressa* assemblage of the Twin Creek Limestone. Loose, muddy bottoms would hinder suspension feeders by clogging feeding mechanisms, inhibiting larval settlement, and preventing attachment by sessile benthic organisms (Wright, 1974). Wright suggests that the firm or hard substrates are required for both epifaunal and infaunal species to occur in the same depositional environment. Such substrates are prevalent during extended periods of sediment starvation. As discussed below, the occurrence of *C. hyatti* Wells and the *P. compressa* assemblage within Lithofacies IIIb is interpreted to represent times of sediment starvation and provides an important marker bed for correlation across this epicontinental sea.

LF IIIc (peloidal packstone) was formed on the seaward side of a circulated, subtidal, lagoon, which was periodically interrupted by storm overwash. These packstones are characteristically high in fossil fragments and quartz silt content. The peloidal packstones at Frazer Lake include thin, discontinuous zones (~10 cm thick) of rounded echinoderm, brachipod, bivalve, coral, and gastropod fragments. In addition, very fine grained (0.025–0.05 mm), subrounded quartz silt is found interspersed. Storm beds are 10–20 cm thick, comprised of fragments of echinoderms, brachiopods, bivalves, coral, and gastropods. The peloidal packstones from the southern margin are more representative of subtidal to intertidal conditions within middle-ramp settings. These packstones are dominated by peloids with no observable fossil fragments or quartz silt.

4.4. Lithofacies IV: oolitic packstone to grainstone

Lithofacies IV (LF IV: oolitic packstones and grainstones) occurs within the Middle Unit and can be readily subdivided into units dominated by (a) well-sorted grains and (b) poorly sorted grains. Muddy, poorly sorted, oolitic packstones typically show a wide range of ooid sizes from 0.25 mm to 1.50 mm. Individual ooids are distinguished by thin, muddy, concentric laminations (<0.025 mm) and fossil fragment nuclei. Ooid shapes are asymmetric, dependent on fossil shape and size, and oriented lengthwise parallel to bedding. In some cases, ooids are accompanied by abundant mud, ooid clasts, and fossil fragments. Well-sorted oolitic packstones/grainstones are typified by concentric laminations and radial structures averaging about 0.1 mm thickness. The ooids range in diameter from 0.25 mm to 0.50 mm. The ooids are well sorted and are symmetric in shape and highly packed. Well-sorted, oolitic packstones and grainstones can be observed at Benbow Mill Road and Clark's Fork sections. Muddy, poorly sorted packstones are typified by beds at Livingston Canyon.

4.4.1. Environmental interpretation for Lithofacies IV (shoals)

The oolitic packstones/grainstones were deposited in middle-ramp settings on moderate- to high-energy zones shoals. Well-sorted, oolitic packstones and grainstones were deposited on the high-energy, seaward margins of shoals. The muddy, poorly sorted, fossiliferous oolite packstones/grainstones were deposited in moderate-energy conditions on the landward sides of shoals.

4.5. Lithofacies V: fossiliferous wackestone to packstone

Lithofacies V (LF V) is typified by fossiliferous wackestone and packstone/grainstone. It is characterized by low fossil diversity, high mud content, and fossil hash with thick micritic envelopes. The sediment is bioturbated and distinguished by abundant dark, round pellets. Packstones/grainstones occur as thin beds that interrupt thick sequences of green–gray, argillaceous, lime mudstone. Fossil diversity is low and micritic envelopes are thin or absent. Fossils are strongly oriented parallel to bedding.

LF V occurs within the Middle Unit as thin mudstone to grainstone beds (~0.5 m) that interrupt thick sequences of LF IIIa deposits. Individual LF V beds show an upsection decrease in mud content and a subsequent increase in fossil orientation parallel to bedding planes. On a larger scale, sets of LF V beds show an overall upsection decrease in mud content and an increase in grain/fragment sizes and fossil orientation parallel to bedding planes. The top of each successive bed is characteristic of successively more winnowed settings. The trend of lithologies from the center of the Middle Unit is characterized by mudstones at the base and wackestones and packstones near the top. Beds from the upper Middle Unit are characterized by mudstones at the base and packstones and grainstones at the top.

The sets of LF V beds at Clark's Fork Canyon are most representative of these upsection trends. A typical peloidal wackestone from the lower part of the Middle Unit shows rounding of bivalve fragments, and a decrease in thick micrite envelopes. Further upsection, fossiliferous packstones are similar to the lower wackestones but show an overall decrease in skeletal size sorting and rounding, and a slight increase in fossil fragment proportion. Finally, near the top of the Middle Unit, grainstone beds show an increase in skeletal sorting and diversity. Fossil fragments are also more angular. Mud abundance decreases significantly and is restricted between or within large fossil fragments. Micrite envelopes have disappeared, and quartz content has increased to 0.7% of total rock constituents.

4.5.1. Environmental interpretation for Lithofacies V (shallow subtidal storm deposition)

LF V was formed in the middle ramp during storm events. A storm's effect on sedimentary deposits varies with water depth (D_w) and storm-wave base ($\lambda/2$). Specht and Brenner (1979) proposed that storm sediments are deposited in a predictable fashion based on variation in D_w and $\lambda/2$. Mudstones deposited beneath ($>\lambda/2$) storm-wave base are undisturbed by wave energies, but with decreasing water depth, or increasing storm-wave base, muds are increasingly winnowed. Wackestones are the result of incomplete winnowing of mud-size grains and form just below storm-wave base. Packstones and grainstones result from wave energies that winnow most or all interstitial mud. High currents carry larger grains and orient fossils parallel to bedding. Where storm-wave base equals or exceeds water depth, an erosional surface is formed. Application of the Specht and Brenner model to the trends observed in LF V suggests an overall decrease in water depth across the study area during the second half of middle-member deposition. This succession of progressively shallower deposited storm beds provides a record of relative water depth that could not be otherwise determined in the poorly fossiliferous, homogeneous, and muddy Middle Unit.

4.6. Lithofacies VI: dark carbonate mudstones

Lithofacies VI (LF VI) is characterized by dark green–black, shaly to silty carbonate mudstones. Outcrops of LF VI are poorly exposed and additional analysis had to be obtained through well logs. LF VI is typified by several consistent well-log responses. Typical gamma ray logs indicate a high radioactive reading at the base of the Middle Unit and a gradual decrease towards the center of the member. From the center to the top of the Middle Unit, the gamma ray signal reverses, and radioactivity gradually increases upsection. There are a few wells within the basin where anomalous gamma ray readings occur. In these wells, there is a gradual decrease in radioactivity upsection with a few sudden gamma ray kicks.

LF VI comprises all the Middle Unit of the Sawtooth/Piper within the center of the basin. Green–gray muddy carbonate lithologies are observed in the Middle Unit at Benbow Mill Road, and grade to the southwest into green–black siltstones and silty muds at Cinnabar Mountain. Silty mudstone lithologies also occur as far west as Indian Creek, Montana (Gardner et al., 1946; Imlay et al., 1948) and as far south as the correlative Twin Creek Limestone of eastern Idaho and western Wyoming (Peterson, 1955).

4.6.1. Environmental interpretation for Lithofacies VI (subtidal)

Dark gray, shaly mudstones were deposited in quiet, deep-water, outer ramp settings. Since few currents would have existed in these areas, storm currents were the only means to transport skeletal hash from the middle ramp. A few sparsely fossiliferous, dark gray mudstones are interbedded within thick, homogeneous mudstones.

The changing gamma readings across the basin are indicative of changing shale content. The decreasing radiation in the lower and middle sequence indicates a decrease in shale content (Fig. 8). This probably indicates a period of increasing water depth and distance from a terrestrial source. The middle to upper sequence of increasing radiation indicates an increase in shale content and indicates a period of decreasing water depth and/or distance from a terrestrial source.

4.7. Lithofacies VII: microbial buildups

Lithofacies VII (LF VII) is characterized by microbialite. Two fabrics are included in this classification: (1) a clotted internal fabric (thrombolite) and (2) a microbial laminate. Thrombolites are cryptalgal structures that resemble stromatolites but lack distinct laminations and are characterized by macroscopic clotted fabric. Thrombolite occurs in isolated buildups (2 m wide by 1 m thick) that occur at a single horizon within the Middle Unit. The Cedar Mountain outcrop contains several hemispheroical thrombolite patches resting in a rippled, fossiliferous, oolitic, pelloidal packstone to grainstone. Allochems include pelecy-

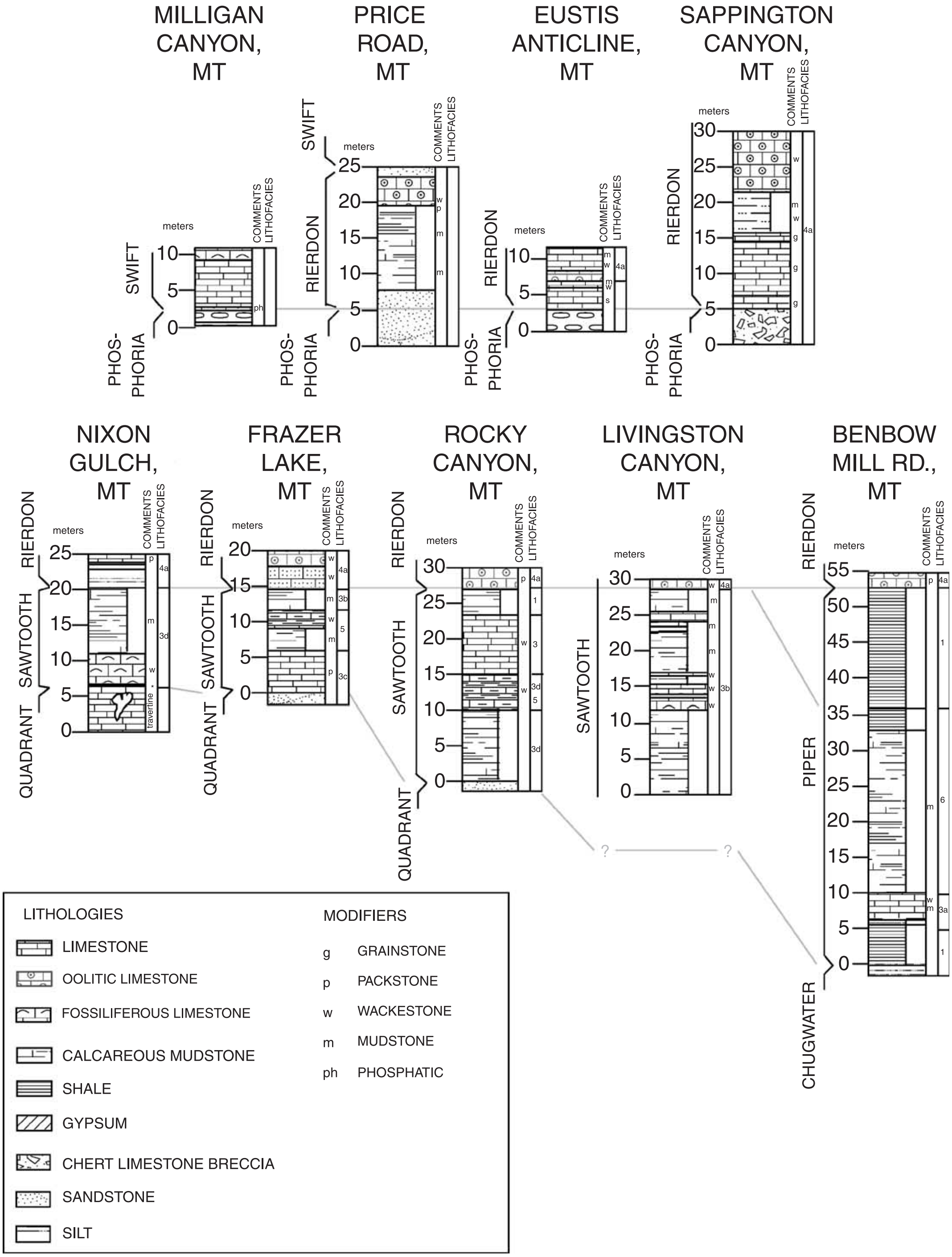

Fig. 8. Nine representative Montana outcrop sections: (1) Milligan Canyon, near the town of Three Forks, (2) Price Road, near the town of Three Forks, (3) Eustis, near the town of Manhattan, (4) Sappington Canyon, on State Route 2 near the town of Three Forks, (5) Nixon Canyon, near the town of Manhattan, (6) Frazer Lake, Bridger Mountains, north of Bozeman, (7) Rocky Canyon, east of Bozeman, (8) Livingston Canyon, Park County, and (9) Benbow Mill Road, near the town of Limestone. Outcrop locations identified in Fig. 4.

pod hash, crinoids, echinoderms, some gastropods, and rounded, elongate micritic fragments.

The microbial laminite fabrics occur throughout the Middle Unit of the Piper and Gypsum Spring formations in Wyoming and Montana and a few isolated occurrences in the Sawtooth Formation along the margin of Belt Island. These microbialites are typically gray to yellow–gray with laminated to thin, wavy/hummocky bedding. Some examples contain minor interbedded gypsum, reddish-brown or gray–green shale, or, rarely, subangular to rounded quartz grains. Outcrop mudstones contain minor pelecypod fragments, occasional small algal heads, minor oncoids, peloids, and burrows.

4.7.1. Environmental interpretation for Lithofacies VII (peritidal to supratidal)

Field and thin section analyses suggest that the thrombolite buildups were deposited in shallow water. Onlapping rippled mudstones contain shallow water benthic fauna (e.g., gastropods, bivalves). Currently, thrombolite has only been observed in the Gypsum Spring Formation along the west side of the Bighorn Basin. These buildups are interpreted to have developed in shallow water (<5 m) during times of sediment starvation. The stromatolites are the most abundant of the microbial facies and exist throughout the middle member of the Piper Formation and the Gypsum Spring Formation. These are shallow water facies as they are found in association with dinosaur footprints (see Kvale et al., 2001) and shallow water benthic fauna.

4.8. Additional lithologies

Three additional lithologies are present within the "lower" Ellis Group: volcanic ash (bentonite), chert breccia, and bedded chert layers. Two bentonite beds occur within the basal Rierdon Formation and lower half of the Piper Formation. Laterally, the layers have been observed by Cobban (1945) in wells in southern Montana and in one outcrop in northwestern Montana. The presence of bentonite layers is interpreted in this study from additional wells in southern Montana. Gamma ray, resistivity, and neutron log signatures were used to identify bentonite beds. Interpretation of these log responses was supported by characteristic well-cutting descriptions.

Chert occurs in the "lower" Ellis Group in two forms: (1) mixed chert–limestone pebble conglomerate or breccia and (2) beds of dark laminated chert. The brecciated chert is found at the base of the Piper and Sawtooth Formations and is mixed with limestone fragments (e.g., the base of section at Clark's Fork Canyon). Laminated chert layers have been reported at multiple stratigraphic intervals in the Ellis Group in the Bighorn Basin (Kvale et al., 2001). Chert horizons have been described in the Gypsum Spring Formation (Imlay, 1956), at the base of the Sundance Formation (Imlay, 1956), and within the Sundance Formation (Imlay, 1956; Kvale et al., 2001).

Piperingos and O'Sullivan (1978) and O'Sullivan and Piperingos (1997) have used the presence of a chert pebble horizon as an indication of an unconformity separating the Piper from the Gypsum Spring Formations. However, no continuous chert–limestone pebble layers were observed in four summer field sessions. The only conspicuous chert–limestone pebble horizon in the study area occurs at the contact between the "lower" Ellis Group and the Triassic Chugwater Formation.

5. Stratigraphic analysis

Stratigraphic relationships within the "lower" Ellis Group were interpreted from characteristic bounding surfaces, stacking patterns, and lateral facies relationships. Biostratigraphic and lithostratigraphic data were used to constrain depositional facies correlations. Compiled biostratigraphic data is shown in Fig. 8 and stratigraphic correlations are represented on cross-sections in Figs. 8, 9, and 10.

Six regionally significant surfaces are recognized in outcrop and wells: (1) a regional unconformity at the base of the Ellis Group, (2) a gradational boundary between the basal gypsum beds and redbeds of the Lower Unit, (3) a gradational to sharp (and locally unconformable) contact at the base of the Middle Unit, (4) a horizon within the Middle Unit marked by the coral *C. hyatti* Wells, thrombolite buildups (LF VII), and the *P. compressa* bivalve assemblage, (5) a gradational boundary between the Middle Unit and Upper Unit, and (6) an abrupt (and locally unconformable) contact between the Upper Unit and the "lower" Sundance Formation.

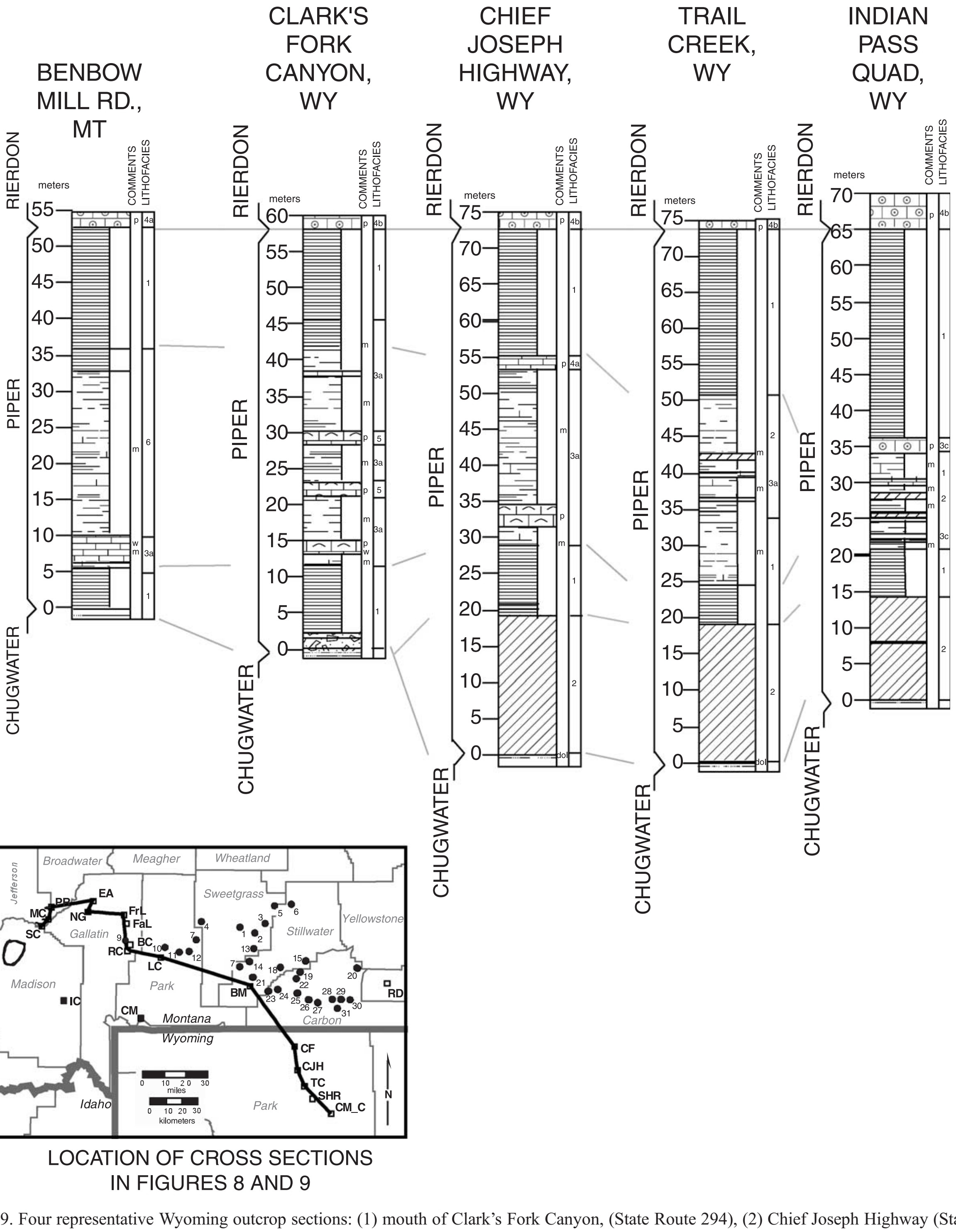

Fig. 9. Four representative Wyoming outcrop sections: (1) mouth of Clark's Fork Canyon, (State Route 294), (2) Chief Joseph Highway (State Route 296), (3) Trail Creek, north of Cody, and (4) Indian Pass, south of Cody.

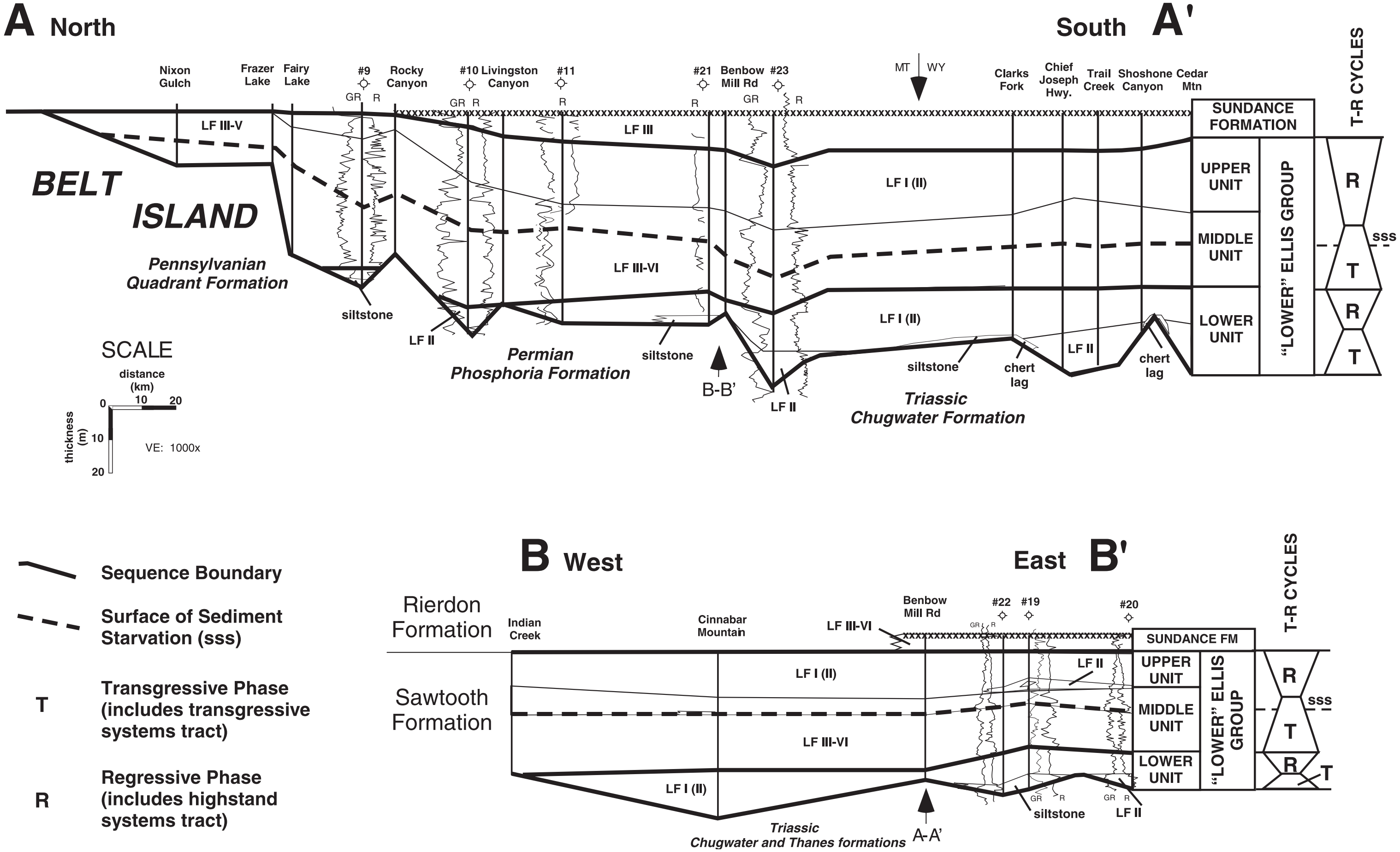

Fig. 10. Stratigraphic cross-sections representing a dip profile (*A–A′*) and depositional strike (*B–B′*). See Fig. 4 for locations of cross-sections.

These surfaces separate various genetically related strata of two T–R cycles in the "lower" Ellis Group. The Lower Unit records the first T–R cycle. This cycle is underlain by a major regional unconformity that separates the Middle Jurassic from Triassic and Paleozoic units below. The first cycle represents deposition during restricted marine and sabhka conditions. The subaqueously deposited lower gypsum beds of the Piper and Gypsum Spring formations correspond to transgressive systems tract (TST) deposition and the lower redbeds represent highstand systems tract (HST) deposition. A sharp to gradational contact at the base of the Middle Unit defines the boundary between the first and second T–R cycles. This contact is also unconformable when associated with local paleohighs such as the Sheridan Arch in northcentral Wyoming and Belt Island in central Montana. Evidence for unconformable relationships includes dessication cracks and dinosaur tracks (Kvale et al., 2001). However, there is no such evidence of exposure or erosion at this contact in locations off-structure. The Lower Unit varies in thickness related to incipient topography that existed prior to deposition of the Ellis Group. The Lower Unit pinches out against Belt Island and thickens dramatically in subbasins in northern Wyoming.

The second T–R cycle is recorded in the Middle and Upper Units. This cycle represents a wider range of depositional environments ranging from more open marine to sabhka settings. The Middle Unit corresponds to the TST and the aggradational phase of the HST, while the upper portion of the Upper Unit represents the progradational HST. A regionally significant horizon marked by the coral *C. hyatti* Wells, thrombolite buildups (LF VII), and the *P. compressa* bivalve assemblage occurs within the Middle Unit and marks maximum sediment starvation during the second cycle. The aggradational phase of the HST of second cycle is characterized by dark green–black, shaly to silty carbonate mudstones of LF VI and is recognized in well logs by gradual gamma ray increase in the upper portions of the Middle Unit (Fig. 10). The aggradational phase is also recognized by increased upsection winnowing in storm beds (LF V). The Middle Unit maintains a fairly consistent thickness across the study area but gradually thickens along the margins of Belt Island and the Sheridan Arch.

The Upper Unit represents deposition during the progradational phase of the HST in the second T–R cycle. The lower contact of the late-HST is gradational from the aggradational units below. The upper contact of the late-HST is sharp against the overlying oolitic limestones (LF IV) of the Rierdon and "lower" Sundance formations. The thickness of the Upper Unit also varies in relation to local structures. The Upper Unit thins along the margin of the Sheridan Arch in northcentral Wyoming and along the southern margin of Belt Island in central Montana. As cross-section A–A' in Fig. 10 indicates, the late-HST of the second cycle (Upper Unit) thins to zero basinward of the TST and early-HST of the second cycle such that north of Bozeman, Montana, the Middle Unit is directly overlain by the "lower" Sundance and Rierdon Formations.

6. Stratigraphic patterns in a foreland basin setting

From a regional standpoint, the Middle Jurassic foreland basin of the Western Interior of the United States was characterized by tectonic subsidence due to flexural loading by thrust sheets, wherein subsidence decreased in a seaward direction away from the fold and thrust belt, in marked contrast to typical passive margin settings, where subsidence increases in a seaward direction (see Fig. 2). However, because the deposits in Wyoming and Montana lay on a west-dipping ramp to the east of the foreland basin trough (i.e., the Twin Creek Trough), they largely behaved like a passive margin setting and the resulting stratigraphic geometries of these ramp deposits strongly reflect the eustatic sea-level signal for the Middle Jurassic (Fig. 11).

Nevertheless, evidence of tectonic movement is not absent in the "lower" Ellis Group. The effects of incipient topography and differential subsidence/uplift are recorded by the variable thicknesses of units over tectonically-active basement structures. Incipient topography was a control during the first T–R cycle as the Lower Unit pinches out against Belt Island and thickens dramatically in subbasins in northern Wyoming. The variable thicknesses of the Middle and Upper Units across Belt Island and the Sheridan Arch can be explained by two episodes of tectonic movements. The first phase involved differential subsidence during deposition of the Middle Unit. Syndepositional

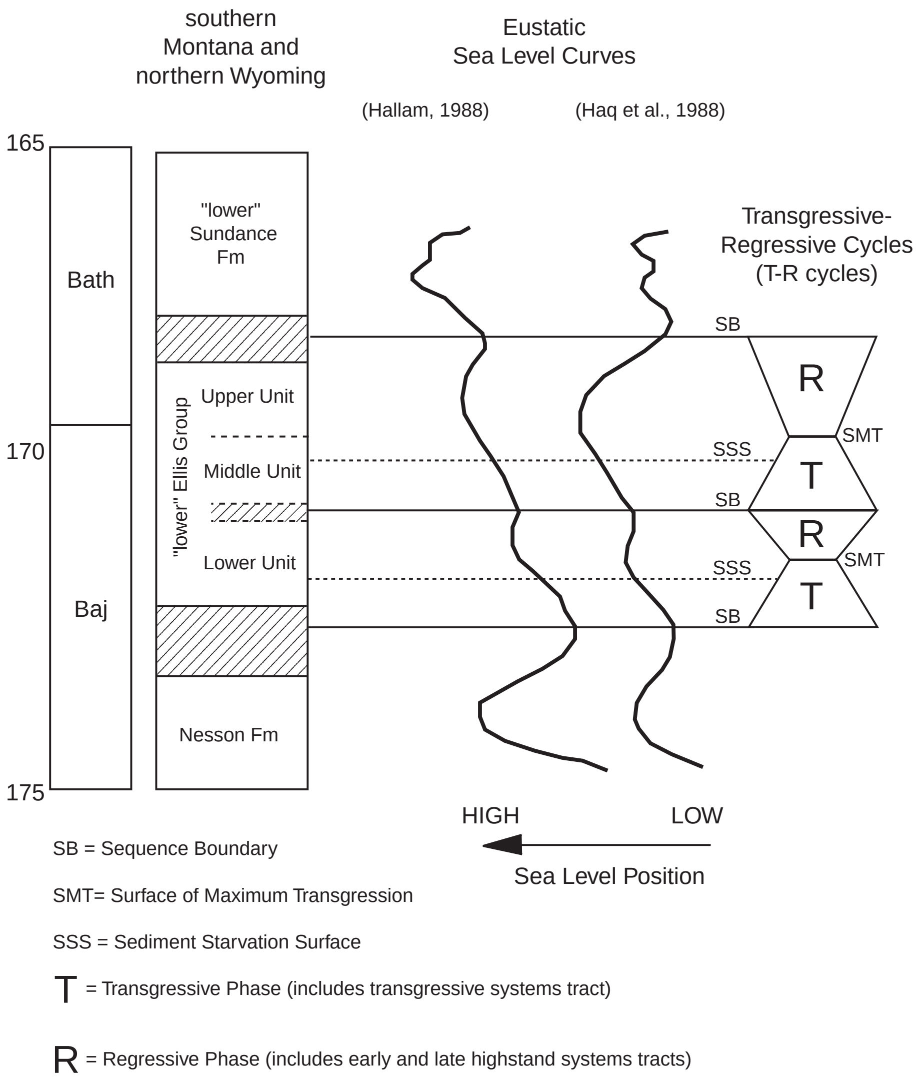

Fig. 11. Comparison of "lower" Ellis Group lithostratigraphy and interpreted T–R cycles to eustatic sea-level curves for the Middle Jurassic by Hallam (1988) and Haq et al. (1988).

tectonic movements affected accommodation space and base level resulting in variable thickness patterns of the Middle Unit across the study area. The second phase involved uplift of structures after deposition of the "lower" Ellis Group, and with regression of the sea, eroded the Upper Unit from the top down. The latter scenario produced thinning of the Upper Unit and generated an erosional unconformity over Belt Island and the Sheridan Arch at the contact between the "lower" Ellis Group and the "lower" Sundance Formation. In fact, this contact is a major regional low-angle unconformity that indicates uplift and/or rapid regression of the sea. The members of the Sawtooth, Piper, and Gypsum Spring formations are progressively removed from the top down as the units onlap Belt Island and the Sheridan Arch. On the crest of Belt Island in central Montana, the "lower" Ellis Group is completely removed, resulting in the Sundance Formation sitting directly on Paleozoic units. In north central Wyoming, the top of the "lower" Ellis Group is removed to the basal gypsum and redbeds of the Lower Unit.

7. Conclusions

1) Future analysis of the depositional evolution of the Middle Jurassic "lower" Ellis Group should be viewed in light of its setting within a retro-arc foreland basin.
2) This paper outlines the lithostratigraphic and sequence stratigraphic framework for the Piper, Sawtooth, and Gypsum Spring formations in southern Montana and northern Wyoming. The "lower" Ellis Group is represented by seven major lithofacies that represent deposition in subtidal to supratidal conditions: (I) red shale and mudstone, (II) gypsum and anhydrite, (III) carbonate mudstone to packstone, (IV) oolitic packstone and grainstone, (V) fossiliferous wackestone to grainstone, (VI) dark, carbonate mudstone, and (VII) microbial buildups.
3) The "lower" Ellis Group records deposition during two T–R cycles, (1) a Bajocian-age cycle dominated by restricted marine conditions as recorded by LF I and II and (2) a Bathonian-age cycle characterized by a wider range of marine environments, including deposition of LF I to VII.
4) Transgressive episodes favored intensified chemical sediment production resulting in thick units deposited in subtidal to peritidal environments. Regressive periods are characterized by supratidal redbed progradation and subsequent shallowing–upward cycles.
5) Six regionally significant surfaces are recognized in outcrop and wells, which bound genetically related strata of two T–R cycles. The first T–R cycle is recorded by the Lower Unit and the second T–R cycle is recorded by the Middle and Upper Units. The first cycle represents deposition during restricted marine and sabhka conditions, while the second cycle represents depositional environments ranging from open marine to sabhka settings.
6) Unconformities in the "lower" Ellis Group occur at T–R cycle boundaries, as defined in this study, which occur at the base of the Lower Unit, the base of the Middle Unit, and the top of the Upper Unit. There is no evidence for a significant unconformity between the Middle and Upper Units as suggested by previous research.
7) The "lower" Ellis Group deposits strongly reflect the eustatic sea-level signal for the Middle Jurassic. Although the units occur in a tectonically-active foreland basin, they were deposited on a ramp margin to the east of the foreland basin trough and, therefore, largely behave much like a passive margin setting. However, ramp deposition was complicated by the effects of incipient topography and local differential subsidence/uplift as recorded by the variable thicknesses of units over tectonically-active basement structures.
8) This study provides a model for mixed sediment deposition on a ramp margin associated with an active foreland basin. This work also supplies a regional sequence stratigraphic and plate tectonic framework for continued analysis of the depositional history of the "lower" Ellis Group.

Acknowledgements

This project has been greatly aided through discussions with Eric Kvale and Lloyd Furer (Indiana Geological Survey), Ernie Mancini (University of Alabama), Allan Thompson, Dick Benson, and Ron Martin (University of Delaware). We are grateful for the field assistance provided by Leah Kasten, Kimberly Minks and Don Slottke. This research was funded, in part, by the US Dept. of Energy, the US Department of the Interior (US Geological Survey), and Wichita State University. However, opinions, findings, and conclusions expressed herein are those of the authors and do not necessarily reflect the views of these institutions.

References

Allen, P.A., Verlander, J.E., Burgess, P.M., Audet, D.M., 2000. Jurassic giant erg deposits, flexure of the United States continental interior, and timing of the onset of Cordilleran shortening. Geology 28, 159–162.

Azeredo, A.C., Wright, V.P., Ramalho, M.M., 2002. The Middle–Late Jurassic forced regression and disconformity in central Portugal; eustatic, tectonic and climatic effects on carbonate ramp system. Sedimentology 49, 1339–1370.

Blakey, R.C., 1997. Paleogeographic evolution of the passive-margin to active-margin transition, early Mesozoic, western North America. Geological Society of America Annual Meeting Abstracts with Programs, p. A-202.

Blakey, R.C., Parnell, R.A., 1995. The volcanic record in the eolian Page Sandstone and related Carmel Formation, Colorado Plateau. In: Miller, D.M., Busby, C. (Eds.), Jurassic magmatism and tectonics of the North American Cordillera, Geological Society of America Special Paper, vol. 299, pp. 393–411.

Blakey, R.C., Umhoefer, P.J., 2003. Jurassic–Cretaceous paleogeography, terrane accretion, and tectonic evolution of western North America. Geological Society of America Annual Meeting Abstracts with Programs, vol. 35, p. A-558.

Brenner, R.L., Peterson, J.A., 1994. Cyclic sedimentation in Jurassic sequences, northern portion of the Western Interior, USA. AAPG Annual Meeting Abstracts with Programs, p. 110.

Burchette, T.P., Wright, V.P., 1992. Carbonate ramp depositional systems. Sediment. Geol. 79, 3–57.

Cobban, W.A., 1945. Marine Jurassic formations of Sweetgrass Arch, Montana. AAPG Bull. 29, 1262–1303.

Crickmay, C.H., 1936. Study in the Jurassic of Wyoming. Geol. Soc. Amer. Bull. 47, 541–584.

Gardner, L.S., Hendricks, T.A., Hadley, H.D., Rogers, C.P. Jr., 1946. Stratigraphic sections of Upper Paleozoic and Mesozoic rocks in South-central Montana. Montana Bureau of Mines and Geology Memoir, vol. 24 (100 pp.).

Hallam, A., 1988. A reevaluation of Jurassic eustasy in the light of new data and the revised Exxon curve. In: Wilgus , C.K., Hastings, B.K., Posamentier, H., Van Wagoner, J., Ross, C.A., Kendall, C.G.St.C. (Eds.), Sea-level change: an integrated approach, Society for Sedimentary Geology Special Publication, vol. 42, pp. 261–273.

Haq, B.U., Hardenbol, J., Vail, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In: Wilgus, C.K., Hastings, B.K., Posamentier, H., Van Wagoner, J., Ross, C.A., Kendall, C.G.St.C. (Eds.), Sea-level change: an integrated approach, Society for Sedimentary Geology Special Publication, vol. 42, pp. 71–108.

Imlay, R.W., 1948. Characteristic marine Jurassic fossils from the Western Interior of the United States. U.S. Geol. Surv. Prof. Pap., 214-B, 13–33.

Imlay, R.W., 1956. Marine Jurassic exposed in Bighorn Basin, Pryor Mountains, and northern Bighorn Mountains, Wyoming and Montana. AAPG Bull. 40, 562–599.

Imlay, R.W., Gardner, L.S., Rogers, C.P. Jr., Hadley, H.D., 1948. Marine Jurassic formations of Montana. US Geological Survey Oil and Gas Investigative Series, Preliminary Chart OC-32.

Kilbarda, Z., Loope, D., 1997. Jurassic aeolian oolite on a palaeohigh in the Sundance Sea, Bighorn Basin, Wyoming. Sedimentology 44, 324–391.

Kvale, E., Johnson, G., Mickelson, D., Keller, K., Furer, L., Archer, A., 2001. Middle Jurassic (Bajocian and Bathonian) dinosaur megatracksites, Bighorn Basin, Wyoming, USA. Palaios 16, 233–254.

Lalicker, C.G., 1950. Foraminifera of the Ellis Group, Jurassic, at the type locality: University of Kansas Paleontological Contributions. Protozoa 2, 3–20.

Love, J.D., 1939. Geology along the southern margin of the Absaroka Range, Wyoming. Geological Society of America Special Paper, vol. 20 (134 pp.).

Love, J.D., 1945. Stratigraphic sections and thickness maps of Jurassic rocks in central Wyoming. US geological survey. Oil Gas Invest. Ser. Prelim.

Meyer J.E., 1984. The stratigraphy of the Gypsum Spring Formation (Middle Jurassic), northwestern Bighorn Basin, Wyoming. MS thesis, University of Wyoming, Laramie (94 pp.).

Nordquist, J.W., 1955. Pre-Rierdon Jurassic stratigraphy in northern Montana and Williston Basin. Billings Geological Society Guidebook, 6th Annual Field Conference, pp. 96–106.

O'Sullivan, R.B., Piperingos, G.N., 1997. Maps showing distribution of erosional clasts on the Middle Jurassic J-2 unconformity in the Western Interior of the United States. US Geological Survey Geologic Investigations, vol. I-2622 (1 pp.).

Peterson, J.A., 1954. Jurassic ostrocoda from the "lower Sundance" and Rierdon Formations, Western Interior United States. J. Paleontol. 28, 153–176.

Peterson, J.A., 1955. Marine Jurassic of Northern Rocky Mountains and Williston Basin. AAPG Bull. 41, 399–440.

Piperingos, G.N., O'Sullivan, R.B., 1978. Principal unconformities in Triassic and Jurassic rocks, Western Interior United States—a preliminary survey. U.S. Geol. Surv. Prof. Pap., 1035-A (29 pp.).

Rayl, R.L., 1956. Stratigraphy of the Nesson, Piper and Rierdon Formations of central Montana. Billings Geological Society Guidebook, 7th Annual Field Conference, pp. 35–45.

Schmude, D.E., 2000. Interplay of paleostructure, sedimentation and preservation of Middle Jurassic rocks, Bighorn Basin, Wyoming. Mt. Geol. 37, 145–155.

Schreiber, B.C., Friedman, G.M., Decima, A., Schreiber, E., 1973. Depostional environments of the Upper Miocene (Messinian) evaporite deposits of the Sicilian Basin. Sedimentology 23, 729–760.

Specht, R.W., Brenner, R.L., 1979. Storm-wave genesis of bioclastic carbonates in Upper Jurassic epicontinental mudstone, east-central Wyoming. J. Sediment. Petrol. 49, 1307–1322.

Stanton, T.W., 1899. Chapter III Mesozoic fossils. In: Hague , A., Iddings, J.P., Weed, W.H., Walcott, C.D., Girty, G.H., Stanton, T.W., Knowlton, F.H. (Eds.), Geology of the Yellowstone National Park: descriptive geology, petrography, and paleontology. US Geological Survey Monograph, vol. 32, pp. 600–632 (Part 2).

Swain, F.M., Peterson, J.A., 1951. Ostracoda from the Upper Jurassic Redwater Shale Member of the Sundance Formation at the type locality in South Dakota. J. Paleontol. 25, 796–807.

Swain, F.M., Peterson, J.A., 1953. Ostracodes from the upper part of the Sundance Formation of South Dakota, Wyoming, and southern Montana. US. Geol. Surv. Prof. Pap. 243-A, 1–17.

Wall, J.H., 1958. Jurassic microfaunas from Saskatchewan, Western Canada. PhD thesis, University of Missouri, Columbia (448 pp.).

Williams, M.K., 2003. Stratigraphic relationships within the Middle Jurassic (Bajocian and Bathonian), Bighorn Basin, Wyoming and Montana. Geological Society of America Annual Meeting Abstracts with Programs, vol. 35, p. A-88.

Wright, R.P., 1974. Jurassic bivalves from Wyoming and South Dakota: a study of feeding relationships. J. Paleontol. 48, 425–433.