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Sevier orogenesis and nonmarine basin filling: Implications of new stratigraphic correlations of Lower Cretaceous strata throughout Wyoming, USA

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Notes

Sevier orogenesis and nonmarine basin filling: Implications of new stratigraphic correlations of Lower Cretaceous strata throughout Wyoming, USA

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ABSTRACT

Lower Cretaceous nonmarine rocks throughout Wyoming have been used to date movements on major thrusts during the Sevier orogeny, evaluate the sedimentary response in the adjacent foreland basin, reconstruct subsidence histories, evaluate the driving mechanisms of that subsidence, and have been applied to basin modeling studies. However, detailed correlation and dating of these strata have been problematic for a century, making most detailed interpretations equivocal. New age data and correlations presented here have important implications for the evolution of the Sevier orogen and controls on basin filling.

Lower Cretaceous strata in Wyoming show the former existence of a foreland basin fill that displays a thick foredeep depozone to the west (the Gannett Group), a thin forebulge depozone throughout central Wyoming (the Cloverly Formation), and thickening into a backbulge depozone in the Black Hills area to the east (the Lakota Formation). Basin subsidence is attributable not only to orogenic loading, but to dynamic loading as well.

New data and correlations indicate that a thrust load was in place during the Neocomian (attributable to movement on the Paris-Willard thrust system) and that sediment supply was high (as represented by the upper Ephraim Formation). Subsequent deposition of the Peterson Limestone in the foredeep during the latest Neocomian and Aptian, and the development of a regional unconformity elsewhere, indicate a reduction in sediment supply that may have been caused by (1) a change to a drier climate, possibly related to progressive mountain-belt uplift and development or intensification of an orographic rain shadow, or (2) a decrease in mountain-belt uplift rate and a reduction in mountain-belt relief. Unconformity development on the forebulge is consistent with the first scenario. Subsequent deposition of the Bechler, upper Cloverly, and upper Lakota Formations during the Early to Middle Albian indicates increased sediment supply, progressive unroofing of the mountain belt, and movement on the Meade-Laketown-Paris-Willard thrust system. These events suggest renewed or accelerated mountain-belt uplift during the early to middle Albian. The Draney Limestone, which overlies the Bechler, correlates with an unconformity at the top of the Cloverly and Lakota Formations and is Albian in age. The Draney Limestone and the unconformity signify a return to conditions similar to those that existed during deposition of the Peterson Limestone. The results presented here differ from those of some researchers who contend that a foredeep did not exist during initial deposition of these strata, and that deposition was not coincident with thrusting during early stages of the Sevier orogeny.

Keywords: Gannett, Cloverly, Lakota, Sevier orogeny, Lower Cretaceous.

INTRODUCTION

The Sevier orogenic belt developed in association with an Andean-type plate boundary located at the western edge of North America. Sediment that eroded from the Sevier mountains accumulated in an adjacent retroarc foreland basin. The resultant cordillera is one of the most extensively studied in the world and has been the basis of many concepts of orogen development, thrust belt mechanics, basin filling, and their interrelationships (Jordan, 1981; Wiltschko and Dorr, 1983; DeCelles et al., 1995; Burgess and Moresi, 1999; White et al., 2002; DeCelles, 2004).

Lower Cretaceous rocks throughout Wyoming record nonmarine deposition in the Cordilleran foreland basin during the early stages of the Sevier orogeny. Detailed correlation and dating of these strata have been problematic for a century (Darton, 1904; Stokes, 1944; Moberly, 1960; Eyer, 1969; May et al., 1995; Way et al., 1998). Correlations have been hampered primarily because of disparities between different methods of correlation and dating (see review in Way, 1997). This is unfortunate because these strata and their correlatives have been used to date movements on major thrusts in the mountain belt, evaluate the associated sedimentary response in the basin, reconstruct subsidence histories, and evaluate the driving mechanisms of that subsidence (Armstrong and Oriel, 1965; Jordan, 1981; Wiltschko and Dorr, 1983; Heller et al., 1986; DeCelles et al., 1993; DeCelles and Currie, 1996; Currie, 2002; DeCelles, 2004; also see discussion in Lageson and Schmitt, 1994). Many of the resultant concepts have been applied to basin modeling studies (e.g., Jordan, 1981; Jordan and Flemings, 1991; Johnson and Beaumont, 1995). Additionally, some researchers have contended that a foredeep did not exist during initial deposition of these strata, and that deposition was not coincident with thrusting during early stages of the Sevier orogeny (Heller and Paola, 1989; Heller et al., 2003). The purpose of this paper is to reconcile the apparent disparities between the different methods of correlation, present new stratigraphic correlations and refined ages of strata, and discuss the implications of these correlations as they relate to the evolution of the Sevier orogen and its associated foreland basin.

STRATIGRAPHY

Lower Cretaceous strata in Wyoming are represented by the Gannett Group in the thrust belt to the west, the Cloverly Formation in central Wyoming, and by the Lakota Formation in the

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Black Hills to the east (Figs. 1 and 2). Previous correlations have relied primarily upon lithostratigraphy and biostratigraphy, and the main disparities are between these two methods. Additionally, different biostratigraphic methods yield different correlations depending upon the type of fossil used. The following discussion focuses on reconciling these differences, as well as on explaining apparent disparities in fission-track ages and magnetostratigraphy. The strata discussed herein have been adequately described in detail elsewhere. The following discussion is intended to give brief background information and to address those characteristics pertinent to this study.

Lithostratigraphy

Cloverly Formation

The Cloverly Formation is typically 20–80 m thick and has been informally subdivided by earlier workers into three lithostratigraphic intervals, designated A, B, and C (Fig. 2; Meyers et al., 1992; May et al., 1995). This nomenclature is adopted herein; however, some redefinition of interval boundaries is in order. The lower A interval corresponds to the Pryor Conglomerate Member of other workers (e.g., Moberly, 1960; Kvale and Vondra, 1993), and locally to some basal conglomerates of the Little Sheep Mudstone Member that more properly should be assigned to the Pryor Conglomerate Member. The A interval is characterized by fluvial chert-bearing conglomerates, conglomeratic sandstones, and quartz arenites. The coarse-grained population consisting of granules and pebbles is dominated by phosphatic gray and black chert (Moberly, 1960; Ostrom, 1970; Meyers et al., 1992). The sand-size population is dominantly quartz, with quartz ranging from 46%–97% (mean of 82%; Hooper, 1962a; DeCelles and Burden, 1992). Chert constitutes 0.7%–53% (mean of 5%–30%) of the sand-size population in conglomerates and sandstones. Chert grains include spicular (most common), black (phosphatic), and chalcedonic varieties (Hooper, 1962a; Furer, 1970; DeCelles and Burden, 1992). Gray chert and black chert typically constitute less than 10% of the sand-size population (Moberly, 1960; Hooper, 1962a; Meyers et al., 1992). Hence, gray chert and black chert dominate the granule and pebble population, whereas they are typically a minor component of the sand-size population. Paleocurrent indicators in the A interval are dominantly to the northeast (MacKenzie and Ryan, 1962; Meyers et al., 1992).

The base of the A interval, and the contact with the underlying Morrison Formation, is typically the base of a chert-bearing conglomerate or conglomeratic sandstone, as discussed in the previous paragraph. Locally, however, the base of the A interval is a mudstone of a few meters thick. The mudstone is typically gray, black, purplish-gray, or dark green, locally carbonaceous and laminated (Moberly, 1960; DeCelles and Burden, 1992; Elliott, 2002). The organic-rich mudstones have been interpreted as oxbow lake, abandoned channel, and floodplain deposits (Elliott, 2002). In east-central Wyoming (e.g., Alcova and Arminto areas), previous workers have included a thicker section of mudstone below the conglomerate in the Cloverly Formation (DeCelles and Burden, 1992; Meyers et al., 1992; May et al., 1995). However, as will be discussed later, much of that mudstone is likely Morrison Formation. The practice of assigning a thick lower mudstone interval to the Cloverly Formation gave the chert-bearing conglomerate the appearance of being higher in the section. Hence, the conglomerate was considered part of the C interval, which gave the appearance that Cloverly conglomerates progressively stepped upsection from west-central to east-central Wyoming. However, data to be presented later indicate that the chert-bearing conglomerates in east-central Wyoming belong to the A interval. Hence, Cloverly conglomerates do not progressively step upsection to the east. A-interval conglomerates and sandstones are typically overlain by several meters of A-interval mudstones that are various shades of brown or gray and locally carbonaceous, or by B-interval mudstones.

The middle Cloverly B interval is characterized by fluvial sandstones and conglomerates that are compositionally distinct from those of the A interval. The B interval corresponds to the lower part of the Little Sheep Mudstone Member of other workers (e.g., Moberly, 1960; Kvale and Vondra, 1993). Pebbles and cobbles in B-interval sandstones and conglomerates are dominantly intraformational limestone and mudstone, and extraformational pink and white quartzite, chert, silicified limestone (some with body fossils), crystalline quartz, chert conglomerate (some containing both black and red chert, others with black chert but lacking red chert), and some unidentified lithologies (May, 1992; Wiesemann and Suttner, 1999; Wiesemann, 2001). All extraformational pebble and cobble lithologies can be matched with rocks in the thrust belt to the west (Zaleha and Wiesemann, 2005). Most of these lithologies are not found in the A interval. Most chert is light-colored, including gray and red. Dark-colored chert, common in A-interval conglomerates and sandstones, constitutes less than 10% of B-interval sandstones and conglomerates (Meyers et al.,

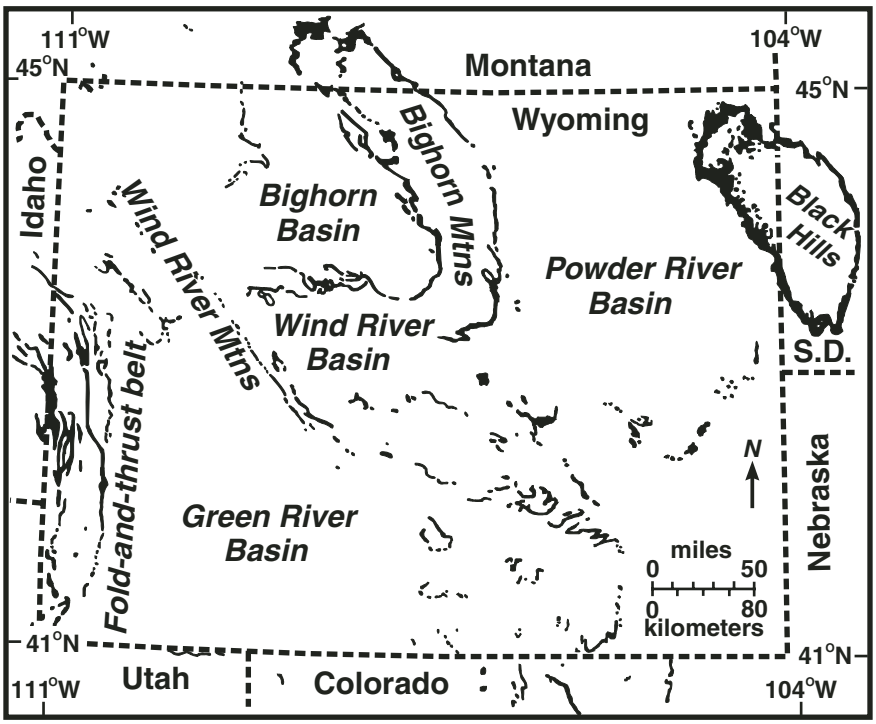

Figure 1. Regional outcrop map of Lower Cretaceous rocks in Wyoming, USA. S.D. is South Dakota.

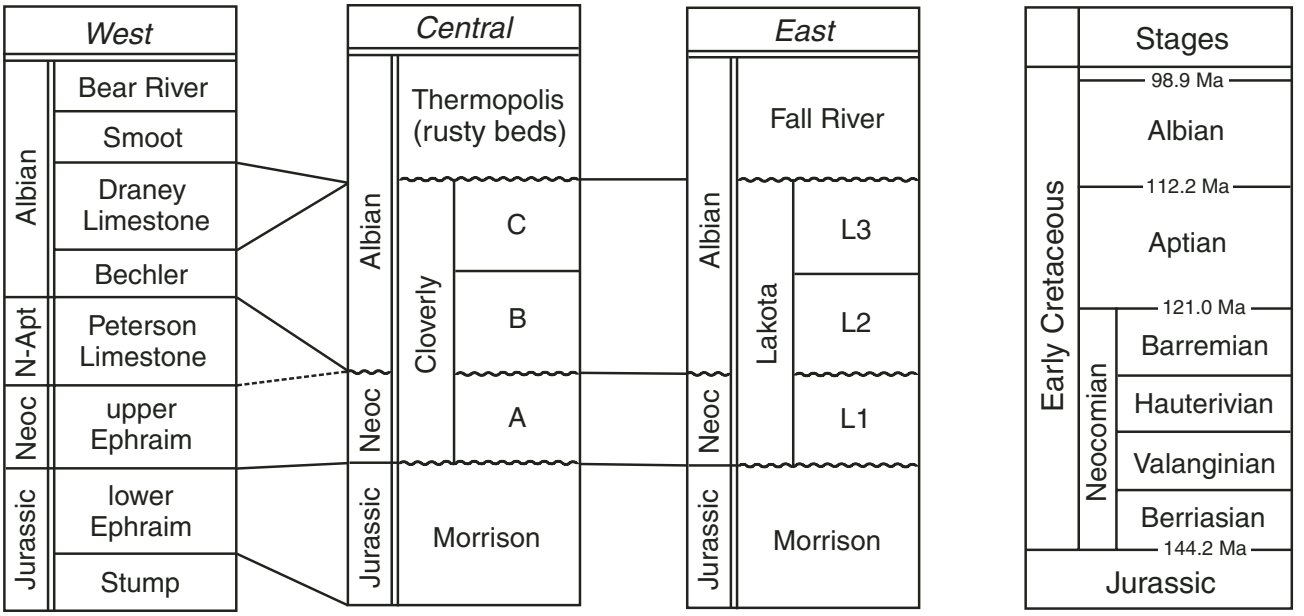

Figure 2. Stratigraphy of Lower Cretaceous rocks in western, central, and eastern Wyoming, and the Early Cretaceous part of the geologic time scale (after Gradstein et al., 1995). The correlations are based on the data presented in this paper. N—Neocomian.

1992). Paleocurrent indicators in the B interval are dominantly to the northeast (MacKenzie and Ryan, 1962; Meyers et al., 1992).

B-interval mudstones typically overlie B-interval sandstones and conglomerates. The mudstones are typically various shades of brown, orange, red, and gray. They have been interpreted as lacustrine and floodplain deposits, and paleosols. Clay minerals include smectite, illite, and kaolinite, and largely reflect depositional and/or pedogenic environments (Elliott et al., 2000; Elliott, 2002). However, the large amount of smectite in some mudstones is indicative of altered volcanic ash (Elliott, 2002). Locally, bioturbated limestones of lacustrine and pedogenic origin are interbedded with the mudstones (Meyers et al., 1992; Elliott et al., 2000; Elliott, 2002).

The upper Cloverly C interval primarily consists of mudstones, diamictites, and wackes (Elliott, 2002; Elliott et al., 2000, 2002; Zaleha and Wiesemann, 2005). The mudstones are characteristically bright shades of purple, orange, red, brown, and gray. In the Bighorn Basin, the C interval roughly corresponds to the upper part of the Little Sheep Mudstone and the lower Himes Members of the Cloverly Formation (Moberly, 1960). Elsewhere, the C interval has been informally referred to as the lilac beds because of prominent purple mudstones and bright coloration (Love, 1948). Many mudstones of the C interval exhibit planar lamination and wave-ripple cross-lamination, and have been interpreted as lacustrine and playa deposits (Elliott, 2002; Elliott et al., 2002). Other mudstones exhibit features indicative of pedogenesis (e.g., root and burrow traces, ped structure, slickensides, and clay cutans) and are interpreted as paleosols (Elliott, 2002).

Diamictites and wackes of the C interval are widespread, quite distinctive, and can be used for stratigraphic correlation throughout the Wind River, Bighorn, and western Powder River basins. A thorough discussion of these deposits is presented by Zaleha and Wiesemann (2005). The diamictites and wackes are typically gray, but may be green locally (the "green beds" of May et al., 1995, and DeCelles and Burden, 1992), because of diagenesis (Elliott, 2002). However, the green coloration should not be used as the basis for identification and correlation, because diagenetically green beds also exist below A-interval conglomerates (misidentified as C-interval conglomerates by May et al., 1995, and DeCelles and Burden, 1992). Rather, the suite of features as described by Zaleha and Wiesemann (2005) must be used. The diamictites and wackes were deposited by rivers laden with volcaniclastic sediment, or hyperconcentrated flows (Zaleha and Wiesemann, 2005). However, the presence of altered volcanic ash alone, as revealed by clay mineralogy, is unreliable for correlation in Wyoming because clay mineralogy is, in large part, controlled by paleoenvironment, and volcanic ash was apparently deposited in Wyoming throughout the Early Cretaceous (Tabbutt and Barreiro, 1990; Elliott et al., 2000; Elliott, 2002). Polished extraformational pebbles and cobbles associated with the diamictites and wackes, long regarded as dinosaur gastroliths, are simply clasts transported by the hyperconcentrated flows. Clast lithologies can be correlated to rocks that were exposed in the mountain belt to the west, and are identical to those in the B interval. Provenance of the clasts is consistent with Early Cretaceous movement on the Meade-Laketown-Paris-Willard thrust system (Zaleha and Wiesemann, 2005).

Lakota Formation

The Lakota Formation is typically 15–140 m thick and has been informally subdivided into three lithostratigraphic intervals, designated L1, L2, and L3 (Fig. 2; Way et al., 1998). The lower L1 interval is dominantly mudstone (~80%) and corresponds to the Chilson Member of other workers (Post and Bell, 1961; Gott et al., 1974; Dahlstrom and Fox, 1995). Mudstones are typically gray to dark gray, carbonaceous, laminated, and noncalcareous. Coals less than 2 m thick are present locally (Waage, 1959; Mapel and Pillmore, 1963; Gott et al., 1974; Way et al., 1998). Fluvial sandstones of the L1 interval are typically very fine- to medium-grained quartz arenites with less than 10% dark chert (Gott et al., 1974; Way, 1997; Way et al., 1998). Paleoflow during L1 deposition was dominantly to the north and northeast (Rankin, 1997; Way et al., 1998; Zaleha et al., 2001). The L1 interval is absent in some areas of the northwestern Black Hills, such as southwestern Crook County (e.g., Inyan Kara Creek area; Way et al., 1998). The

L1 interval is typically thickest in the southern Black Hills.

The Minnewaste Limestone is a lacustrine limestone that is restricted to the southern Black Hills, and it marks the top of the L1 interval there (Rankin [1997] mistakenly placed the Minnewaste in the L2 interval). Where thickest (24 m), the Minnewaste is nearly pure limestone. As the limestone thins toward its margins, it grades into sandy limestone and eventually to calcareous sandstone. Thicknesses of 3–6 m are most typical (Gott et al., 1974).

The middle L2 interval corresponds to the lower part of the Fuson Member of other workers (Post and Bell, 1961; Gott et al., 1974; Dahlstrom and Fox, 1995). The L2 interval is dominated by fine- to medium-grained fluvial sandstones and conglomerates, and, in some places, this interval contains no mudstone. However, in some areas of the southern Black Hills, the L2 is dominantly mudstone (Rankin, 1997). Sandstones are typically cherty litharenites to quartz arenites (Gott et al., 1974; Way et al., 1998). Compositions of extraformational sand grains, pebbles, and cobbles are very similar to those of the Cloverly B and C intervals and include white, black, red, and pink chert; pink quartzite; silicified limestone with crinoids and fusulinids; sandstone; conglomerate (some containing both black and red chert, others with black chert but lacking red chert); and mudstone (Waage, 1959; O'Malley, 1994; Way et al., 1998). Black chert tends to be most abundant as granules and pebbles in conglomerates (Waage, 1959). Many sandstones contain less than 10% black chert (O'Malley, 1994; Rankin, 1997). Additionally, L2 sandstones apparently contain more volcanically derived components than L1 sandstones. Paleoflow was dominantly to the north and northeast (O'Malley, 1994; Rankin, 1997; Way et al., 1998).

Mudstones are a minor constituent of the L2 interval and are absent locally. They are typically various shades of gray or mottled red, pink, and yellow (Post and Bell, 1961; Gott et al., 1974; Way et al., 1998). Some L2 mudstones are calcareous or carbonaceous (Post and Bell, 1961). In places, the top of the L2 interval is marked by a silicified paleosol that exhibits carbonaceous root traces (Way et al., 1998).

Locally, the L1-L2 contact is an angular unconformity, with lower L1 strata dipping 50° to 90° below nearly horizontal L2 strata (Izett et al., 1961; Bolyard and McGregor, 1966; Way et al., 1998; Zaleha et al., 2001; note that Bolyard and McGregor misidentified this unconformity as the Morrison-Cloverly contact). The unconformity represents faulting and folding prior to and coincident with L2 deposition (Way et al., 1998; Zaleha et al., 2001). Elsewhere, the unconformity is not angular, but marked by missing strata. For example, in some areas, the L2 interval directly overlies the Jurassic Morrison Formation or the upper part of the Redwater Shale Member of the Sundance Formation (which underlies the Morrison; Waage, 1959; Izett et al., 1961; Gott et al., 1974). The absence of L1 strata throughout much of the northern Black Hills is likely because of truncation by the unconformity. In other areas, where L1 and L2 strata are present and the contact is not angular, the contact is difficult to recognize as a major unconformity.

The upper L3 interval corresponds to the upper part of the Fuson Member of other workers (Post and Bell, 1961; Gott et al., 1974; Dahlstrom and Fox, 1995). The L3 interval consists of sandstones and mudstones. In many places, particularly throughout much of the northern Black Hills, the lower part of the L3 interval is dominated by conglomeratic sandstones of fluvial origin (O'Malley, 1994). Paleoflow during L3 deposition was dominantly to the north and northwest (Gott et al., 1974; O'Malley, 1994; Way et al., 1998). L3 sandstones are quartz-rich, but do contain chert (including black chert) and other lithic grains (O'Malley, 1994; Way et al., 1998). Locally, these sandstones contain extraformational pebbles and cobbles, the compositions of which are comparable to those of the L2 interval and the Cloverly B and C intervals, and include black, red, and pink chert; white and pink quartzite; silicified limestone; pink, quartz sandstone; pink and red sandstone and conglomerate; and mudstone (O'Malley, 1994; Way et al., 1998). Many of these clasts were derived from the thrust belt to the west. However, some of the pink and red sandstones and quartzites are markedly similar to the Cambrian Deadwood Formation and the Proterozoic Sioux Quartzite, and likely were derived from the Transcontinental Arch in eastern South Dakota. There, rocks equivalent in age to the Lakota Formation overlie the Deadwood Formation and the Sioux Quartzite. Such an eastern source is consistent with paleoflow of many of the channels to the northwest. Both eastern and western sources also are consistent with the finding of Gott et al. (1974).

Sandstones in the upper L3 interval are fine- to coarse-grained and quartz-rich. They are typically interbedded with carbonaceous mudstones, and locally exhibit abundant *Arenicolites* burrow traces (O'Malley, 1994; Way et al., 1998). Other trace fossils are conspicuously absent. Hence, the upper portion of the L3 interval appears to represent transitional marine environments or tidally influenced fluvial channels. In the southern Black Hills, there is evidence that at least some of these channels occupied incised valleys (Gott et al., 1974; Dahlstrom and Fox, 1995).

Mudstones of the L3 interval are typically dusky red, orange, light to dark gray, and locally carbonaceous (Gott et al., 1974; O'Malley, 1994; Way et al., 1998). In some areas of the southern Black Hills, the L3 interval is dominated by a succession of mudstones commonly referred to as the "variegated mudstones" (Rankin [1997] mistakenly placed these strata in the L2 interval). Locally, the L2-L3 contact is marked by an L2 sandstone overlain by the variegated mudstones. Elsewhere, the contact exists within a succession of mudstones. The variegated mudstones are typically gray, dusky red, and green, and generally lack carbonaceous material (Gott et al., 1974; Dahlstrom and Fox, 1995). Relatively thin limestones are interbedded locally. Most of the variegated mudstones are likely of floodplain and lacustrine origin (Gott et al., 1974; Dahlstrom and Fox, 1995). In places, a white, generally structureless silty sandstone is present within the variegated mudstones. Locally, this sandstone contains extraformational pebbles and cobbles (Dahlstrom and Fox, 1995). Throughout much of the Black Hills, and especially where the variegated mudstones are present, some L3 mudstones contain polished extraformational pebbles and cobbles similar to those in L2 and L3 sandstones and conglomerates (Waage, 1959; Post and Bell, 1961; Mapel and Pillmore, 1963; Gott et al., 1974; Way et al., 1998).

Gannet Group

The part of the Gannett Group of concern here consists of four formations: the Ephraim, the Peterson Limestone, the Bechler, and the Draney Limestone (Fig. 2). The Ephraim Formation is divisible into two informal intervals referred to as the lower and upper Ephraim. The lower Ephraim is typically a few tens of meters thick. Researchers generally agree that it is Jurassic and correlative to the Morrison Formation (Eyer, 1969; Furer, 1970; Heller et al., 1986). Hence, the lower Ephraim is not of primary concern here.

The upper Ephraim is a siliciclastic nonmarine unit that is dominantly red, brown, and gray mudstones of floodplain, pedogenic, and lacustrine origin (Eyer, 1969). DeCelles et al. (1993) have shown convincingly that much of the Ephraim type section at Red Mountain (easternmost Idaho), which is dominated by pebble to boulder conglomerate, is actually part of the Bechler Formation. Nodular carbonates are typically interbedded with the mudstones and are likely of pedogenic and lacustrine origin. Fluvial channel deposits are represented by lenticular and tabular sandstones and conglomerates. These deposits are typically meters thick, but some are greater than 10 m thick (Eyer, 1969; DeCelles et al., 1993). Paleoflow was to

the east, northeast, and north (Derman et al., 1984; Heller and Paola, 1989; DeCelles et al., 1993, citing Sippel, 1982). Compositionally, the Ephraim conglomerates are dominated by chert. The presence or absence of red chert could be significant because of its limited stratigraphic range in both the Cloverly and Lakota Formations. However, some Ephraim conglomerates are dominated by gray and black chert, and lack red chert (Armstrong and Cressman, 1963; Middleton and Ore, 1976; this study), whereas red chert is apparently common in others (DeCelles et al., 1993). It is unclear whether this variation reflects rivers with different source areas, or a stratigraphic variation reflecting a change in sediment provenance through time. Total thickness of the Ephraim is quite variable, but is generally 100–300 m.

The Peterson Limestone consists of limestones interbedded with gray and red calcareous mudstones (Eyer, 1969; Drummond et al., 1996). Abundant charophytes and ostracods, and sparse pelecypods indicate a lacustrine origin. The Peterson Limestone is typically meters to more than 75 m thick (Eyer, 1969; Drummond et al., 1996).

The general character and paleoenvironments of the Bechler Formation are nearly identical to the upper Ephraim, and the two are not easily distinguished where the Peterson Limestone is absent. However, red chert is apparently more common and can be found in most Bechler conglomerates. The amount of sandstone and conglomerate varies greatly, and some sections lack coarse clastics (Eyer, 1969; Furer, 1970). In contrast, the Bechler at Red Mountain contains numerous pebble to boulder conglomerates of alluvial fan origin (DeCelles et al., 1993). The contact between the Ephraim and Bechler at Red Mountain (the Peterson is covered and may be absent) is an angular unconformity, and intraformational angular unconformities also exist within the Bechler (DeCelles et al., 1993). Paleoflow during Bechler deposition was to the east, northeast, and north (Derman et al., 1984; Heller and Paola, 1989; DeCelles et al., 1993). The thickness of the Bechler is highly variable, but is generally on the order of 100–500 m (Eyer, 1969).

The Draney Limestone consists of limestones and gray calcareous mudstones that are very similar to those of the Peterson Limestone. Abundant charophytes and ostracods, and sparse pelecypods indicate a lacustrine origin. The Draney Limestone is typically on the order of 40–120 m thick (Eyer, 1969).

Lithostratigraphic Correlations

Lithostratigraphic correlations of Cloverly and Lakota subdivisions are fairly straightforward. The Cloverly A interval correlates with the Lakota L1 interval. Both overlie the Morrison Formation and underlie the first strata with compositionally diverse extraformational pebbles and cobbles. Additionally, mudstones of both intervals are typically carbonaceous. The Cloverly B interval correlates with the Lakota L2 interval. Both are characterized by the presence of extraformational pebbles and cobbles of distinctive lithologies, and sandstones typically contain less than 10% dark chert. Mudstones tend to contain less plant material than those of the A and L1 intervals, calcareous nodules are common, and colors are more reddish. The Cloverly C interval correlates with the Lakota L3 interval. Of most significance is the presence of extraformational pebbles and cobbles in diamictites and wackes of the C interval, and the existence of similar pebbles and cobbles in L3 mudstones. Additionally, the general characteristics of many L3 mudstone sequences, particularly the variegated mudstones in the southern Black Hills, are similar to those of the C interval. Lastly, both intervals are overlain by marine transgressive deposits of the Cretaceous Seaway.

Lithostratigraphic correlation of the Gannet Group to the Cloverly Formation is more complicated. Both the upper Ephraim and Cloverly A interval overlie the Morrison or correlative strata. Compositionally, the upper Ephraim conglomerates that are rich in gray and black chert, and lack red chert, are similar to conglomerates of the A interval, whereas those that contain red chert are not. This may indicate that some Ephraim rivers were connected to Cloverly rivers, whereas others were not. Many of the conglomeratic clasts within the Bechler and Cloverly B interval are markedly similar to conglomerates and conglomeratic sandstones of the upper Ephraim. The angular unconformity between the Ephraim and Bechler at Red Mountain attests to reworking of the Ephraim. Further, the angular unconformities at Red Mountain and those between L1 and L2 strata in the Black Hills indicate episodes of intrabasinal deformation that are apparently coeval. Additionally, clast compositions of the Bechler and Cloverly B interval are markedly similar (DeCelles et al., 1993; Zaleha and Wiesemann, 2005). Hence, the upper Ephraim correlates with the Cloverly A and Lakota L1 intervals, and the Bechler correlates with strata comprising both the Cloverly B and C intervals, and the Lakota L2 and L3 intervals. At present, it is not possible to further subdivide the Bechler Formation. Strict lithostratigraphic correlation of the Peterson and Draney Limestones to Cloverly and Lakota strata is not possible. However, clasts of Peterson Limestone within the Bechler at Red Mountain indicate that the Peterson Limestone is more closely affiliated with the upper Ephraim than with the Bechler Formation.

Biostratigraphy

Many problems in correlating Lower Cretaceous rocks throughout Wyoming have been caused by contradictory results from different methods of biostratigraphic correlation. Further, many of the results appeared at odds with some of the fairly straightforward lithostratigraphic correlations. The following discussion presents previously unreported palynological ages and reconciles the apparent disparities among the various biostratigraphic methods.

Palynology

Palynological methods, sample locations, and results are presented in the GSA Data Repository.[1] Results from some other studies also are presented. Palynology indicates that the Cloverly A interval is Neocomian, and that A-interval sandstones and conglomerates overlie either A-interval Neocomian mudstones or mudstones of the Jurassic Morrison Formation (GSA Data Repository [see footnote 1]; DeCelles and Burden, 1992). Palynomorphs from a single sample of the lowermost B interval near Manderson, Wyoming (east-central Bighorn Basin), are Albian (Furer et al., 1997). Palynomorphs from the L2 interval (four samples) and Fall River Formation (two samples) are also Albian (GSA Data Repository [see footnote 1]; O'Malley, 1994; Way, 1997). The Peterson Limestone has yielded a palynological age of Neocomian (DeCelles et al., 1993).

Charophytes

Much of the work using charophyte ages and assemblages to correlate the Cloverly and Lakota Formations and the Gannett Group was done by Peck (1938, 1941, 1957) and Peck and Craig (1962). Unfortunately, subsequent studies have relied heavily on these ages (e.g., Eyer, 1969; Heller et al., 1986; Heller et al., 2003). Of primary importance are *Atopochara trivolvis* and *Flabelochara harrisi*. These species were once thought to be restricted to the Aptian, but are now known to range from Neocomian through Albian (Grambast, 1974; Martin-Closas, 1996; Hardenbol et al., 1998). Hence, charophytes are not useful for the level of resolution required here.

[1]GSA Data Repository item 2006143, palynological age determinations, is available on the Web at http://www.geosociety.org/pubs/ft2006.htm. Requests may also be sent to editing@geosociety.org.

Ostracods

Most ostracods or ostracod assemblages from Wyoming do not provide the resolution necessary to subdivide the Lower Cretaceous, or are of such limited extent as to be restricted to a single formation (Peck, 1941; Peck and Craig, 1962). However, Sohn (1979) concluded that assemblages in the Lakota Formation were Neocomian. Subsequent researchers who relied on this work considered the entire Lakota to be Neocomian. However, most workers failed to recognize that all of Sohn's samples were from the Chilson Member and the Minnewaste Limestone, both correlative to the L1 interval. Similar oversights by numerous researchers, both early and contemporary, to recognize various subdivisions of these Lower Cretaceous rocks, and to carefully report the stratigraphic positions of samples, have contributed greatly to the apparent disparities in various methods of biostratigraphic correlation.

Pelecypods

Nonmarine pelecypods occur in Lower Cretaceous rocks throughout Wyoming (Cobban and Reeside, 1952; Waage, 1959; Katich, 1962). The only species of significance here is *Unio douglassi*, first described by Stanton (1903) from rocks in Montana, and later referred to as *Protelliptio douglassi* (Cobban and Reeside, 1952; Waage, 1959; Young, 1960; Katich, 1962). *Protelliptio douglassi* was thought to be restricted to the interval of the Peterson through Draney Limestones (Cobban and Reeside, 1952; Katich, 1962). Because of the previous work of Peck (1938, 1941) on charophytes and ostracods, and his belief that most of the Lower Cretaceous rocks throughout Wyoming were Aptian, *Protelliptio douglassi* was thought to be restricted to the Aptian. However, *Protelliptio douglassi* also occurs in the basal Fall River Formation, which is generally considered to be Albian (Dahlstrom and Fox, 1995). Palynological ages presented in the GSA Data Repository (see footnote 1) and in Way (1997) support the Albian age of the Fall River Formation. Additionally, *Protelliptio douglassi* has been reported 6 m below the top of the upper Cedar Mountain Formation in Colorado (Young, 1960). Currie (2002) cited Cifelli et al. (1997) as reporting a $^{40}Ar/^{39}Ar$ age of 98.39 ± 0.07 (Late Albian–Cenomanian) for bentonites 15 m below the top of the Cedar Mountain Formation in the San Rafael Swell. Hence, *Protelliptio douglassi* is not useful for the level of resolution required here, particularly considering the Neocomian palynological age of the Peterson Limestone (DeCelles et al., 1993).

Biostratigraphic Correlations

Palynology appears most reliable for biostratigraphic correlation and provides results consistent with the lithostratigraphic correlations presented here previously. Additionally, the ostracod results of Sohn (1979) that indicate a Neocomian age for the Lakota L1 interval are consistent with the palynological ages. Ostracod assemblages from other areas, charophytes, and pelecypods do not provide the resolution required in this study.

Fission-Track Ages

Two studies have attempted to date the Cloverly Formation using zircon fission-track ages (Heady, 1992; Chen and Lubin, 1997). Unfortunately, all of the dates except one had errors ranging from 9 to 28 million years. Considering the stratigraphic position and error associated with each sample, none provide the temporal resolution necessary here. The one possible exception is a 93 ± 8 Ma age (85–101 Ma, or Albian–Late Cretaceous) for the uppermost Cloverly (Chen and Lubin, 1997). However, Chen and Lubin suggested that this sample may have been partially annealed. This suspicion is apparently confirmed by a 104.4 ± 0.5 Ma $^{40}Ar/^{39}Ar$ age for a bentonite within the basal Skull Creek Shale, which overlies the Fall River Formation in the Black Hills (Cobban et al., 1994). Hence, no absolute ages are available that provide the resolution necessary for this study.

Magnetostratigraphy

Two magnetostratigraphic studies have been conducted on the Cloverly Formation with contradictory results. Douglass (1984) sampled two sections and identified a reversal within the Morrison Formation, with all of the Cloverly samples exhibiting normal polarity attributable to the Aptian-Santonian Cretaceous normal superchron. All of the data that he used were class I data, and the methods and results generally appear reliable. However, the data do lack some rigor. The sample intervals were fairly coarse, generally ranging from 4 m to 8 m, and only a few sites were within the Cloverly A interval. Additionally, although alternating field demagnetization was performed on more than 20 samples, it was not conducted on all samples. Hence, results are somewhat lacking in that regard, as well.

The subsequent study by Swierc (1990; results later published by May et al., 1995) yielded results different from those of Douglass (1984). Although variable, the sampling density in Swierc's study was generally much higher. Swierc identified several reversals throughout the Cloverly, including the B and C intervals, which he correlated with the Neocomian and lowermost Aptian part of the magnetic polarity time scale. The Aptian-Albian part of the Cretaceous normal superchron was not recognized. However, numerous aspects of Swierc's study call into question the reliability of the results: (1) Many samples lacked stability during thermal demagnetization. (2) Alternating field demagnetization was performed on only a few samples because of "generally inconclusive" results. (3) Much of the reversal data are class II and III data, in contrast to most of the normal polarity data which are class I. (4) Only one reversal has convincing class I data. However, Swierc interpreted a normal polarity overprint on this, as well as most other reversals. This reversal exists in the C interval in a purple zone known to have undergone extensive diagenetic alteration (Elliott, 2002), calling into question the ability to distinguish an overprint given the methods used. (5) Plotted pole positions, which should show a clustering of normal and reversed polarity in an antipodal relationship if the data are reliable, are not convincing. (6) Normal polarity pole positions show much better clustering and agreement with Cretaceous poles from other studies than do reversed poles. Swierc attributed this to the interpreted normal polarity overprint on the reversal data. However, given the above considerations, this explanation is suspect. (7) Finally, Swierc and May et al. (1995) tied the magnetostratigraphy to the magnetic polarity time scale using the mean fission-track ages without proper consideration of the large errors.

The magnetostratigraphic data generally yield inconclusive results. Extracting consistent, reliable magnetic data from Cloverly rocks appears to be quite challenging. Additionally, Cronin et al. (2001) pointed out the difficulties of conducting paleomagnetic investigations on Cretaceous rocks in general. Although the results are inconclusive, they do suggest that the Cloverly is dominated by normal polarity, which is consistent with much of the formation being Albian. If reversals are present within the A interval, they are easily attributable to the Neocomian. If reversals are present within the B and/or C intervals, it is possible that they represent poorly documented subchrons of the Cretaceous normal superchron (Gradstein et al., 1995; Cronin et al., 2001).

Synthesis and New Correlations

The upper Ephraim, Cloverly A interval, and Lakota L1 interval are correlative and Neocomian. Based on palynology, most deposits appear to be Barremian and possibly Hauterivian, but some may be as old as Valanginian. Hence, the contact with the underlying Morrison Formation and correlatives is unconformable and represents millions of years. The Peterson Limestone

is Neocomian and likely Aptian, and correlates with the Cloverly A-B and Lakota L1-L2 unconformity (see below). The unconformity represents the Aptian in central and eastern Wyoming. The Bechler Formation, Cloverly B and C intervals, and Lakota L2 and L3 intervals are correlative and Albian, but no younger than Middle Albian. The B-C and L2-L3 contacts appear to be conformable. The Draney Limestone correlates with the unconformity at the top of the Cloverly and Lakota Formations and is Albian (see following discussion).

IMPLICATIONS

Regional thickness trends of Lower Cretaceous nonmarine strata clearly show the former existence of a foreland basin fill that displays a thick foredeep depozone to the west (represented by the Gannett Group), a thin forebulge depozone throughout central Wyoming (represented by the Cloverly Formation), and thickening into a backbulge depozone in the Black Hills area (represented by the Lakota Formation; Figs. 3 and 4; DeCelles, 2004, documented similar trends). These features correspond well with those to the south in Utah and Colorado (Currie, 2002). Basin development is attributable to orogenic loading and flexural subsidence (Jordan, 1981; Royse, 1993; Taylor et al., 2000; Currie, 2002; DeCelles, 2004). The scales of the foredeep, forebulge, and backbulge are consistent with flexural models of plates with relatively high flexural rigidities, e.g., 10^{24} Nm (Jordan, 1981; Currie, 2002; DeCelles, 2004). Additionally, the styles of syndepositional structures that have been documented throughout the basin are consistent with these structural settings. Syndepositional compressional structures have been documented in ancient foredeep deposits (DeCelles et al., 1993); extensional structures have been documented in ancient forebulge deposits (Meyers et al., 1992; May et al., 1995; Zaleha et al., 2001); and transpressional and compressional structures have been documented in backbulge deposits (O'Malley, 1994; Way, 1997; Way et al., 1998; Zaleha et al., 2001).

The thickness trends and stratigraphic correlations presented herein have important implications for the development and evolution of the Sevier orogen and controls on basin filling. The clearly defined foredeep deposits of the upper Ephraim (Fig. 4) indicate that a thrust load was in place during the Neocomian, and is attributable to movement on the Paris-Willard thrust system (DeCelles, 2004). Sediment deposition and preservation on the forebulge, represented by the Cloverly A interval (Figs. 3 and 4), suggest that regional subsidence was due not only to orogenic loading, but also dynamic loading by viscous mantle corner flow associated with subduction (vis-à-vis, dynamic topography; DeCelles, 2004).

The physical connection between fluvial systems of the upper Ephraim and Cloverly A interval is unclear. Because of the similarity of their grain compositions, the A and L1 fluvial systems were apparently linked. The compositions of some Ephraim sandstones and conglomerates are similar to those of the A interval, whereas others are not. Most notable are the Ephraim channel deposits that contain red chert. It is unclear whether the presence of red chert in some Ephraim deposits, and its absence in others, represent coeval fluvial systems with different provenance, or a stratigraphic variation representing a change in provenance through time. The former suggests that the foredeep may have been partitioned. One possible scenario is that easterly to northeasterly flowing Ephraim rivers dominated by black and gray chert, but lacking red chert, flowed into Cloverly A rivers, and Ephraim rivers containing red chert flowed in a basin-axial direction to the north and, hence, were not connected with distal parts of the basin.

Widespread deposition of the Peterson Limestone adjacent to the ancient thrust belt indicates a

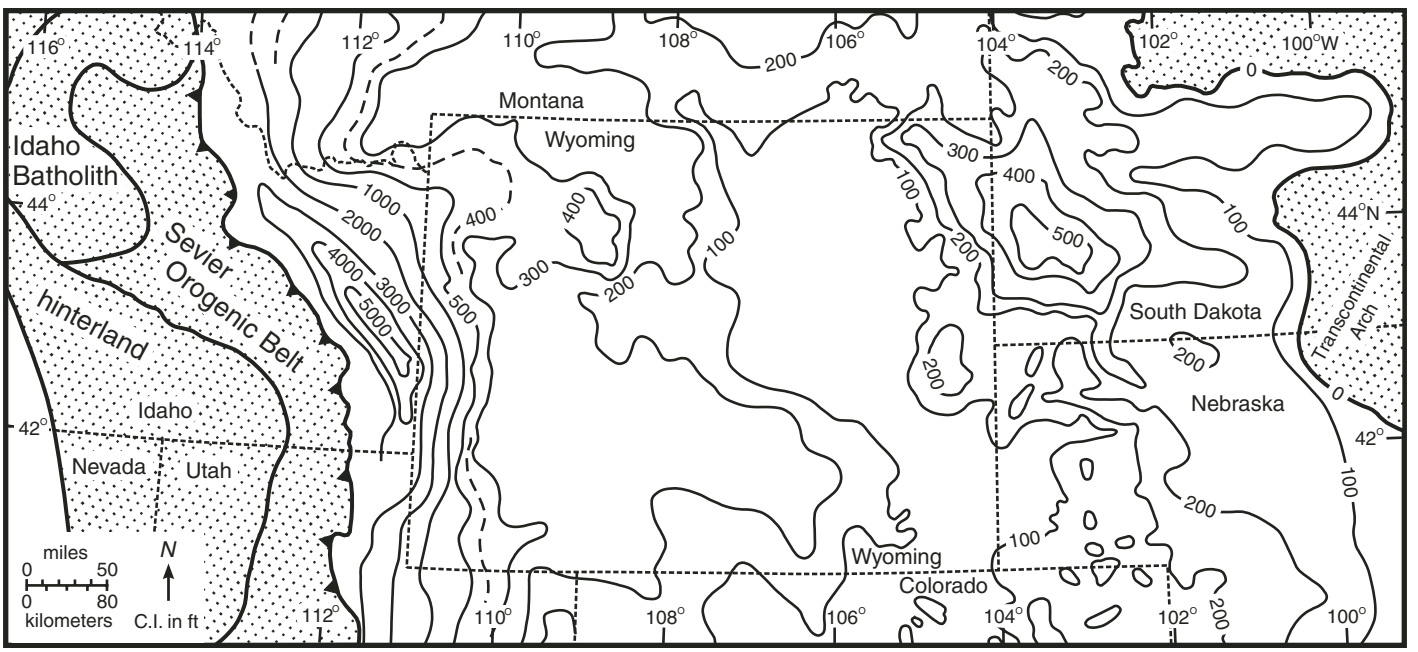

Figure 3. Regional isopach map of Lower Cretaceous rocks in relation to the position of the Early Cretaceous Sevier orogen (modified from McGookey et al., 1972). The foreland basin fill exhibits a thick foredeep depozone in eastern Idaho and western Wyoming, a thin forebulge depozone throughout central Wyoming, and a thicker backbulge depozone in the Black Hills area of northeastern Wyoming and southwestern South Dakota. DeCelles (2004) documented similar trends. The thrust front is the Early Cretaceous position of the Meade-Laketown-Paris-Willard thrust system. C.I. is contour interval.

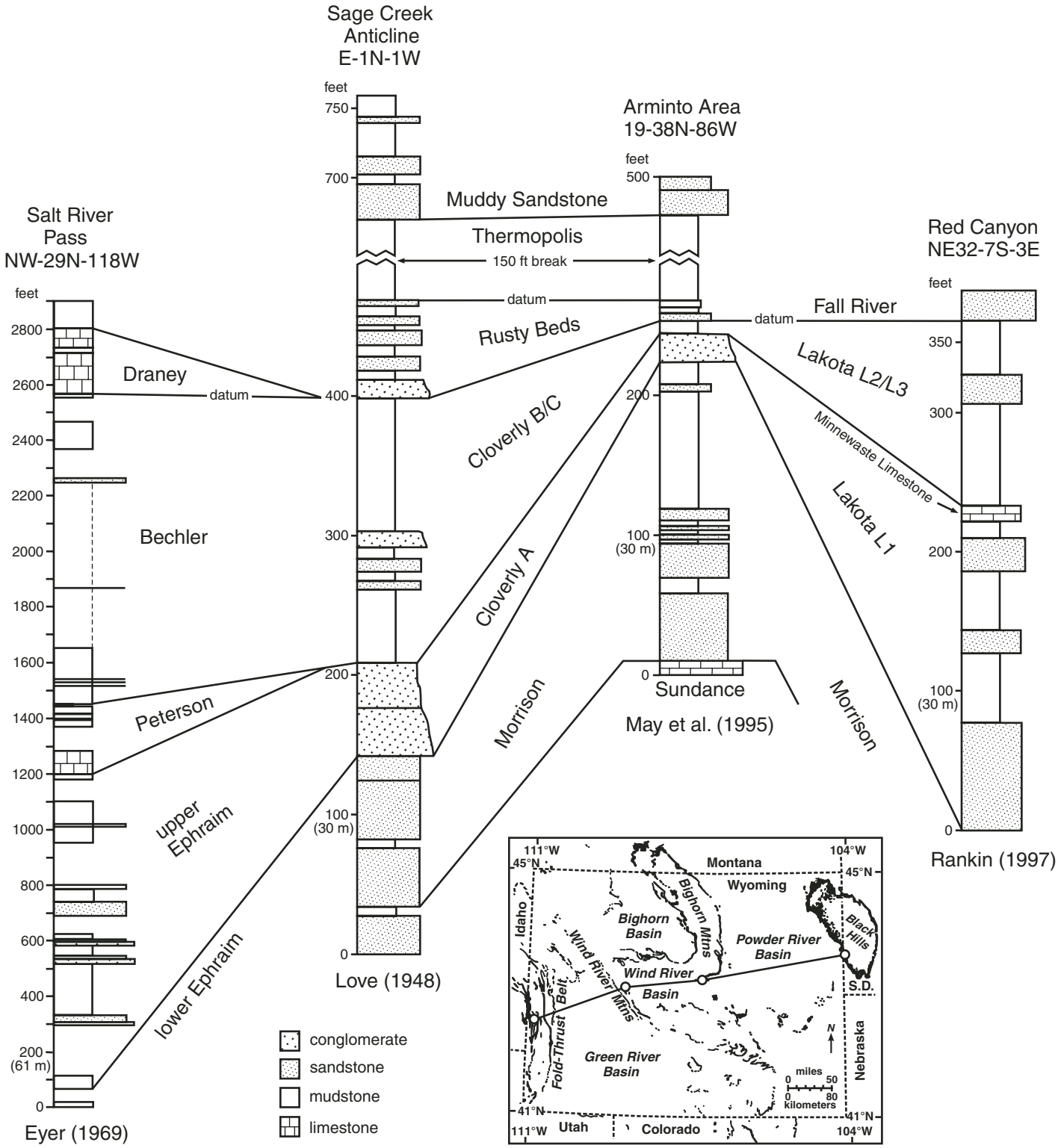

Figure 4. Stratigraphic cross section showing the correlations of Lower Cretaceous rocks presented in this paper. Sections have been redrafted from the references noted. Scales of the Sage Creek anticline, Arminto area, and Red Canyon sections are the same. Scale of the Salt River Pass section is one-fifth (or 0.2×) those of the other sections. The inset is Figure 1 showing the line of section.

reduction in sediment supply to the basin (Fig. 5). This may have been caused by a change to a drier climate, possibly related to progressive mountain-belt uplift and development or intensification of an orographic rain shadow (Drummond et al., 1996; Elliott, 2002; Elliott et al., 2002). Alternatively, a reduction in sediment supply may indicate a decrease in the rate of mountain-belt uplift and a reduction in mountain-belt relief. In this case, the amount of subsidence necessary to accommodate the Peterson Limestone could have been maintained by dynamic loading. A reduction in sediment supply farther east is indicated by deposition of the Minnewaste Limestone. These events likely began in the Neocomian, as indicated by the Neocomian palynological age of the Peterson, and Neocomian biostratigraphic ages of the Minnewaste Limestone in the uppermost Lakota L1 interval. However, at least part of the Peterson may be Aptian. The Aptian is not represented by Cloverly or Lakota rocks. The unconformity between the Cloverly A and B intervals and the Lakota L1 and L2 intervals likely corresponds to this reduction in sediment supply and is consistent with continued mountain-belt uplift and coeval foredeep subsidence and forebulge uplift. It is likely that this reduction in sediment supply began in the latest Neocomian and persisted into the Aptian.

The Bechler, Cloverly B and C, and Lakota L2 and L3 intervals signify an increase in sediment supply to the basin. The change in clast compositions from the Ephraim, Cloverly A, and Lakota L1 intervals to these units is attributable to progressive unroofing of the mountain belt and movement on the Meade-Laketown-Paris-Willard thrust system (Wiltschko and Dorr, 1983; Craddock, 1992; DeCelles et al., 1993; DeCelles, 1994, 2004; Zaleha and Wiesemann, 2005). An increase in sediment supply and progressive unroofing suggest renewed or accelerated mountain-belt uplift during the Early to Middle Albian. The presence of syndepositional structures within the basin and reworking of upper Ephraim clasts into the overlying units testify to tectonic activity. Sediment deposition and preservation on the forebulge, represented by the Cloverly B and C intervals (Figs. 3 and 4), again suggest that regional subsidence was due not only to orogenic loading, but also to dynamic loading. However, the thickness of this interval throughout central Wyoming is highly variable, generally ranging from 0 m to 70 m. Thickness changes from 30 m to nearly zero have been noted over distances on the order of a few tens of kilometers (e.g., Ten Sleep area). Correlations of lithologic sections and well logs indicate that these thickness variations are due to erosional truncation by overlying channels of the rusty beds and possibly subaerial erosion during development of the Cloverly–rusty beds unconformity (consistent with Hooper, 1962b).

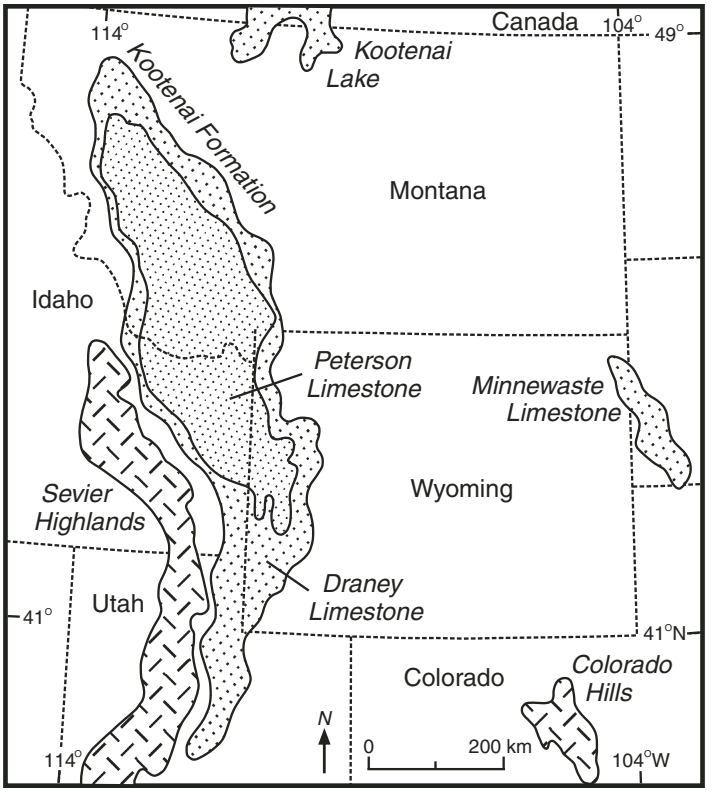

Figure 5. Regional map showing the distribution of Lower Cretaceous lacustrine deposits (modified from McGookey et al., 1972)

A return to widespread carbonate deposition of the Draney Limestone adjacent to the mountain belt again indicates a reduction in sediment supply. Possible causes follow those mentioned already for the Peterson Limestone: increased aridity possibly related to mountain-belt uplift and intensification of an orographic rain shadow (Drummond et al., 1996; Elliott, 2002; Elliott et al., 2002), or a decrease in the rate of mountain-belt uplift and a reduction in relief. In the latter case, the amount of subsidence necessary to accommodate the Draney Limestone could have been maintained by dynamic loading. The unconformity between the Cloverly Formation and the rusty beds, and between the Lakota and Fall River Formations, appears to correlate with this reduction in sediment supply and is consistent with continued mountain-belt uplift and coeval foredeep subsidence and forebulge uplift.

These results are notably different from those of Heller and Paola (1989) and Heller et al. (2003). Their interpretations and, indeed, the apparent problems that they addressed were based, in part, on equivocal correlations that relied primarily on ostracods and charophytes, particularly *Atopochara trivolvis* (see Biostratigraphy section herein). Those correlations gave the impression that thickness trends were inconsistent with flexural loading, and that the onset of Early Cretaceous deposition was not coincident with thrusting. However, the new correlations presented herein eliminate these discrepancies and clearly reveal that Lower Cretaceous strata reflect foredeep, forebulge, and backbulge depozones with scales that are consistent with flexural models of plates (Jordan, 1981; Royse, 1993; Currie, 2002; DeCelles, 2004). Additionally, Heller et al. (2003) invoked a style of dynamic subsidence in which much of the lithosphere slopes away from the mountain belt. This is inconsistent with dynamic subsidence models that simulate regional lithospheric tilt toward the mountain belt (Catuneanu et al., 1997; Burgess and Moresi, 1999; White et al., 2002).

CONCLUSIONS

Regional thickness trends of Lower Cretaceous nonmarine strata throughout Wyoming show the former existence of a foreland basin fill that displays a thick foredeep depozone to the west (represented by the Gannett Group), a thin forebulge depozone throughout central Wyoming (represented by the Cloverly Formation), and thickening into a backbulge depozone

in the Black Hills area (represented by the Lakota Formation). Basin development is attributable to orogenic loading and flexural subsidence, and also to dynamic loading.

The thickness trends and stratigraphic correlations presented herein have important implications for the development and evolution of the Sevier orogen and controls on basin filling. The upper Ephraim, Cloverly A interval, and Lakota L1 interval are correlative and are Neocomian in age. The contact with the underlying Morrison Formation and correlatives is unconformable and represents millions of years. The clearly defined foredeep deposits of the upper Ephraim indicate that a thrust load was in place during the Neocomian, and is attributable to movement on the Paris-Willard thrust system. Cloverly A and Lakota L1 fluvial systems appear to have been physically connected, whereas only some Ephraim rivers may have been linked to Cloverly A rivers.

The Peterson Limestone is Neocomian and likely Aptian, and correlates with the Cloverly A-B and Lakota L1-L2 unconformity, and likely the Minnewaste Limestone. The unconformity represents the Aptian in central and eastern Wyoming. The Peterson Limestone and the unconformity indicate a reduction in sediment supply to the basin. This may have been caused by a change to a drier climate, possibly related to progressive mountain-belt uplift and development or intensification of an orographic rain shadow. The development of the unconformity on the forebulge is consistent with this scenario. Alternatively, a reduction in sediment supply may indicate a decrease in the rate of mountain-belt uplift and a reduction in mountain-belt relief. The reduction in sediment supply likely began in the latest Neocomian and persisted into the Aptian.

The Bechler Formation, Cloverly B and C intervals, and Lakota L2 and L3 intervals are correlative and are early to Middle Albian in age. These strata indicate an increase in sediment supply to the basin, progressive unroofing of the mountain belt, and movement on the Meade-Laketown-Paris-Willard thrust system. Such events suggest renewed or accelerated mountain-belt uplift during the Early to Middle Albian.

The Draney Limestone correlates with the unconformity at the top of the Cloverly and Lakota Formations and is Albian in age. The Draney Limestone and the unconformity signify another reduction in sediment supply, which, again, may have been caused by increased aridity possibly related to mountain-belt uplift and intensification of an orographic rain shadow, or a decrease in the rate of mountain-belt uplift and a reduction in relief.

The results presented herein differ from those of some researchers who contend that a foredeep did not exist during initial deposition of these strata, and that deposition was not coincident with thrusting during early stages of the Sevier orogeny.

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