SEQUENCE STRATIGRAPHIC EXPRESSION OF FLEXURAL SUBSIDENCE: MIDDLE JURASSIC TWIN CREEK LIMESTONE, WYOMING, U.S.A.

by

BOLTON HOWES

(Under the Direction of Steve Holland)

ABSTRACT

In southwestern Wyoming, the Bajocian to Callovian Twin Creek Limestone records the incipient deposition on a foreland basin in the Sundance Seaway. The sequence stratigraphy of the Twin Creek Limestone is described in the Wyoming Range of southwestern Wyoming, and the geometry of the foreland basin is described mathematically based on estimates flexural rigidity of the underlying crust and the subsidence caused by a thrust load in central Idaho. Four depositional sequences are described. These sequences are correlated to the Bighorn Basin based on existing biostratigraphic correlations and descriptions of the sequence stratigraphic architecture of Middle Jurassic strata in the Bighorn Basin. Modeling of the flexural subsidence of the foreland basin indicates that to account for the geometry of the foreland basin some form of long-wavelength subsidence must be superimposed on the flexural subsidence associated with the thrust load in central Idaho.

INDEX WORDS: carbonate rocks; Jurassic; foreland basin; sequence stratigraphy
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CHAPTER 1
INTRODUCTION AND LITERATURE REVIEW

This thesis has been written as a manuscript intended for submission to the *Journal of Sedimentary Research*. The second chapter includes the manuscript, with an introduction, geological setting, methods, results, discussion, and conclusion. The third chapter is a summary of the conclusions. This project characterizes the sequence stratigraphic architecture of the Middle Jurassic Twin Creek Limestone in southwestern Wyoming, describes how the Twin Creek Limestone records a response to rapid flexural subsidence, and mathematically describes the flexural profile of the foreland basin in which the Twin Creek Limestone was deposited. The correlation and description of the Jurassic strata of Wyoming has long interested geologists. Veatch (1907) first described the Twin Creek Limestone, and sixty years later Imlay (1967) formally defined the seven members of the Twin Creek Limestone. Imlay’s (1967) work was also the first attempt at correlating the Twin Creek Limestone to other strata deposited in the Sundance Seaway. Subsequently, Pipiringos and O’Sullivan (1978), Blakey et al. (1996), and Sprinkel et al. (2011) correlated the Twin Creek Limestone to other units deposited in the Sundance Seaway. Blakey et al. (1996) and Sprinkel et al. (2011) describe the Twin Creek Limestone in Utah and focus on correlations in southern portions of the Sundance Seaway. Pipiringos and O’Sullivan (1978) conducted an influential study of regional unconformities, but it predates the application of sequence stratigraphic principles to correlation.

Other previous work on the Twin Creek Limestone has demonstrated that flexural subsidence caused by a thrust load in central Idaho led to thick accumulations of Jurassic strata
in southwestern Wyoming and eastern Idaho (Bjerrum and Dorsey 1995). This thick succession of rock deposited in a basin with asymmetric subsidence rates provides an opportunity to study how flexural subsidence is expressed in successions of carbonate rocks. Determining how deposition of the Twin Creek Limestone responded to rapid subsidence provides information about how carbonate sediment accumulates and the distribution of depositional environments changes in response to rapid subsidence. Since it is known that the emplacement of a thrust load caused the rapid subsidence of the basin (Bjerrum and Dorsey 1995), the subsidence can be mathematically described to understand the shape of the basin (Nádai 1963; Turcotte and Schubert 2002). A mathematical description of the foreland basin and its implications are included in the second chapter of this thesis.
CHAPTER 2

SEQUENCE STRATIGRAPHIC EXPRESSION OF FLEXURAL SUBSIDENCE: MIDDLE JURASSIC TWIN CREEK LIMESTONE

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1 Howes, B.J. and S.M. Holland. To be submitted to *Journal of Sedimentary Research*.
Abstract

The Middle Jurassic Twin Creek Limestone in southwest Wyoming was deposited during a period in which the rate of thrust-induced flexural subsidence rapidly increased. A sequence stratigraphic analysis and a reconstruction of the subsidence rates and foreland basin geometry were undertaken to understand the stratigraphic expression of this rapid subsidence and the origin of the depositional sequences in the Twin Creek Limestone. The Twin Creek Limestone was deposited on a westward-dipping mixed carbonate-siliciclastic ramp, with facies and depositional environments that include offshore lime mudstone, deep subtidal lime mudstone, ooid shoal packstone-grainstone, shallow-subtidal lime mudstone, peritidal laminated lime mudstone and microbialite, as well as red mudstone and small-scale trough cross-stratified sandstone deposited in a desert environment. Four depositional sequences bounded by subaerial unconformities are present with the Gypsum Spring (GS), Sliderock-Rich (SL-R), Boundary Ridge (BR), Watton Canyon-Leeds Creek-Giraffe Creek (WC-LC-GC), and Preuss (Pr) sequence boundaries characterized locally by brecciated limestone, microkarst, and fluvial deposits. The sequence boundaries are commonly also transgressive surfaces, in some cases having deep marine facies abruptly overlying peritidal or desert facies. Thick (80 – 500 m) packages of sediment deposited in deep subtidal and offshore settings mark the onset of rapid subsidence. A backstripping analysis indicates that rapid subsidence during the WC-LC-GC sequence drowned the Twin Creek ramp. The westward thickening of the WC-LC-GC sequence represents the flexural subsidence of the foreland basin owing to thrust-sheet emplacement in central Idaho. Reconstruction of the deflection profile of the Twin Creek foreland basin suggests
that the forebulge, while a large structural feature, cannot be the sole cause of the formation of Jurassic unconformities in Wyoming.

**Introduction**

On most modern tropical carbonate platforms and reefs, carbonate sedimentation exceeds most observed rates of subsidence or eustatic rise, which means that normal rates of subsidence or eustatic sea-level rise should not be able to drown a carbonate platform (Schlager 1981; Read et al. 1986, Tipper 1997). Nonetheless, drowned carbonate platforms are common in the ancient stratigraphic record (Bernoulli and Jenkyns 1974; Bechstaedt et al. 1978; Eliuk 1978; Schlager 1981). Two scenarios for drowning have been proposed (Schlager 1981). The first is rapid pulses of accommodation from sudden rise in eustatic sea level or from earthquake-induced subsidence. The second is poisoning of the carbonate platform, which suppresses the carbonate accumulation rate. Colder temperatures and decreased light availability in subtropical settings hamper biological production of carbonate, leading to slower accumulation rates compared with tropical settings (Kemp and Sadler 2014). The diminished accumulation rate on subtropical carbonate ramps effectively makes them behave like the poisoned shelves of Schlager (1981).

The Middle Jurassic Sundance Seaway in Wyoming is one such subtropical ramp (Imlay 1967, McMullen et al. 2014, Clement and Holland 2016; Danise and Holland 2017; Fig.1). In the middle to late Bajocian, the foreland basin in which the Sundance Seaway was developed underwent rapid flexural subsidence caused by the emplacement of thrust loads in central Idaho, probably a northern extension of the Luning-Fencemaker fold and thrust belt (Bjerrum and Dorsey 1995). This rapid subsidence is recorded by the Twin Creek Limestone, which spans the Bajocian to early Callovian in southwest Wyoming. This study examines how an ancient subtropical carbonate ramp responded to flexural subsidence by investigating two end member
hypotheses. The first is that carbonate accumulation rates were fast enough to fill accommodation space created by the flexural subsidence, leading to aggradational to progradational stacking patterns. The second is that because of slower carbonate sedimentation rates in subtropical settings, the sedimentation rates were not be able to keep up with subsidence rates, triggering retrogradational stacking. Understanding the stratigraphic expression of rapid flexural subsidence is important for understanding how carbonate ramps in general respond to changes in subsidence rates and for understanding the depositional history of the Sundance Seaway.

Geologic setting

The Twin Creek Limestone overlies the Lower Jurassic Nugget Sandstone, is overlain by the Upper Jurassic Preuss Formation (Veatch 1907), and is exposed in the Wyoming Range of southwest Wyoming and easternmost Idaho (Fig. 2A). The Twin Creek Limestone is divided into seven members reflecting a range of depositional environments. In ascending order the members are: the Gypsum Spring, Sliderock, Rich, Boundary Ridge, Watton Canyon, Leeds Creek, and Giraffe Creek Members (Imlay 1967; Fig. 2B). The Leeds Creek Member is the thickest of all the members, and it thickens from 80 m in the eastern part of the Wyoming Range to 500 m in the west. Although most members vary little in their lithology, the Giraffe Creek Member varies from oolitic grainstone and microbialite in the east to lime mudstone interbedded with sandstone in the west. The amount of terrigenous sand in the Giraffe Creek Member increases to the west.

The Twin Creek Limestone records incipient deposition in the Sundance Seaway on a westward-facing ramp on the distal side of a retroarc-foreland basin (Lawton 1994; Bjerrum and Dorsey 1995; Parcell and Williams 2005). Flooding of this seaway began in the early Bajocian and continued in western Wyoming through the middle Oxfordian and is recorded by the
shallow-marine siliciclastic rocks of the Preuss and Stump Formations (Imlay 1980). The Sundance Seaway extended from southern Utah to British Columbia with a boreal entranceway that may have been as far north as the southern Yukon Territory (Brenner and Peterson 1994; Lawton 1994; Parcell and Williams 2005; Blakey 2015). Estimates of the paleolatitude of the Twin Creek Limestone vary from 20–30° N (Kocurek and Dott 1983) to ~35°N (Blakey 2015), both of which are consistent with a subtropical climate (Purser 1973; Fig. 1).

The chronostratigraphy of the Twin Creek Limestone is based on ammonites in the Sliderock, Rich, Watton Canyon, Leeds Creek, and Giraffe Creek Members, which bracket the ages of the unfossiliferous Gypsum Spring and Boundary Ridge Members (Fig. 3). The Sliderock and Rich Members contain *Stemmatoceras, Megasphaeroceras* cf. *M. rotundum*, and *Sohlites spinosus* (Imlay 1962, 1967, 1980; Fig. 3), which place the Sliderock and Rich Members in the middle to late Bajocian. The placement of the Sliderock Member in the middle Bajocian constrains the youngest possible age for the Gypsum Spring Member to the early to middle Bajocian. The Leeds Creek Member has been biostratigraphically correlated to the Stockade Beaver Member of the Bighorn Basin, which was deposited in the late Bathonian, which means that the Giraffe Creek Member must be late Bathonian to Callovian, owing to the Callovian age of the Preuss Sandstone (Imlay 1967).

In southwest Wyoming, the Twin Creek Limestone is exposed on thrust sheets formed in the Cretaceous Sevier Orogeny that are roughly perpendicular to depositional dip of the Twin Creek Limestone (DeCelles 1994; Fig. 2A). The leading edges of the Hogsback and Absaroka thrusts are 30 km apart. Palinspastic reconstruction shows that there has been 21 km of shortening on the Hogsback thrust and ~30 km of shortening on the Absaroka thrust (DeCelles 1994), which means the outcrops exposed on the thrust sheets were originally 81 km apart.
Outcrops on the Absaroka and Crawford thrust sheets were ~100 km apart prior to crustal shortening. The shortening associated with the Ogden and Willard thrusts is less constrained, but combined there has been ~100 km of shortening on the two thrust sheets (DeCelles 1994). In total, there has been ~180 km of shortening in the Wyoming Range, and the leading edge of the Hogsback thrust was ~315 km from the leading edge of the Ogden thrust at the time of deposition (DeCelles 1994).

Six regional unconformities recognized by chert-pebble lags (J-0 through J-5) divide Jurassic strata in the western United States (Pipiringos and O’Sullivan 1978), and the timing of the J-1 through J-4 unconformities falls within the study interval. The positions of these unconformities have not been determined in the Twin Creek Limestone of southwest Wyoming, but the positions in the Bighorn Basin are well-constrained (Parcell and Williams 2005; McMullen et al. 2014; Clement and Holland 2016). The sequence stratigraphic architecture of the Twin Creek Limestone is developed here independent of this previous work on regional unconformities, but is subsequently correlated to the Bighorn Basin, where this framework is established.

**Methods**

Five stratigraphic columns of the Twin Creek Limestone were measured across the Wyoming Range in southwest Wyoming (Fig. 2A, Appendix A; Appendix B). At each section, lithology, sedimentary structures, body fossils, and trace fossils were documented. Multiple hand samples from each facies were thin-sectioned and stained with alizarin red-S for facies analysis.

The subsidence history of the Twin Creek Limestone was reconstructed by backstripping the Twin Creek Limestone, using an Airy backstripping routine to correct for compaction and isostatic loading (Watts 1988; Sahagian and Holland 1991). The measured stratigraphic columns
in this study were used for the backstripping except for the poorly exposed Thomas Fork section in the western thrust (Fig. 2A), which is based on the measurements made by Imlay (1967). Backstripping was performed with the Backstrip program (Holland 2015).

To reconstruct the dimensions of the foreland basin, deflection profiles for a line load were calculated based on the deflection on an infinite elastic slab overlying an inviscid (Nádai 1963). The vertical displacement \( y \) at any distance \( x \) from the line load is

\[
y = y_0 e^{-Lx} \cos(Lx) + \sin(Lx)
\]  

(1)

where \( y_0 \) is the vertical displacement at the load and \( L \) is the flexural rigidity, which is equal to

\[
L = \frac{(\rho_m - \rho_f)g^{\frac{1}{4}}}{4D}
\]  

(2)

where \( \rho_m \) is the density of the asthenosphere, \( \rho_f \) is the density of the basin fill (assumed to be water), \( D \) is flexural rigidity, and \( g \) is gravitational acceleration. For the foreland basin containing the Twin Creek Limestone, the best estimate for the maximum deflection \( y_0 \) of the foreland basin is 3.25 km and the best estimate for \( D \) is \( 5 \times 10^{24} \) Nm (Bjerrum and Dorsey 1995). Equation 1 implies several important scales of the foreland basin (Turcotte and Schubert 2002). The distance from the load to the forebulge \( W_{\text{basin}} \) is

\[
W_{\text{basin}} = \frac{3\pi}{4L}
\]  

(3)
The width of the forebulge \((W_{bulge})\) is one-third larger than that of the foreland basin:

\[
W_{bulge} = \frac{\pi}{L}
\]  

(4)

The height of the forebulge scales linearly with the maximum deflection \((y_0)\):

\[
y_b = -e^{-\pi} y_0 = 0.0432 \cdot y_0
\]  

(5)

with the height of the forebulge approximately equal to 4% of the maximum displacement in the basin \((y_0)\), directly underneath the thrust load.

**Facies**

Seven facies reflecting seven depositional environments are present in the Twin Creek Limestone in southwest Wyoming. Each is characterized by a distinctive set of lithologies, bedding, sedimentary structures, fossils, and vertical transitions to other facies (Table 1). These facies represent a series of environments along a homoclinal carbonate ramp, including offshore, deep subtidal, shallow subtidal, ooid shoal, tidal flat, desert, and a siliciclastic offshore transition environments.

**Facies LM: Lime Mudstone**

The pervasive very thin bedding and absence of body and trace fossils indicates that Facies LM was deposited under low oxygen conditions. The lack of current or wave-generated sedimentary structures, along with the fine grain size and very thin bedding suggests that Facies LM was deposited below storm wave base in offshore settings (Calvet and Tucker 1988; Sami
and Desrochers 1992). Facies LM is present in the Leeds Creek Member, and it thickens to the west, consistent with a western depositional dip. No facies grades vertically into Facies LM, making Facies LM the most depositionally down-dip environment in this study.

**Facies ALM: Lime Mud with Argillaceous Partings**

The presence of thinly- to very thinly-bedded lime mudstone with argillaceous partings, interbedded with vortex-rippled and hummocky cross-stratified lime mudstone suggests that Facies ALM was deposited under low shear stress conditions punctuated by episodes of higher shear stress generated by waves and combined flow (Nøttvedt and Kreisa 1987; Fig. 4). This mix suggests deposition between fair-weather and storm wave base in the deep subtidal environment (Bádenas and Aurell 2001; Elrick and Read 1991). Medium beds of oolitic-skeletal grainstone cap some Facies ALM bedsets. These oolitic-skeletal grainstone caps are interpreted as proximal storm deposits transported downslope from ramp-margin banks and ooid shoals (cf. Elrick and Read 1991; Fig. 4B). Facies ALM gradationally overlies Facies LM, indicating that the two facies were deposited laterally adjacent to one another based on Walther’s Law.

**Facies BLM: Bioturbated Lime Mudstone**

The dominance of medium to thick beds of highly-bioturbated gray lime mudstone suggests that Facies BLM was deposited in a shallow subtidal environment (Pope and Read 1998). The intense bioturbation and medium to thick bedding is unique to Facies BLM, and they suggest that this environment had the best-developed infauna of any depositional environment in the Twin Creek Limestone. Despite the extent of bioturbation, fossils are rare in Facies BLM, and this probably means that the bioturbation is from non-skeletonized burrowers, such as polychaetes and soft-shelled arthropods. That Facies BLM gradually overlies Facies ALM indicates that that these two facies were laterally adjacent based on Walther’s Law. Facies BLM
is most prevalent in the eastern sections (Twin Creek, LaBarge Creek, Cabin Creek), consistent with a western depositional dip (Imlay 1967; Blakey 2015).

**Facies OG: Ooid Packstone-Grainstone**

The abundance of thick-bedded oolitic packstone to grainstone, bearing large-scale trough cross stratification and a lack of bioturbation suggests that Facies OG was deposited in an ooid shoal (Elrick and Read 1991; Smith and Read 2001; Fig. 5). Thin-bedded oolitic grainstone lacking cross lamination and cross bedding is also present and is interpreted to represent deposition distal to an ooid shoal. Ooids in the thin-bedded oolitic grainstone are broken, and both concentrically and radially laminated ooids are present, suggesting transport from their place of origin (Simone 1980, and Flugel 2010; Fig. 6F). Many ooids in the Twin Creek Limestone have undergone “eggshell diagenesis” (Wilkinson and Landing 1978; Fig. 5D), which occurs when dissolution removes the aragonitic nucleus of the ooid and the ooid is crushed during compaction. Cementation prior to compaction would have prevented the crushing of the ooids (cf. Bromley 1991), so cementation after compaction is more likely. Facies OG gradationally overlies Facies LM and Facies ALM, but Facies ALM also grades vertically into Facies BLM without passing through Facies OG. Because modern oolitic shoals are not laterally continuous (Purser 1973), the vertical gradation of Facies ALM into Facies BLM without passing through Facies OG likely indicates a local lack of ooid shoals.

**Facies YRM: Yellow to Red Mudstone and Microbialite**

The abundance of microbial laminae, 2D vortex ripples, the bivalve trace *Lockeia*, and gradational contacts with Facies RM and Facies BLM suggest that Facies YRM was deposited in a peritidal setting (Barnaby and Read 1990; Fig. 6A–E). Thin beds of structureless ooid grainstone are also found among the microbial laminites and vortex ripples of Facies YRM, and
these ooids were likely transported to intertidal settings during storm events (Selg 1988). That Facies YRM gradually overlies both Facies BLM and Facies OG suggests that Facies YRM passed seaward into open shallow subtidal and ooid shoal environments, which also suggests that Facies YRM could form in the sheltered area behind an ooid shoal, but ooid shoals are not required for the development of Facies YRM.

**Facies RM: Red Mudstone**

The dominance of red to brown mudstone, the absence of body and trace fossils, and gradational underlying contacts with Facies YRM suggest that Facies RM was deposited on a supratidal mud flat (Evans et al. 1969; Fig. 6D). Ferric iron is the likely cause of the yellow-red color of the sediment, which indicates deposition under oxic conditions, and suggests a low organic carbon input or flushing by oxygen-rich meteoric water (Maynard 1982). The red to brown color is similar to the red and brown color of the desert mud flat facies of the Sundance Seaway in Wyoming and southern Montana (Parcell and Williams 2005, Clement and Holland 2016). The gradual upward transition from Facies YRM into Facies RM signals that Facies RM was adjacent to Facies YRM. Facies RM is always overlain by a flooding surface, indicating that it is the most depositionally updip environment in this study.

**Facies PRLM: Planar-Laminated Lime Mudstone and Vortex-Rippled Lime Mudstone**

The dominance of very thinly-bedded and planar-laminated sandy lime mudstone interbedded with 3D vortex-rippled sandy lime mudstone suggests that Facies PRLM was deposited in a low shear stress environment that experienced periods of elevated shear stress, similar to Facies ALM (Fig. 4C). Facies PRLM differs from Facies ALM in that it includes terrigenous siliciclastics, which suggests Facies PRLM was deposited in the offshore-transition of a siliciclastic margin (Goldring et al. 1991). Facies PRLM is present at Leeds Creek, the
westernmost section measured in this study, and only in the Giraffe Creek Member. Both the upper and lower contacts of Facies PRLM are sharp, and Facies PRLM abruptly overlies Facies LM. The pervasive ripple lamination of Facies PRLM suggests that it was deposited in a shallower environment than Facies LM.

**Facies Model**

Facies relationships in the Twin Creek Limestone indicate that deposition took place on a homoclinal carbonate ramp (Read 1985; Burchette and Wright 1992; Fig. 7A). Gradual vertical transitions among facies indicate lateral relationships among adjacent depositional environments. Gradual transitions are represented by either a gradual change in lithology such as Facies ALM and Facies LM or through interbedding of distinct lithologies as in the transition of Facies ALM to Facies OG.

Five of the seven facies present in the Twin Creek Limestone have repeated gradual transitions that reveal the arrangement of depositional environments on the ramp. Facies LM (lime mudstone) is the most basinward facies, and it is interpreted to have been deposited in an offshore setting. Facies LM grades vertically into Facies ALM (lime mudstone with argillaceous partings), interpreted as recording deposition in a deep subtidal setting. Facies ALM passes vertically into Facies BLM (bioturbated lime mudstone), interpreted as shallow subtidal. Facies BLM grades vertically into Facies YRM (yellow to red lime mudstone), interpreted as peritidal flats. Facies YRM grades vertically into Facies RM (red mudstone), interpreted to have been a desert mudflat, the most landward environment in the study.

The distribution of ooid shoals in the Twin Creek Limestone is more complicated. The thick-bedded manifestation of Facies OG grades upward into Facies BLM and Facies YRM. That Facies OG can grade vertically into Facies BLM suggests that Facies BLM was sometimes
deposited in the sheltered area behind an ooid shoal. Facies ALM can also pass upwards into Facies BLM without an intervening Facies OG, which suggests that Facies BLM could also be deposited without the shelter provided by an ooid shoal. It also suggests that ooid shoals were discontinuous features on the Twin Creek ramp, consistent with the distribution of ooid shoals on modern carbonate ramps (Purser 1973; Alsharhan and Kendall 2003).

Facies PRLM (planar-laminated lime mudstone and vortex-rippled lime mudstone) is present in this study only at Leeds Creek, and it is the only marine facies with a substantial terrigenous siliciclastic component. Imlay (1967) measured stratigraphic columns west of Leeds Creek and found that the thickness and amount of siliciclastic material increased to the west. The westward thickening of this siliciclastic wedge implies a western sediment source, likely the thrust load in central Idaho (Bjerrum and Dorsey 1995). The westward thickening of the siliciclastic wedge suggests that Facies PRLM represents an offshore-transition depositional environment lying on the eastward-facing siliciclastic coast (Fig 7B).

There are many similarities between the facies model for the Twin Creek and the facies models that have been developed in the Bighorn Basin and southwestern Wyoming (Parcell and Williams 2005; McMullen et al. 2014; Clement and Holland 2016). The model from Parcell and Williams (2005) has equivalents to Facies LM (their Facies VI), OG (IV), YRM (III), and RM (I), all with similar environmental interpretations. Parcell and Williams (2005) do not document a separate facies between offshore (VI) and shallow subtidal (V) environments, which is where Facies ALM, interpreted as deep subtidal, occurs in the Twin Creek Limestone. The model from Clement and Holland (2016) recognizes equivalents to Facies YRM (their LLM) and RM (RM), with similar environmental interpretations. Noticeably absent from the Clement and Holland (2016) study are the downdip facies ALM and LM, which is expected because their study
focused on a depositionally updip setting. Clement and Holland (2016) also describe salina and sabkha deposits (their Facies G) and a paleosol (their Facies PM). Both of these facies are found in depositionally updip settings, and are correspondingly absent in the more downdip Twin Creek Limestone. In addition, the shallow subtidal facies in the Bighorn Basin and southern Montana are fossiliferous (Parcell and Williams 2005; Clement and Holland 2016), whereas fossils are largely absent from the shallow subtidal facies (Facies BLM) in the Twin Creek Limestone (Facies BLM). Although trough cross-bedded oolitic facies are present in the Bighorn Basin and southern Montana (McMullen et al. 2014), the cross-bedded oolitic grainstone facies of the Twin Creek Limestone are thicker and more extensive.

The facies model of the Twin Creek Limestone also bears a strong resemblance to other carbonate-ramp facies models, particularly in the outer ramp (Facies LM, and ALM) and mid-ramp (Facies BLM) settings (Burchette and Wright 1992). For example, on a Mississippian carbonate ramp also deposited on a foreland basin, lime mudstone deposited in an offshore setting passes landward into argillaceous wackestone deposited between fair-weather and storm wave base (Al-Tawil et al. 2003). This Mississippian ramp continues landward through shallow subtidal, ooid shoal, tidal flat, and supratidal desert environments, similar to those in the Twin Creek Limestone. The conspicuous difference between the Mississippian ramp and the Twin Creek Limestone is that the Mississippian ramp is much more fossiliferous and bioturbated.

The facies model developed here for the Twin Creek Limestone also resembles the facies model developed for Jurassic carbonate ramps outside of the Sundance Seaway. For example, the Twin Creek Limestone facies model is similar to a carbonate ramp from the Neuquén Basin in west-central Argentina (Legarreta 1991), particularly in the outer and inner ramp settings. Like the Twin Creek Limestone, the carbonate ramp in the Neuquén Basin has offshore lime
mudstone and shale passing landward into deep subtidal wackestone with storm deposits. The inner-ramp of the Neuquén Basin has ooid shoals that pass landward into peritidal facies with microbialite and thin-bedded oolitic grainstone. The Neuquén Basin ramp differs from the Twin Creek Limestone in that coral build-ups dominate the mid-ramp depositional environments, whereas coral is absent from the Twin Creek Limestone. The paucity of fossils, coral build-ups, and bioturbation in Twin Creek Limestone may reflect the elevated salinity and temperatures postulated for the Sundance Seaway (McMullen et al. 2014; Clement and Holland 2015; Danise and Holland 2017).

**Sequence Stratigraphic Interpretation**

The Twin Creek Limestone contains four unconformity bounded depositional sequences in the Wyoming Range of southwest Wyoming (Fig. 8). Each sequence is named based on the lithostratigraphic units within the sequence.

**GS Sequence Boundary and GS Sequence**

The GS sequence boundary lies at the contact of the Gypsum Spring Member on the Lower Jurassic Nugget Sandstone (Pipiringos and O’Sullivan 1978; Brenner and Peterson 1994; Kvale et al. 2001; Parcell and Williams 2005). The contact is marked by an abrupt shift from the large-scale trough cross-bedded sandstone of the eolian Nugget Sandstone to red mudstone or oolitic grainstone of the Gypsum Spring Member. A biostratigraphic gap spanning the Aalenian and early Bajocian stages is also present, as the upper Nugget Sandstone contains an Early Jurassic fossil assemblage (Lockley et al. 1992; Hamblin et al. 2000; Lockley 2011). The GS sequence is recorded by Facies RM at LaBarge Creek and Cabin Creek and by Facies OG at Pine
Creek (Fig. 8). Within the study area, the GS sequence lacks vertical changes in facies, so it is not possible to identify stacking patterns or systems tracts within the sequence.

**SL-R Sequence Boundary and the SL-R Sequence**

The SL-R sequence boundary is a combined sequence boundary and flooding surface that is also the contact between the Sliderock Member and the underlying Gypsum Spring Member. At Pine Creek, the sequence boundary has been subjected to modern weathering, but is marked by an abrupt change from brecciated oolitic grainstone to lime mudstone with argillaceous partings (Facies ALM; Fig 8). The oolitic grainstone is interpreted to be brecciated as a result of dissolution caused by the circulation of meteoric waters during subaerial exposure (cf. Knight et al. 1991). At all other localities, the sequence boundary is poorly exposed and represented only by a distinct change from red soil, weathered from Facies RM, to gray soil, weathered from Facies ALM (Fig. 8).

That Facies ALM directly overlies the sequence boundary indicates the contact between the GS and SL-R sequences is a combined sequence boundary and transgressive surface. At Cabin Creek and LaBarge Creek, the SL-R sequence boundary is overlain by shallowing-upward cycles with deep subtidal deposits at their base and shallow subtidal caps. At Pine Creek, the base of the SL-R sequence consists entirely of deposits that lack shallow subtidal cycle caps, suggesting greater depths to the west. At all localities, deep subtidal cycles get thicker and more distal through the lower SL-R sequence, indicating retrogradational stacking, placing the lower part of the SL-R sequence in the transgressive systems tract (Fig. 8). In the middle of the SL-R sequence, the cycles become thinner and shallower (Facies BLM returns), indicating progradational stacking and a gradual transition into the highstand systems tract (Figure 9A). The uppermost portion of the SL-R sequence shallows into peritidal cycles capped by skeletal
packstone. The progressively thinner and shallower cycles of the middle and upper SL-R sequence places it in the late highstand systems tract (Fig. 8).

**BR Sequence Boundary and BR Sequence**

The BR sequence boundary is marked by an abrupt basinward shift from shallow subtidal and peritidal facies to supratidal desert mudflat facies that takes place at the contact between the Boundary Ridge Member and the underlying Rich Member. At LaBarge Creek and Cabin Creek, the sequence boundary is marked by an abrupt shift from Facies YRM to the red mudstone of Facies RM. At Pine Creek and Twin Creek, the sequence boundary is a contact between Facies YRLM and the small-scale trough cross-stratified sandstone of Facies RM. Internally, there are no vertical facies changes within the BR sequence. The lack of internal facies changes makes it impossible to identify stacking patterns and systems tracts (Fig. 9A; Fig. 8). In the Bighorn Basin, supratidal mud flat and sabkha facies are best developed in the highstand systems tract (Clement and Holland 2016), suggesting it is most likely that the Facies RM deposits of the BR sequence are part of the highstand systems tract.

It is also possible that the BR sequence is not a separate sequence, but represents the late highstand systems tract of the SL-R sequence. At Twin Creek, the contact interpreted as the sequence boundary lies at the contact of two facies that are laterally adjacent in the facies model (Facies YRM and Facies RM, Fig. 7A). While Facies YRM and RM are laterally adjacent, their contact at Twin Creek is abrupt and not gradational as would be expected at a within sequence contact. Moreover, at the other locations where the BR sequence boundary is visible, it is a non-Waltherian contact between Facies BLM or ALM and Facies RM (Fig. 5). Therefore, the interpretation that the BR sequence is separate from the SL-R sequence is favored.
The WC-LC-GC sequence boundary is at the contact of the Watton Canyon Member on the Boundary Ridge Member. An abrupt disconformable transition from Facies RM to Facies BLM marks the WC-LC-GC sequence boundary (Fig. 8). The boundary lacks evidence for prolonged subaerial exposure, but it is a large flooding surface and the rocks above the contact have an aggradational to retrogradational stacking pattern, which suggests that they overlie a sequence boundary, and that they are in the early transgressive systems tract.

Aggradational to retrogradational cycles represent the increasing accommodation rate of the early transgressive systems tract. These cycles are best developed at Pine Creek, where it is represented by meter-scale peritidal cycles with ooids coated by iron oxide, indicating diagenesis in oxic conditions (Maynard 1982), consistent with subaerial exposure. At Cabin Creek, and LaBarge Creek, the early transgressive systems tract is represented by cycles that shallow upward from deep subtidal to shallow subtidal and occasionally peritidal environments, with silicified horizons and anhydrite pseudomorphs indicative of subaerial exposure (Smith et al. 1993). Several large flooding surfaces, represented by abrupt transition from shallow marine facies to deep subtidal or offshore environments, mark the transition from early to late transgressive systems tract. The late transgressive systems tract has deep subtidal cycles with fossiliferous grainstone caps. These grainstone cycle caps become thinner and more widely spaced up section (Fig. 8) indicating retrogradational stacking the transgressive systems tract. In the westernmost sections (Pine Creek and Leeds Creek), these grainstone caps are absent, leaving uninterrupted offshore deposits (Fig. 8; Fig. 9C).

The maximum flooding surface lies where the grainstone caps are furthest apart at LaBarge Creek and Cabin Creek and within the uninterrupted offshore deposits at the Leeds
Creek section. Towards the top of the uninterrupted offshore deposits the appearance of shelly pavements suggests gradual shallowing into the highstand systems tract (Fig. 8).

In the west, the contact between the Leeds Creek and Giraffe Creek Member is a surface of forced regression represented by an abrupt contact between Facies ALM and Facies OG at LaBarge Creek and Facies LM and Facies PRLM at Leeds Creek (Fig. 9C). At LaBarge Creek and Leeds Creek, the Giraffe Creek Member represents the falling stage systems tract of the WC-LC-GC sequence. At Cabin Creek, the contact between the Leeds Creek Member and the Giraffe Creek member is a gradual transition from Facies ALM to Facies OG. As the most updip section, Cabin Creek may have experienced a longer, more erosive period of subaerial exposure associated with the Pr sequence boundary that removed the falling stage deposits, leaving only progradational late highstand deposits (Fig. 8).

*Pr Sequence Boundary*

The Pr sequence boundary marks a major transition from predominantly carbonate deposition to siliciclastic deposition, which takes place at the contact between the Preuss Sandstone and the underlying Giraffe Creek Member. This change may be associated with northward drift of North American continent (Johnson 1992), but more likely represents the rapid progradation of sediment derived from the uplifted thrust loads to the west (Bjerrum and Dorsey 1995). At Cabin Creek, the contact is marked by red mudstone overlying ooid shoal facies. At LaBarge Creek, a knife-edge contact between peritidal carbonates and the overlying Preuss Sandstone marks the Pr sequence boundary. The Pr sequence boundary at Leeds Creek separates the underlying Facies PRLM and the overlying red siliciclastic sandstone and mudstone of the Preuss Sandstone (Fig. 8).
Decompacted subsidence curves from the Twin Creek Limestone provide estimates of subsidence patterns through the Middle Jurassic in western Wyoming (Fig. 10). These curves show a sharp increase in subsidence rates in the middle to late Bathonian. In distal areas to the east, there was a shift from ~100 m of subsidence from 170.3–167.2 Ma (3.2 * 10^-5 m/yr) to 120 m of subsidence in the next ~300,000 years (4.0 * 10^-4 m/yr). In proximal areas to the west, there was a shift from ~200 m of subsidence from 170.3–167.2 Ma (6.5 * 10^-5 m/yr) to 300 m in the next ~300,000 years (0.001 m/yr). The high subsidence rates in the middle to late Bathonian agree with the timing of peak subsidence rates from northern Utah (Bjerrum and Dorsey 1995). The timing of peak subsidence at Thomas Fork is more poorly constrained because it is based on Imlay’s (1967) published column, which is less detailed than those in this study.

The middle to late Bathonian subsidence rates at the western locations (Pine Creek/Leeds Creek and Thomas Fork) were at least ~0.001 m/yr, roughly equal to the maximum rate of carbonate accumulation observed in the Holocene (Schlager 1981). At LaBarge Creek and Cabin Creek to the east, the middle to late Bathonian subsidence rates were lower, but at least .0004 m/yr. It is also important to note that these peak subsidence rates are higher than the average sedimentation rates for subtropical carbonate platforms (Kemp and Sadler 2014), and that because of strong temperature and salinity gradients (Danise and Holland 2017), the Twin Creek Limestone may have had low carbonate accumulation rates even for a subtropical ramp.

While the peak subsidence rates found in this study (0.0004–0.001 m/yr) are high, they are underestimates of the actual peak subsidence rate. These decompacted subsidence curves provide estimates of the magnitude and relative rates of subsidence through time, but there is uncertainty in the absolute rates because of the scarcity of absolute age data from the Twin Creek.
Limestone. Backstripping likely provides minimum subsidence rates because a rate derived from backstripping results necessarily averages rates between the data points. There may well have been brief periods of rapid subsidence in the Middle Jurassic followed by tectonic quiescence, and this backstripping analyses would have averaged across these periods of higher and lower subsidence rates.

**Stratigraphic Expression of Rapid Subsidence**

During the middle to late Bathonian, the emplacement of thrust loads in central Idaho led to rapid subsidence of the ramp on which the Twin Creek Limestone was deposited (Bjerrum and Dorsey 1995). A dip-oriented cross section proximal to the thrust load, like the one presented in this study (Fig. 8), is ideal for investigating the stratigraphic expression of rapid subsidence. This cross section demonstrates that the middle to late Bathonian WC-LC-GC sequence thickens to the west, from 120 m at LaBarge Creek to 300 m at Leeds Creek (Fig. 8). The accommodation rate in the west was therefore nearly three times greater than to the east. The deeper-water facies present during the WC-LC-GC sequence further supports elevated accommodation rates in the west (Fig. 8). The SL-R sequence thickens westward in a manner similar to the WG-LC-GC sequence, but the fact that the sequence is less thick, and that Facies LM is not present in the SL-R sequence demonstrates that the accommodation rates were not as high as during the WC-LC-GC.

In most tropical environments, carbonate accumulation rates can keep pace with normal rates of eustatic sea-level change and subsidence (Schlager 1981; Read et al. 1986; Tipper 1997). During the rapid subsidence in the middle to late Bajocian, shallow-water depositional environments in the lower WC-LC-GC sequence quickly transition to the deeper-water depositional environments, generating retrogradational stacking in the middle and upper WC-
LC-GC sequence. There are likely two reasons that deposition on the Twin Creek ramp was not able to keep up with the subsidence rates. The first is that the Twin Creek Limestone was deposited on a subtropical ramp, so its accumulation rates may have been slower than most tropical ramps (Kemp and Sadler 2014). The second is that because of steep salinity and temperature gradients in the Sundance Seaway (Danise and Holland 2017), depositional rates on the Twin Creek ramp may have been slower because it behaved like a “poisoned platform” (Schlager 1981).

**Correlation to the Bighorn Basin**

Although the sequence stratigraphic architecture of the Middle Jurassic strata in the Bighorn Basin is well defined (Parcell and Williams 2005; McMullen et al. 2014; Clement and Holland 2016), how these sequences correlate into the Twin Creek Limestone has not been understood. Existing biostratigraphic correlation and sequence stratigraphic descriptions of the Middle Jurassic strata in the Bighorn Basin (Imlay 1967; Parcell and Williams 2005; McMullen et al. 2014; Clement and Holland 2016), along with the sequence stratigraphic description of the Twin Creek Limestone presented in this study can be used to correlate the Twin Creek Limestone to the Bighorn Basin (Fig. 3).

Imlay’s (1967) biostratigraphic correlations indicate that the Sliderock and Rich Members are equivalent to the middle member of the Gypsum Spring Formation as defined by Clement and Holland (2016), which means that the underlying Gypsum Spring Member of the Twin Creek Limestone probably correlates to the lower member of the Gypsum Spring Formation in the Bighorn Basin (Fig. 3). Imlay’s biostratigraphic correlations also indicate that the Watton Canyon, Leeds Creek, and Giraffe Creek Members of the Twin Creek Limestone correlate to the Canyon Springs, Stockade Beaver Shale, and Hulett Members of the Sundance
Formation, respectively. This constrains the unfossiliferous Boundary Ridge Member to correlate to the upper member of the Gypsum Spring Formation. The Bighorn Basin contains two sequence boundaries, the J-2a and J-3, which are not present in the Twin Creek Limestone. This is because the downdip location of the Twin Creek Limestone did not experience enough of a relative sea-level fall to record subaerial exposure (Fig. 8).

**Width and Dimensions of the Foreland Basin**

The stratigraphy of the Twin Creek Limestone, and its correlation to the Bighorn Basin, has implications for understanding the mechanisms driving subsidence in the Sundance Seaway. The terms used here to name the components of the basin follow the naming scheme of Allen and Allen (2013). Based on the estimated flexural rigidity ($5 \times 10^{24}$ Nm) of the plate underlying the Sundance Seaway in Utah (Bjerrum and Dorsey 1995), the width of the foreland basin (from directly under the topographic load to the eastern edge of the forebulge) is 405 km (Eq. 3). This width matches the estimated width of the Sundance Seaway in Utah and Canada (Fig. 1). The Sundance Seaway was much wider through Wyoming and Montana, where it extends more than 2000 km east of the topographic load in central Idaho. Achieving this much greater width of the Sundance Seaway across Wyoming and southern Montana solely through load-induced flexural subsidence would necessitate a flexural rigidity of the crust in Wyoming and Montana three orders of magnitude greater than in Utah and Canada, which is unlikely given the observed values of flexural rigidity in sedimentary basins (Turcotte and Schubert 2002), and it would also require a steep flexural rigidity gradient from Utah to Wyoming and from Montana to Canada. A more parsimonious explanation for the width of the Sundance Seaway across Wyoming and Montana is that long wavelength subsidence, such as dynamic topography driven by mantle downwelling (Heine et al. 2008; Peterson et al. 2010), was superimposed on foreland basin
subsidence. A similar mechanism was invoked to explain the widening of the Western Interior Seaway during the Late Cretaceous (Catuneanu et al. 1997).

Based on the deflection profile of the foreland basin, there was approximately 140 m of uplift on the forebulge. However, the presence of marine facies in the Twin Creek Limestone and Bighorn Basin within the WG-LC-GC (J-2, J-2a, and J-3) sequence indicates that there were positive subsidence rates across the foreland basin, including on the forebulge. If the Jurassic deposits on the Ogden Thrust were deposited directly under the thrust load, then the outcrop on the Hogsback Thrust (LaBarge Creek, Twin Creek, and Cabin Creek) would be ~315 km from the thrust load, placing them on the forebulge (Fig. 11). While the thickness of the WG-LC-GC sequence thins from ~600 m in the west to ~120 m in the columns on the Hogsback Thrust, the accommodation rate is positive through the sequence, contradicting the expectation of uplift on the forebulge during flexural subsidence (Nádai 1963). If the Jurassic deposits on the Ogden thrust were deposited 100 km from thrust load, the columns on the Hogsback Thrust would be deposited in the backbulge basin. Subsidence does occur in the backbulge basin, but it is less than 0.2% of the subsidence directly under the load (Turcotte and Schubert 2002), insufficient to account for the thickness of the WG-LC-GC sequence on the Hogsback Thrust. A mechanism other than flexural subsidence must be contributing to the subsidence on the forebulge and backbulge. Long-wavelength subsidence superimposed on flexural subsidence would explain both the westward thickening of the WG-LC-GC sequence and the relatively high subsidence rates on the forebulge and backbulge.

Previous work has suggested that the Middle Jurassic sedimentary sequences (J-1–J-5) were created by the erosion of the flexural bulge that migrated across Wyoming in response to episodic thrusting (Bjerrum and Dorsey 1995). This explanation is unlikely for two reasons.
First, the thrust sheets of the Luning-Fencemaker fold and thrust belt, which created the topographic load associated with the subsidence of the Sundance Seaway, are concentrated in a 100 km wide east-to-west band that runs north to south across central Nevada and Idaho (Bjerrum and Dorsey 1995). Because of the mathematical relationship between the thrust load and the position of the forebulge, the emplacement of these thrust loads would cause the forebulge to migrate within a 100 km band (Nádai 1963), which cannot explain the correlation of a single unconformity across distances greater than this. Second, this study identifies the Middle Jurassic unconformities west of the forebulge, and McMullen et al. (2014) and Clement and Holland (2016) have identified these unconformities up to 530 km east of the thrust sheet, equivalent to the distance from the topographic load to distal edge of the forebulge based on the deflection profile. The uplift of the forebulge could not have caused subaerial exposure across this entire distance. The forebulge uplift on the forebulge is large enough to have a real effect, but it is unclear what that effect was in the Twin Creek Limestone. It is clear that based on the lateral extent of the subaerial unconformities, another mechanism or multiple mechanisms must be driving the formation of depositional sequences. The most likely mechanism driving the formation of Jurassic sequences is eustatic sea level. Estimates of eustatic sea level through the Middle Jurassic suggest that there were sea-level fluctuations in the range of 10–30 m (Miller et al. 2005). Changes in eustatic sea level explain the presence subaerial sequences in the Bighorn Basin, which cannot be recognized in the deeper water deposits of the Twin Creek Limestone, as well as the ability to correlate sequence boundaries across hundreds of kilometers.

Conclusions

1. In the Wyoming Range of southwestern Wyoming, the Jurassic Twin Creek Limestone is divided into four depositional sequences, with sequence boundaries defined by brecciated
limestone, and abrupt basinward shifts in facies. In ascending order, these are the GS, SL-R, BR, and WC-LC-GC, which are equivalent to the J-1, J-1a, J-1b, J-2, J-2a, and J-3 sequences in the Bighorn Basin as described by Parcell and Williams (2006), McMullen et al. (2014), and Clement and Holland (2016). The J-2a and J-3 sequence boundaries of the Bighorn Basin are not expressed in the Twin Creek Limestone and are presumably correlative conformities. The surface of forced regression separating the Leeds Creek and Giraffe Creek Members in the western sections could be the downdip equivalent to the J-3 sequence boundary. This study interprets this contact as a basal surface of forced regression, placing the overlying rocks the falling stage systems tract and making the contact between the Giraffe Creek Member and the Preuss Formation (the Pr sequence boundary) both the J-3 and J-4 sequence boundaries.

2. Emplacement of thrust sheets in central Idaho caused rapid subsidence and drowning of the Twin Creek Ramp in Wyoming and Idaho during the middle to late Bathonian WC-LC-GC sequence. This subsidence was asymmetric with higher rates and total subsidence in the west, which are reflected by westward thickening of the WC-LC-GC sequence. This study shows that subsidence rates associated with load-induced flexural subsidence can be high enough to drown a carbonate platform, particularly if the platform is at subtropical latitude or is environmentally stressed, which would lead to lower carbonate accumulation rates.

3. Load-induced flexural subsidence cannot account for the width of the Sundance Seaway across Wyoming because it would require an unrealistically rigid crust. Based on a flexural rigidity of $5 \times 10^{24}$ Nm (Bjerrum and Dorsey 1995), thrust-load driven flexure could have generated subsidence up to approximately 400 km from the crustal load located in central Idaho (Bjerrum and Dorsey 1995; Blakey 2015). Another factor such as dynamic topography
driven by mantle downwelling is necessary to explain the subsidence observed across eastern Wyoming, Montana, North Dakota, and South Dakota.
CHAPTER 3

CONCLUSION

The Bajocian–Callovian Twin Creek Limestone records four depositional sequences, which are the GS, SL-R, BR, and WC-LC-GC sequences in ascending order. The GS sequence boundary is placed at the contact between the Nugget Sandstone and the overlying Gypsum Spring Member. The GS sequence correlates to the J-1 sequence in the Bighorn Basin (Imlay 1967; Clement and Holland 2016). A combined sequence boundary and flooding surface at the contact between the Gypsum Spring and Sliderock Members marks the SL-R sequence boundary. The Sliderock and Rich Members represent the transgressive systems and highstand systems tract. The SL-R sequence is equivalent to the J-1a sequence in the Bighorn Basin (Imlay 1967; Clement and Holland 2016). The BR sequence boundary is marked by an abrupt basinward shift of facies. The BR sequence lacks vertical facies changes, but based on the well-developed sabkha facies the BR sequence deposits are placed in the highstand systems tract. The BR sequence correlates to the J-1b sequence in the Bighorn Basin (Imlay 1967; Clement and Holland 2016). The WC-LC-GC sequence boundary lies at the contact between the Boundary Ridge and Watton Canyon. The WC-LC-GC sequence contains thick transgressive and highstand systems tracts deposits, and the contact between the Leeds Creek and Giraffe Creek Member in the western sections is a surface of forced regression. The WC-LC-GC is equivalent to the J-2 and J-3 sequences of the Bighorn Basin (Imlay 1967; McMullen et al. 2016), which cannot be recognized as separate units in the Twin Creek Limestone because of its downdip setting. The Pr sequence boundary is the contact between the Giraffe Creek Member and the overlying Preuss
Sandstone and is equivalent to the J-4 sequence boundary in the Bighorn Basin (Imlay 1967; McMullen et al. 2014).

Subsidence generated by thrust-load emplacement caused the WC-LC-GC deposits to be much thicker in the western sections than the eastern columns. While there are thick deposits of Facies LM in the eastern and western locations, generally facies in the western region typically record deeper-water environments, as indicated by the scarcity of storm deposits. The westward thickening and deepening of the WC-LC-GC sequence indicate that the carbonate ramp was not able to keep up with subsidence rates, which led to the drowning of the Twin Creek Limestone.

Based on the mathematical description of the flexural profile, the foreland basin was approximately 400 km wide. With a height of approximately 140 m, the corresponding forebulge would have been a significant feature on the landscape, but there is no stratigraphic evidence of the forebulge, suggesting that there was probably long-wavelength subsidence superimposed on the thrust-driven flexural subsidence. The width of the Sundance Seaway in Wyoming and Montana appears to be controlled by long-wavelength subsidence caused by mantle downwelling superimposed on foreland basin subsidence. Because foreland basin subsidence cannot be responsible for the formation of the regional Jurassic conformities described in eastern Wyoming and Montana, the formation of these unconformities is more likely controlled by fluctuations in eustatic sea level.
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## Tables

Table 1. —Facies Descriptions. Boldface indicates the most characteristic features of each facies.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Sedimentology</th>
<th>Paleontology</th>
<th>Geometry and Contact Relationships</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM, lime mudstone (offshore)</td>
<td><strong>Very thin-bedded gray lime mudstone with mm-scale light brown argillaceous partings</strong></td>
<td>Unfossiliferous</td>
<td>Bedsets are tens of meters thick, and thicken to the south and west. Facies grades vertically into Facies ALM</td>
</tr>
<tr>
<td>ALM, lime mudstone with argillaceous partings (deep subtidal)</td>
<td><strong>Thinly- to very thinly-bedded lime mudstone separated by yellow argillaceous partings.</strong> Hummocky cross stratification and orange dolomitic vortex ripples are common.</td>
<td><strong>Crinoids (Isocrinus), bivalves (Camptonectes), oysters (Liostrea)</strong></td>
<td>Bedsets are ~1–5 m thick. The number of vortex-rippled beds generally increases upward through a bedset. Bedsets are capped by oolitic/skeletal grainstone caps. Facies ALM grades vertically into Facies BLM and Facies OG.</td>
</tr>
<tr>
<td>BLM, bioturbated lime mudstone (shallow subtidal)</td>
<td><strong>Medium- to thickly-bedded highly bioturbated gray lime mudstone.</strong></td>
<td>No body fossils, Local light gray vertical burrows</td>
<td>1–3 m thick. Gradationally underlain by Facies ALM. Grades vertically into either Facies OG or Facies YRM</td>
</tr>
<tr>
<td>OG, ooid grainstone (oolid shoal)</td>
<td><strong>Thickly-bedded oolitic grainstone with large-scale trough cross stratification</strong> and lack of bioturbation. Thin-bedded oolitic packstone and</td>
<td>Unidentifiable shell fragments, probably the scallop Camptonectes</td>
<td>0.5–2 m thick. Grades vertically into Facies BLM and Facies YRM</td>
</tr>
<tr>
<td>Facies</td>
<td>Description</td>
<td>Unfossiliferous</td>
<td>Thickness</td>
</tr>
<tr>
<td>--------</td>
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</tr>
<tr>
<td>YRM, yellow to red mudstone and microbialite (peritidal)</td>
<td>Red to yellow planar laminated and vortex-rippled lime mudstone with microbial laminae. 2D and 3D current ripples, interference ripples.</td>
<td>Lockeia trace fossils</td>
<td>1–5 m thick.</td>
</tr>
<tr>
<td>RM, red mudstone (supratidal mud flat)</td>
<td>Yellow to red mudstone, rare medium-bedded sandstone beds with trough cross lamination.</td>
<td>Unfossiliferous</td>
<td>5–10 m thick</td>
</tr>
<tr>
<td>PRLM, planar-laminated lime mudstone and vortex-rippled lime mudstone (offshore transition)</td>
<td>Very thinly-bedded planar-laminated lime mudstone interbedded with 3D vortex-rippled sandy lime mudstone.</td>
<td>Unfossiliferous</td>
<td>~15 m thick.</td>
</tr>
</tbody>
</table>
Fig. 1.— Paleogeographic reconstruction of western North America during the Bajocian Stage (~170 Ma), based on the paleogeographic reconstruction of Blakey (2015) and modified from Clement and Holland (2015). Box in western Wyoming indicates location of Fig. 2.
Fig. 2.— A) Jurassic outcrop (blue) in Wyoming, Utah, and Idaho as well as the locations of the five measured columns and the Thomas Fork column from Imlay (1967) included in the backstripping analysis. Cross-section A–A’ is indicated. Red: Cabin Creek, blue: LaBarge Creek, green: Twin Creek, orange: Leeds Creek, yellow: Pine Creek, purple: Thomas Fork. B) Lithostratigraphic column showing members of Twin Creek Limestone.
Fig. 3.— Chronostratigraphic chart for the Middle Jurassic of southwestern Wyoming and the Bighorn Basin, modified from Danise and Holland (2017). Biostratigraphy is based on Imlay (1967).
Fig. 4.— Outcrop and thin section photographs of Facies ALM and Facies PRLM. **A)** Outcrop photograph of Facies ALM. Thin-bedded lime mudstone interbedded with thin beds of vortex-rippled dolomitic lime mudstone. **B)** Thin section photograph of a grainstone cap on a deep subtidal bedset. Ec: echinoderms; O: ooids. Photograph was taken at 2x magnification under cross-polarized light.
Fig. 5.— Outcrop and thin-section photographs of Facies OG. A) Outcrop photograph of contacts between Facies OG and Facies BLM at LaBarge Creek. The scale of Facies OG suggests it is not the main ooid body in the area. Jacob staff marked in 10 cm increments. B) Outcrop photograph of Facies ALM grading vertically into Facies OG at Cabin Creek. C) Outcrop photograph of large-scale trough cross-stratification in Facies OG in the Giraffe Creek Member at LaBarge Creek. D) Thin section photograph of Facies OG. E: eggshell diagenesis. Photograph taken at 2x magnification under cross-polarized light.
Fig. 6.— Outcrop and thin section photographs of Facies YRM and RM. A) Outcrop photograph of microbialite in Facies YRM B) Outcrop photograph of wave-ripple lamination in Facies YRM C) Outcrop photograph of thin-bedded yellow mudstone in Facies YRM D) Outcrop photograph of small-scale trough cross-stratification in red sandstone of Facies RM E) Outcrop photograph of repeated cycles of Facies YRM and thin-bedded Facies OG F) Thin section photograph of Facies OG from Fig. 6E. C: chert; O: ooids; and Fe: iron-oxide coating. Photograph taken under 4x magnification and plain light.
Fig. 7.— A) Facies model showing interpreted facies relationships in the Twin Creek Limestone.

B) Schematic cross-section of the Sundance Seaway in southwestern Wyoming with an eastward facing siliciclastic wedge and a westward facing carbonate ramp.
Fig. 8.— Stratigraphic cross section and sequence-stratigraphic interpretation of the five measured columns in the Twin Creek Limestone of southwestern Wyoming. GS: Gypsum Spring Sequence, SR/R: Sliderock and Rich Sequence, BR: Boundary Ridge Sequence, WC/LC: Watton Canyon and Leeds Creek Sequence, TST: transgressive systems tract, HST: highstand systems tract, LST: lowstand systems tract, FSST: falling stage systems tract.
**Fig. 9.**— Outcrop photographs of key sequence stratigraphic intervals. A) Progradational parasequences (flooding surfaces indicated by white lines) near the top of the SL/R sequence and the BR sequence boundary (red line). B) Thick, monotonous Facies LM deposits from the transgressive systems tract of the LC/GC sequence (flooding surfaces indicated by white lines). A two-lane dirt road in upper left corner for scale. C) Surface of forced regression (indicated by white line) separating the transgressive systems tract from the falling stage systems tract of the LC/GC sequence at the Leeds Creek section. 1.5 m Jacob staff marked in 10 cm increments.
Fig. 10.— Decompacted subsidence curves for four stratigraphic sections in southwestern Wyoming showing increase in subsidence rate beginning in the middle to late Bathonian. The nearby Leeds Creek and Pine Creek sections were combined into a complete section, and the Thomas Fork section measured by Imlay (1967) was added to provide data from the westernmost thrust sheet. Black dots represent ages known with confidence, points without dots have greater uncertainty in their age.
[Diagram: Graph showing the relationship between horizontal distance (km) and deflection (km). The x-axis represents horizontal distance ranging from 0 to 500 km, while the y-axis represents deflection ranging from 0 to 5 km. Markers labeled 'Cra', 'Abs', and 'Hog' are indicated at specific points along the graph.]
Fig. 11.— Deflection profile of the Twin Creek Limestone based on a flexural rigidity of $5 \times 10^{24}$ Nm and a maximum deflection of 6 km. Estimated positions, with uncertainty, of the Crawford (Cra), Absaroka (Abs), and Hogsback (Hog) based on a palinspastic restoration of the Wyoming Range (DeCelles 1994).
Appendix A: Coordinates of measured columns

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<tr>
<th>Locality</th>
<th>Longitude</th>
<th>Latitude</th>
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<tbody>
<tr>
<td>Cabin Creek</td>
<td>-110.785</td>
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<td>LaBarge Creek</td>
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<td>Twin Creek</td>
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<td>Pine Creek</td>
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<td>Leeds Creek</td>
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<td>Thomas Fork Canyon</td>
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<td>42.403</td>
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</table>
Appendix B: Measured Columns
**Key for Stratigraphic Sections**

**Carbonate Ramp Facies Association**
- RM: Mud flat
- YRM: Peritidal flat
- OG: Ooid shoal
- BLM: Shallow Subtidal
- ALM: Deep Subtidal
- LM: Offshore
- Belemnite
- Bivalve
- Gastropod
- Crinoid
- *Gryphaea*
- *Camptonectes*
- Lithoclast
- Ooid
- Gypsum nodules
- Concretion
- Ripple lamination
- Trough cross-stratification
- Planar lamination
- HCS
- Vortex ripples
- Wavy lamination
- Breccia
- Stromatolitic microbial lamination
- Silicified anhydrite nodules
- Bioturbation

**Wave-dominated Shelf Facies Association**
- PRLM: Offshore transition