CEDAR MOUNTAIN AND DAKOTA FORMATIONS AROUND DINOSAUR NATIONAL MONUMENT

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UTAH DNR GEOLOGICAL SURVEY

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Cover photo: *View of the Cretaceous section along U.S. Highway 191 at Steinaker Reservoir, north of Vernal, Utah.*

ISBN: 978-1-55791-863-5

SPECIAL STUDY 143
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UTAH DEPARTMENT OF NATURAL RESOURCES
2012

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Bibliographic citation for this report:

Sprinkel, D.A., Madsen, S.K., Kirkland, J.I., Waanders, G.L., and Hunt, G.J., 2012, Cedar Mountain and Dakota Formations around Dinosaur National Monument—evidence of the first incursion of the Cretaceous Western Interior Seaway into Utah: Utah Geological Survey Special Study 143, 21 p., 6 appendices.

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CEDAR MOUNTAIN AND DAKOTA FORMATIONS AROUND DINOSAUR NATIONAL MONUMENT

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ABSTRACT

The Lower Cretaceous section exposed in northeastern Utah includes the Cedar Mountain and Dakota Formations. The Cedar Mountain Formation consists of fluvial-lacustrine and pedogenic carbonate beds and includes important dinosaur sites. Its age in northeastern Utah is early to late Albian from a radiometric age (detrital U-Pb zircons) of 104.46 ± 0.95 Ma associated with a well-preserved sauropod skull, chemostratigraphic analysis, and palynology in the overlying Dakota Formation. Part of the Cedar Mountain Formation was deposited during the Kiowa–Skull Creek depositional cycle.

The Dakota Formation consists of fluvial sandstone and mudstone beds; however, locally it includes a thin interval of marine mudstone and shale beds. Dinoflagellate cysts recovered from this basal marine interval represent peak sea level during the Kiowa–Skull Creek depositional cycle and the first marine incursion of the Cretaceous Western Interior Seaway into Utah. The age for this event is middle late Albian. Only nonmarine palynomorphs were recovered from beds above the marine interval. An ash bed in the middle Dakota yielded a U-Pb zircon age of 101.4 ± 0.4 Ma, which correlates to the newly defined Muddy-Mowry depositional cycle.

The Mowry Shale consists of siliceous marine shale that represents widespread open-marine conditions for the area. The radiometric age of the Mowry is between 98.5 ± 0.5 Ma and 97.2 ± 0.7 Ma ($^{40}Ar/^{39}Ar$ sanidine) from bentonite beds in Wyoming. However, the biostratigraphic age is controversial because of downward revision to key neogastroplitid ammonite zones, revision of the Albian-Cenomanian boundary age to 99.6 Ma, and recently published palynostratigraphic work.

INTRODUCTION

The well-exposed geology of northeastern Utah displays classic examples of sedimentological features, varied depositional environments, and geologic structures. The Cretaceous section preserved in the region is no exception (figures 1 and 2). The focus of our work is on the stratigraphy and age of the Cedar Mountain and Dakota Formations. These formations represent a transition from nonmarine fluvial-lacustrine deposition to marine deposition as the advancing Western Interior Seaway flooded areas of low relief at peak sea level in early late Albian time.

Interest in the Cedar Mountain and Dakota Formations has recently increased because of regional mapping by the Utah Geological Survey (Sprinkel, 2006, 2007) and because they are significant petroleum reservoirs in the Uinta Basin. Exposures of these formations in and around Dinosaur National Monument provide an opportunity to study their reservoir characteristics and regional stratigraphic relations (Currie and others, 2008). Also of significant interest is the recovery of marine microplankton from the basal Dakota Formation and recent radiometric data, which provide evidence of the timing of the first marine incursion of the Cretaceous Western Interior Seaway into northeastern Utah. Finally, the discovery of the well-preserved sauropod dinosaur skull (*Abydosaurus mcintoshi*) in the upper Cedar Mountain Formation in Dinosaur National Monument (Chure and others, 2010) and excavation of an ornithopod dinosaur skeleton have increased the need for refined geologic correlations of Lower Cretaceous units throughout Utah. This paper describes the local stratigraphy, offers a preliminary interpretation of the changes in the depositional environment through time, and briefly discusses the significance of the paleogeographic setting of the Lower Cretaceous strata in northeastern Utah.

STRATIGRAPHY

The Lower Cretaceous section is generally well exposed along the south and north flanks of the Uinta Mountains. Exposures along the south flank that are in and around Dinosaur National Monument form a sinuous outcrop belt that wraps around the limbs of Laramide folds associated with the Uinta Mountains uplift (figure 2). We measured five sections through the Cedar Mountain and Dakota Formations (figure

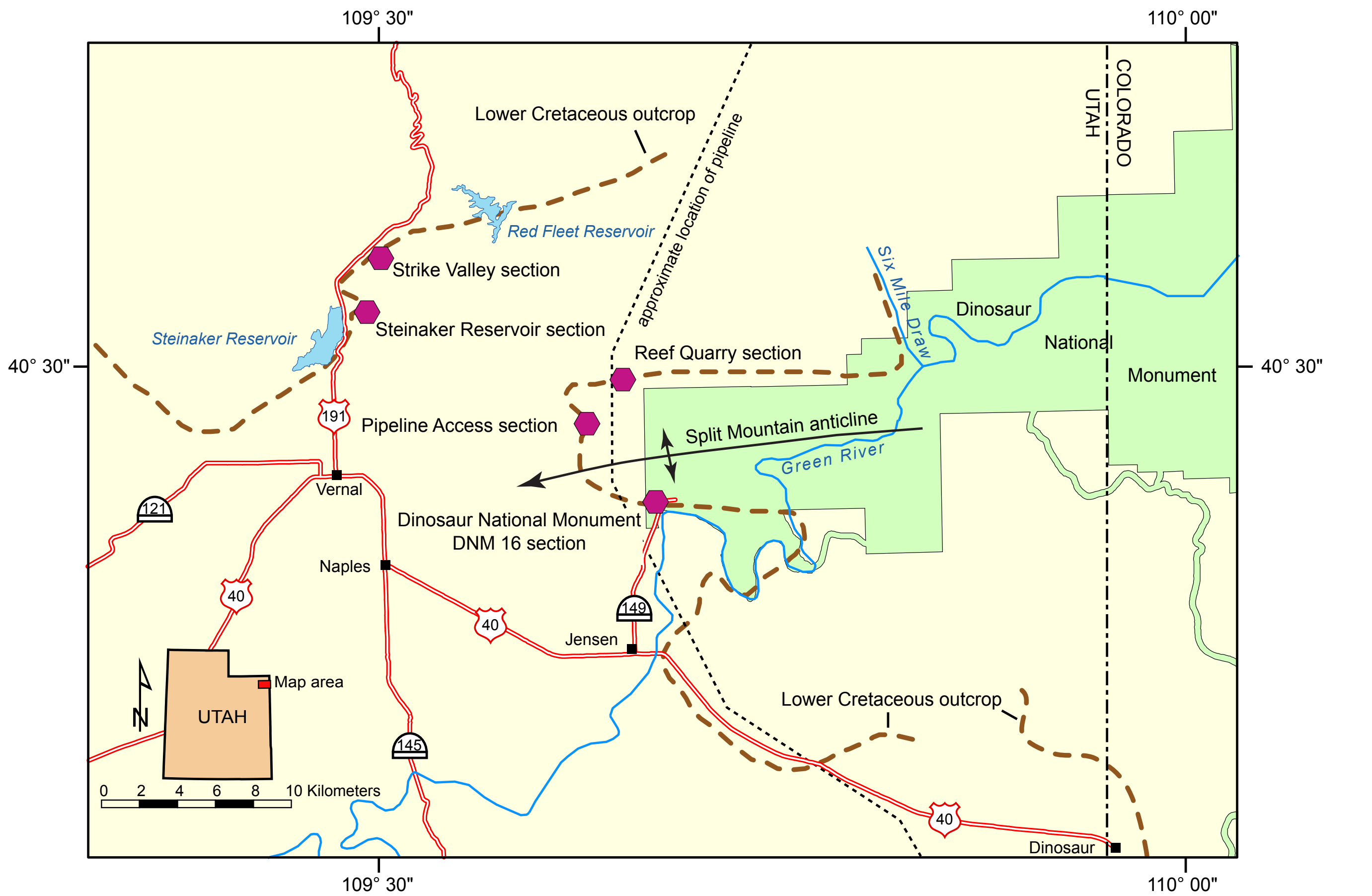

Figure 1. *Lower Cretaceous strata form a sinuous outcrop belt (dashed line) in the western part of the Dinosaur National Monument area along the south flank of the Uinta Mountains. Five sections were measured through the Cedar Mountain Formation and Dakota Formation.*

3; appendix A); two of the measured sections are along U.S. Highway 191 near Steinaker Reservoir State Park, two are near a major pipeline on the nose of Split Mountain anticline, and one is located near the *Abydosaurus mcintoshi* Quarry west of the famed Carnegie Quarry in Dinosaur National Monument (figure 2). These sections illustrate the stratigraphic succession as well as lithologies, thicknesses, and contacts for the region. In addition, they contain important radiometric, fossil vertebrate, and palynologic information.

Cedar Mountain Formation

The Cedar Mountain Formation is recognized across central and eastern Utah. It was first described by Stokes (1944, 1952) from exposures on the flanks of its namesake northeast of Castle Dale, Utah, for beds of variegated mudstone with intercalated sandstone, lacustrine limestone, pedogenic carbonate, and a discontinuous basal conglomerate. Calcareous nodules and highly polished stones ("gastroliths") are common to the Cedar Mountain Formation. Stokes (1944, 1952) divided the formation into two members, the basal Buckhorn Conglomerate Member and an informal upper shale member, and this basic two-fold subdivision is used in northeastern Utah. Kirkland and others (1997) and Kirkland and others (1999) also recognized the Buckhorn Conglomerate, but they subdivided the rest of the Cedar Mountain Formation into four members based on lithostratigraphy and relationships observed throughout the outcrop belt on the Colorado Plateau south of the Uinta Basin. These members are (in ascending order) the Yellow Cat, Poison Strip, Ruby Ranch, and Mussentuchit. The lower three were initially assigned tentative ages based on dinosaur biostratigraphy: Barremian for the Yellow Cat Member in the northern Paradox Basin, Aptian for the Poison Strip Member, and Aptian to middle Albian for the Ruby Ranch Member. Radiometric dates indicate a latest Albian to earliest Cenomanian age for the capping Mussentuchit Member (Cifelli and others, 1997; Kirkland and others, 1999; Garrison and others, 2007), which preserves a fauna indicating a strong affinity with Asia. The relationships of these strata in central Utah have been clarified in recent years with the recognition that the Yellow Cat Member extends below the interval of extensive calcretes development (Aubrey, 1998; Ayers, 2004) to include a strongly mottled iron-stained interval that also contains common floating chert pebbles and preserves an Early Cretaceous dinosaur fauna (Kirkland and Madsen, 2007). In addition, the Yellow Cat Member is shown to be correlative, at least in part, with the Buckhorn Conglomerate (Greenhalgh and Britt, 2007). Some of the member names have been applied to the Cedar Mountain Formation in the Vernal area by Chure and others (2010) although Kirkland and Madsen (2007) have refrained from extending this terminology across the Uinta Basin in the Vernal area.

Lithologic Description and Thickness

The Cedar Mountain Formation in northeastern Utah predominantly consists of variegated mudstone, siltstone, and claystone in hues of purple, red, green, and gray (figure 3; appendix A). It is generally calcareous, but the base and top of the formation are generally noncalcareous. The base of the Cedar Mountain is marked by variable lithofacies that range from the Buckhorn Conglomerate Member (a chert-pebble conglomerate with sandstone lenses) to a mottled, yellow-orange chert-pebble mudstone to sandy mudstone, similar to what Greenhalgh and Britt (2007) described for the basal Cedar Mountain in the Green River and Moab areas. The Buckhorn Conglomerate is not present in our measured sections; however, as much as 30 m of the Buckhorn Conglomerate Member forms the base of the Cedar Mountain in the eastern part of Dinosaur National Monument (Currie, 1997, 1998). The Buckhorn Conglomerate has also been mapped near the western side of Steinaker Reservoir (Haddox, 2005; Haddox and others, 2010). Elsewhere, the base of the Cedar Mountain Formation consists of a mudstone interval containing scattered chert pebbles generally less than 10 m thick. The interval has a persistent limonitic zone above the contact characterized by a strong mottled yellow-orange color (figures 4 through 7). This may represent an extensive weathered soil horizon or series of soil horizons developed at and above the top of the Morrison Formation during the early phases of Cedar Mountain deposition (Bilbey, 1992).

Above the basal chert-pebble mudstone interval, the Cedar Mountain Formation is a mudstone and siltstone unit 20 to 55 m thick with interbedded pedogenic carbonate nodules and calcrete, discontinuous layers of red or white silcrete (chert), and discontinuous sandstone beds. Calcrete beds at the base of the interval are thicker in the Steinaker Reservoir and Dinosaur sections, whereas multiple thin calcrete beds and intervals of pedogenic carbonate nodules are more common in the Strike Valley and Reef Quarry sections (figure 3; appendix A). This interval typically yields abundant carbonate debris that covers the slopes, as well as common, highly polished multicolored pebbles, interpreted as "gastroliths" (Stokes, 1952), as is typical of the Ruby Ranch Member of east-central Utah. The nodules weather to a reddish color giving most exposures a similar purplish-gray appearance even at a distance. Discontinuous sandstone lenses and beds are also part of this unit. Sandstone beds in the upper Cedar Mountain Formation at Dinosaur National Monument have morphology or bed forms indicative of low-sinuosity anastomosing river systems (Master and others, 2004). The sandstone beds are brown, highly calcareous, and cross-bedded, and often contain sandy brown concretions and display abundant bioturbation (figure 8). The lowest sandstone is typically more massive than the other sandstone beds and usually contains coarse pebbles and rip-up clasts of carbonate at its base; this sandstone fines upward and commonly shows polygonal structures and spheroidal weathering on bedding surfaces. One of the sandstone beds in the upper part of this interval from Dinosaur National Monument (appendix A; unit 27 in Dinosaur National Monument DNM 16 section) has yielded the first complete, well-preserved, Cretaceous sauropod skulls to be found in North America (figures. 3, 9), *Abydosaurus mcintoshi* (Chure and others, 2010).

The upper part of the Cedar Mountain Formation in this region is siltstone and mudstone with some interbedded thin sandstone, which is generally calcareous. The uppermost part is usually a light gray-brown mudstone, 0 to 20 m thick, char-

Figure 2. *The Cretaceous section as exposed at Steinaker Reservoir State Park along U.S. Highway 191. The lower part of the Cedar Mountain Formation is exposed along the shore of the reservoir. The Dakota Formation is at road level (right side of photograph) and is overlain by the Mowry Shale. The ridge is capped by the Frontier Formation. View to the east.*

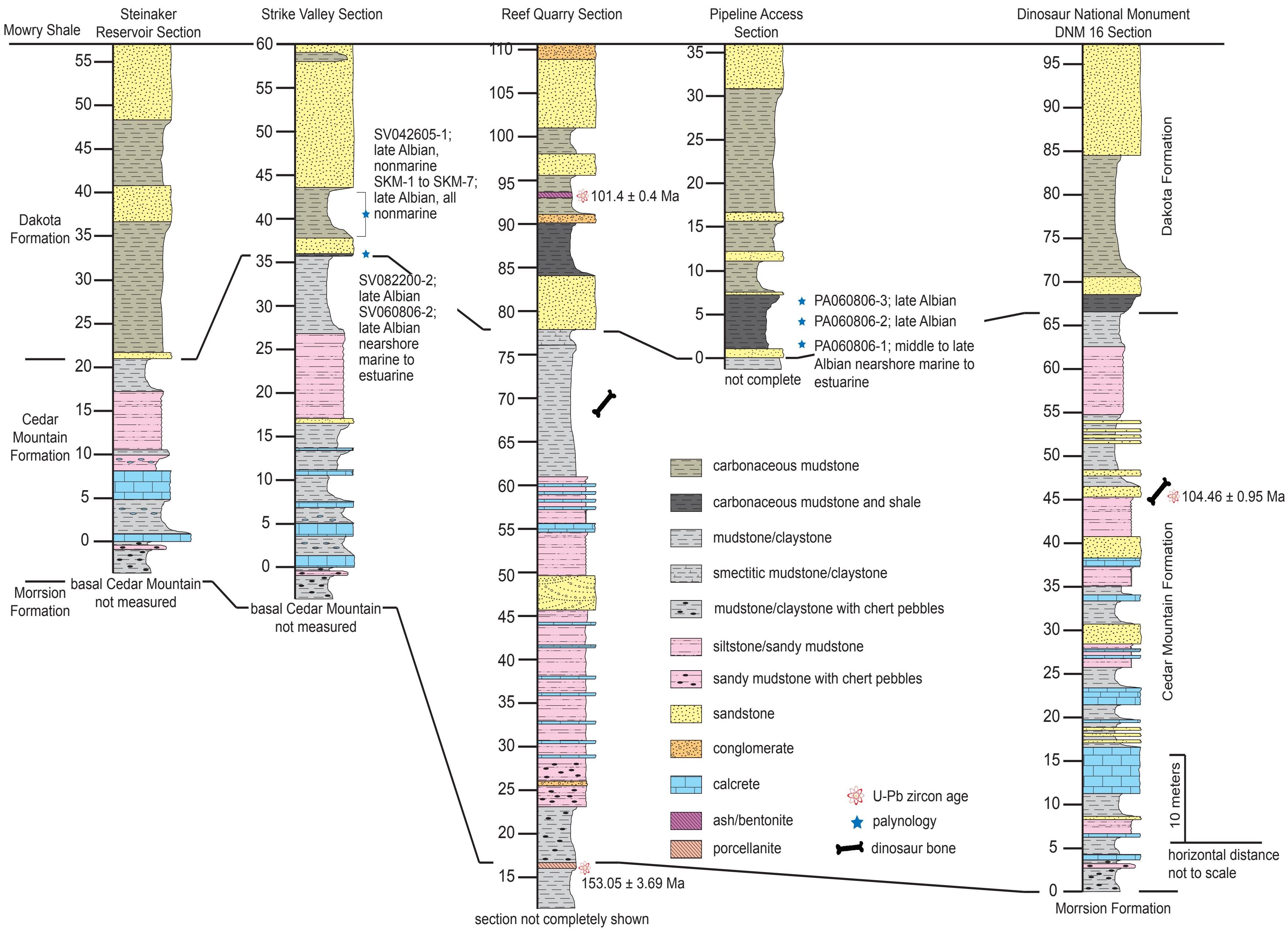

Figure 3. *Graphical representation of the five sections measured through the Cedar Mountain Formation and Dakota Formation showing lithotypes, thicknesses, palynology, and U-Pb zircon sample locations. U-Pb age in Cedar Mountain Formation at DNM 16 section is from Chure and others (2010).*

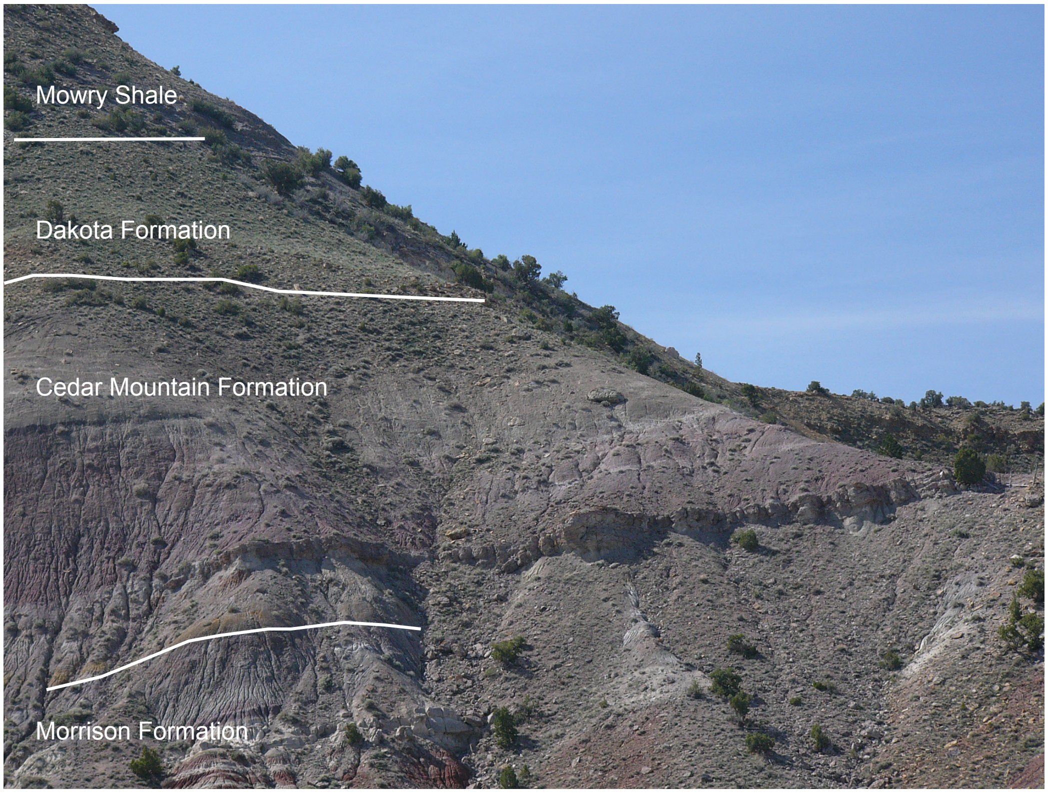

Figure 4. *Strike Valley section. The base of the Cedar Mountain Formation is placed at the base of the sandy mudstone interval below the prominent calcrete ledge (in shadow). The mudstone interval contains chert pebbles and the base commonly forms a yellow iron-rich alteration zone. Note that the calcrete thins to a featheredge to the left. View to the south.*

Figure 5. *Morrison through Frontier Formations as seen from the Strike Valley section. The yellow iron-rich alteration zone forms the base of the Cedar Mountain Formation. The resistant calcrete bed in the foreground forms the base of the sandy mudstone and calcrete interval. View to the east.*

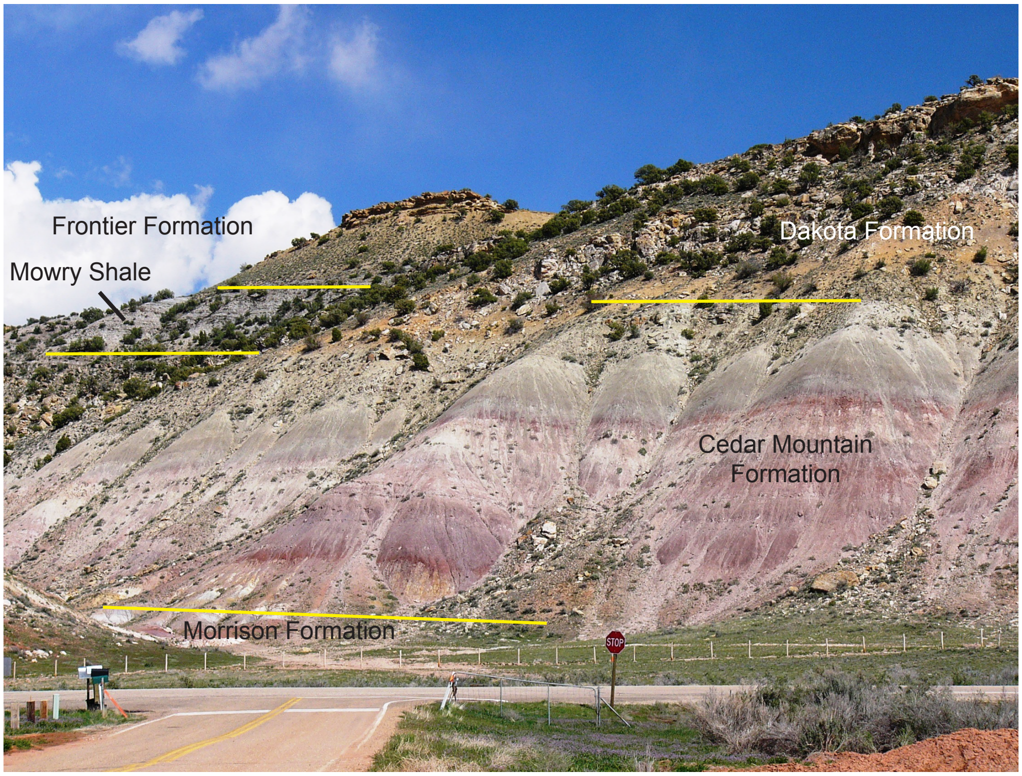

Figure 6. Steinaker Reservoir section. Similar to the Strike Valley section, the Cedar Mountain Formation has a basal yellow-orange sandy mudstone with scattered chert pebbles, a mudstone and calcrete interval, and a capping light-gray mudstone. The marine shale beds at the base of the Dakota Formation are not preserved in this section. View to the east.

Figure 7. Well-exposed section of the Morrison and Cedar Mountain Formations in Six Mile Draw showing the thick yellow alteration zone at the base of the Cedar Mountain Formation. Also seen are several resistant calcrete beds (yellow arrow) that are part of the mudstone and calcrete interval. View to the northeast.

acterized by a deeply weathered "popcorn" appearance and scattered gypsum crystals. This interval is reminiscent of the Mussentuchit Member of the Cedar Mountain Formation of the western San Rafael Swell, but is not as purely smectitic (there are bentonite mines near the type section) and does preserve abundant organic matter that yielded the diverse palynoflora described by Tschudy and others (1984) from the western San Rafael Swell. As noted below in the "Discussion" section, it is not the same age, based on radiometric ages obtained from ashes in the Mussentuchit on the San Rafael Swell (Cifelli and others, 1999; Garrison and others, 2007). The top of the Cedar Mountain Formation in northeastern Utah may include bleached beds. The Ruby Ranch Member of the Cedar Mountain Formation in east-central Utah also exhibits bleaching in its type area where directly overlain by the Dakota Formation (Kirkland and others, 1997; Kirkland and others, 1999).

The total thickness of the Cedar Mountain Formation varies from 70 m in Dinosaur National Monument to 21 m and 39 m in the sections along U.S. Highway 191. Thinning of the Cedar Mountain may be due to subtle paleotopography developed on the underlying Morrison Formation, augmented by scouring the top of the Cedar Mountain by the overlying Dakota Formation (Currie, 1997; Currie and others, 2008).

Figure 8. Trace fossils formed mostly by burrowing organisms in one of the sandstone beds of the Cedar Mountain Formation. Pick handle (about 40 cm) shown for scale. Photograph taken along the east shore of Steinaker Reservoir.

Stratigraphic Contacts

The contact between the Morrison and Cedar Mountain Formations is somewhat subtle, especially where the Buckhorn Conglomerate Member is missing, because both formations tend to weather deeply, covering the contact with debris. Thus, trenching the section is the best means to locate the contact. The contact between the Morrison and Cedar Mountain Formations is unconformable. In the eastern part of Dinosaur National Monument the Buckhorn Conglomerate was deposited in paleovalleys scoured into the underlying Morrison (Currie, 1997, 1998). Where the Buckhorn is missing, we place the contact at the base of a mottled, yellow-orange chert-pebble mudstone that underlies the prominent calcrete zone (figures 4 through 7). We believe the yellow-orange-red chert-pebble mudstone in northeastern Utah is similar to the mottled, yellow-orange chert-pebble mudstone in the Green River and Moab areas of Utah, where Cretaceous dinosaurs have been recovered from this unit at several sites across east-central Utah. Evidence that supports the partial equivalence of the Buckhorn Conglomerate and

Figure 9. Dinosaur National Monument DNM16 section. The steeply dipping Lower Cretaceous strata provide exposures typical of the Cedar Mountain and Dakota Formations. A newly named sauropod skull, Abydosaurus mcintoshi, was extracted from a sandstone bed in the upper part of the Cedar Mountain Formation (at about the yellow arrow). Three detrital zircons (of 63 total), also obtained from the skull bed, yielded a U-Pb age of 104.46 ± 0.95 Ma that indicates the Abydosaurus mcintoshi skull bed is no older than middle Albian (Chure and others, 2010). View to the west.

Yellow Cat Member are equivalents include: (1) the recognition that the Buckhorn Conglomerate laterally grades into a sandy lithofacies of the Yellow Cat west of Hanksville, Utah, and (2) lenses of pebbles and cobbles of a Buckhorn character in a mudstone matrix occur in the lower Yellow Cat at the western limits of its outcrop south of Green River, Utah (Greenhalgh and Britt, 2007; Kirkland, 2007; Kirkland and Madsen, 2007). In addition in the Vernal area, the mudstone beds below our proposed contact are medium-greenish-gray to purplish-gray to somewhat mottled yellow and smectitic, typical of the Brushy Basin Member of the Morrison Formation, and the mudstone beds above our contact are non-smectitic and grade upward to a pedogenic carbonate-rich interval typical of the Cedar Mountain Formation. For mapping purposes, the base of the yellow-orange chert-pebble mudstone seems like a reasonable operational definition of the contact between the Morrison and Cedar Mountain Formations, especially where the Buckhorn Conglomerate is missing.

Locally, a brittle, light-gray, siliceous siltstone bed (porcellanite) marks the top of the Morrison Formation (figures 3 and 10). We initially interpreted this bed as an altered volcanic ash, but all of the recovered zircon grains were detrital, well rounded, and only a few tens of microns across (Paul O'Sullivan, Apatite to Zircon, Inc., 2010, personal communication). Laser ablation dating of the zircon grains revealed a population of grains with an age of 153.05 ± 3.69 Ma at ± 2 sigma (appendices B and C), which suggests that these are reworked grains from the Upper Jurassic Morrison Formation (Kowallis and others, 1998). In addition to the zircon grains that are consistent with Morrison Formation, a large number of grains are Precambrian in age, which in total represent a typical spectrum of zircon ages found in coarser clastic sediments in the Morrison Formation (Dickinson and Gehrels, 2008; Hunt and others, 2011).

Age

The age of the Cedar Mountain Formation in central and southern Utah is considered Barremian(?) to earliest Cenomanian based on dinosaur biostratigraphy (similar to the Wealden dinosaur fauna on the Isle of Wight in southern Britain) and radiometric data (Kirkland and others, 1997; Kirkland and others, 1999; Martill and Naish, 2001; Kirkland and Madsen, 2007; Ward and others, 2007; Biek and others, 2010). The age of the Cedar Mountain Formation exposed in northeastern Utah is poorly constrained. Three detrital zircons (of 63 total), dated at 104.46 ± 0.95 Ma using U-Pb analysis, indicate that the *Abydosaurus mcintoshi* skull bed is no older than middle Albian at Dinosaur National Monument (Chure and others, 2010); however, Kirkland and others (1997) have noted the Cedar Mountain Formation in central Utah is older. In addition, Burton and others (2006) and Britt and others (2007) reported U-Pb detrital zircon ages ranging from 124 to 109 Ma (early Aptian to middle Albian) collected at various stratigraphic horizons from other Cedar Mountain sections in central Utah. Additional evidence for the age comes from recent chemostratigraphic work measuring excursions of carbon isotopic ratios from paleosols in the Cedar Mountain Formation; this new technique may have great utility for dating calcareous intervals where materials used for other dating techniques are lacking (Ludvigson and others, 2010a). Smith and others (2001), Ludvigson and others (2003b), and Kirkland and others (2003) provide evidence for linking these excursions with known

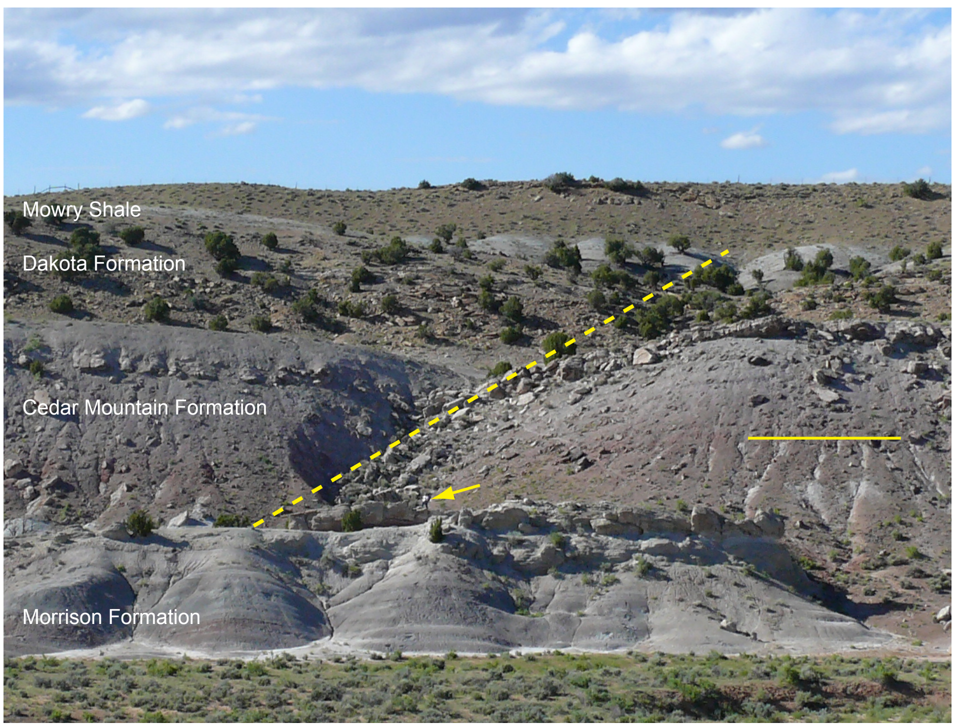

Figure 10. *Reef Quarry section. The yellow dashed line shows the approximate traverse of the measured section. The solid yellow line is the contact between the Morrison and Cedar Mountain Formations. The upper part of the Cedar Mountain Formation is light-gray-brown mudstone, and contained an ornithopod dinosaur skeleton that was completely excavated and fully reclaimed. Zircons were extracted from a bentonitic bed within the Dakota Formation; 44 of 50 grains yielded U-Pb ages between 96-109 Ma, and 21 grains yielded ages between 100 and 104 Ma, giving a final age of 101.4 ± 0.4 Ma at ± 2 sigma. The Cedar Mountain Formation rests on a hard, brittle siltstone bed (porcellanite) containing zircons with spectra common to the Morrison Formation. The yellow arrow points to Jim Kirkland standing on brittle siltstone bed for scale. View to the north.*

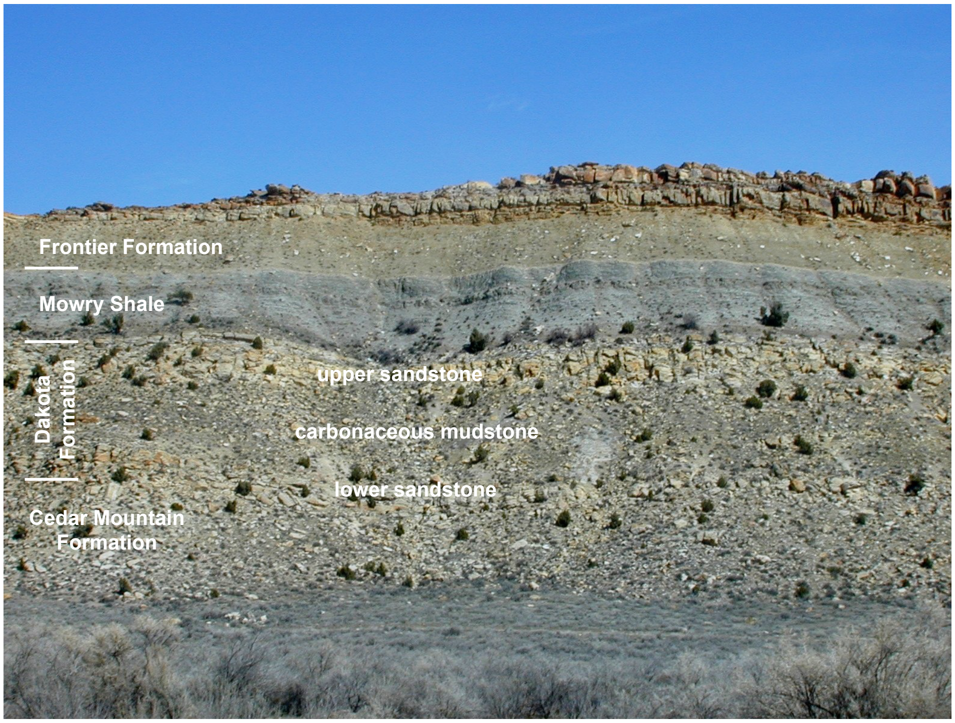

Figure 11. *The Dakota Formation commonly consists of a basal sandstone, a middle carbonaceous mudstone, and an upper sandstone; a marine mudstone and shale locally underlies the basal sandstone. In some places, the lower sandstone may also be missing or covered by debris. The lowermost marine mudstone and shale unit of the Dakota is not preserved at this location. The upper prominent sandstone unit is always preserved. Photograph taken along U.S. Highway 191 near Steinaker Reservoir. View to the southeast.*

marine carbon isotope records, based in part on work done in Dinosaur National Monument. Chemostratigraphic evidence from the section containing the *Abydosaurus mcintoshi* skull bed in the monument suggests this horizon is early Albian age (Kirkland and others, 2003; Ludvigson and others, 2003a), in contrast to the middle Albian zircon age. A nearly 20-m-thick mudstone separates this horizon from the lowest Dakota Formation. A recently excavated ornithopod dinosaur skeleton from higher up section at the Reef Quarry section is currently under study; it may be of future use in correlating these strata with other Lower Cretaceous deposits yielding similar dinosaurs elsewhere in North America. The late Albian age of the upper Cedar Mountain Formation is constrained by a U-Pb zircon age of 101.4 ± 0.4 Ma and middle to late Albian palynomorphs obtained from the overlying basal Dakota Formation (see age of Dakota Formation below and appendices D to F).

Dakota Formation

The Dakota Formation is widely distributed throughout the eastern half of Utah. It was first named as the Dakota Group by Meek and Hayden (1862) for outcrops in Nebraska. Since then, the Dakota has been extensively studied in the Rocky Mountain region in which it has undergone a colorful history of nomenclature changes (see MacLachlan and others, 1996; U.S. Geological Survey, undated). Of note, Young (1960) referred to this interval on the Colorado Plateau as the Naturita Formation. Naturita has generally not been an accepted name for this section of rocks on the Colorado Plateau; only recently has Naturita Formation been reapplied to these strata (Carpenter and others, 2008). We use Dakota Formation for the strata that overlie the Cedar Mountain Formation and underlie the Mowry Shale in northeastern Utah. The term Dakota Sandstone has been formally used in geologic maps and reports in the eastern Uinta Mountains (Hansen, 1965; Hansen and others, 1983; Sprinkel, 2006, 2007); however, we revise the descriptive term to formation to reflect the lithologic heterogeneity of the Dakota in this region and to be consistent with usage elsewhere in Utah.

The Dakota Formation is composed of medium to coarse-grained sandstone, conglomerate, carbonaceous mudstone and shale, and coal. Sandstone and mudstone (including shale) are the dominant lithologies and their percentages are about equal. The amount of sandstone in the formation ranges from as little as 25% to as much as 75%, and averages a little less than 50%. The amount of mudstone and shale also ranges from about 25% to 75%, with an average being a little more than 50%.

Typically, the Dakota Formation along the flanks of the Uinta Mountains consists of lower and upper light-colored and cross-bedded sandstone ledges separated by dark-colored carbonaceous mudstone and shale. Hansen (1965) described this threefold division of the Dakota south of the Wyoming border in the vicinity east of Lucerne Valley; additionally he pointed out that the lower sandstone is locally missing. We also recognize this general threefold division in the Dinosaur National Monument area (figure 11), but we have also included within the Dakota Formation a mudstone and shale unit that, in places, separates the typical base of the Dakota from the typical top of the Cedar Mountain Formation. We consider this mudstone and shale unit as the base of the Dakota Formation because of its overall lithology and palynomorph assemblage.

Lithologic Description and Thickness

A mudstone and shale unit forms the base of the Dakota Formation in many places, and consists of carbonaceous mudstone with sandstone stringers capped by shale. The carbonaceous mudstone layers are black and organic rich. The top of the unit is dark-gray, siliceous, fissile shale. This unit is important because it contains an assemblage of dinoflagellate cysts that indicate a marine to marginal marine environment of middle to late Albian age (table 1). The mudstone and shale unit varies from 0 to as much as 6 meters thick and is overlain by the lower sandstone unit.

The lower sandstone unit is yellow gray to white, coarse grained, pebbly to very fine grained, upward fining, well sorted, and cross-bedded. In most places, the lower sandstone is a single lens-like bed that is typically less than 2 m thick and tends to weather out into blocks. In some places, the lower sandstone is missing or covered by debris from the overlying carbonaceous mudstone unit.

The middle carbonaceous mudstone unit is dark-gray, organic-rich, earthy mudstone with minor fine-grained sandstone beds and coal that forms slopes. Petrified wood and carbonized logs are common in this lowest part of the unit. This unit varies in thickness from a few meters to as much as 20 m. The dark-gray carbonaceous mudstone unit may rest on thin marine shale beds of the basal mudstone and shale unit where the lower sandstone is not preserved, or on the Cedar Mountain Formation where the lower two units are not preserved (figure 12).

The top of the Dakota Formation is the upper sandstone unit, which regionally forms a continuous and prominent ledge that is 5 to 28 m thick. The upper sandstone is similar to the lower sandstone beds but can be finer grained. At the Reef Quarry section (appendix A, figure 3) a pebble conglomerate bed caps the Dakota Formation. Around Dinosaur National Monument, the upper surface of this ledge is usually quite smooth and exhibits a distinct rusty orange color.

The total thickness of the Dakota Formation ranges from 24 to 53 m. Thickness variation is likely the result of deposition on the paleotopography developed on the Cedar Mountain Formation.

Stratigraphic Contacts

A close examination of the Cedar Mountain and Dakota Formations in the northeastern Utah outcrop belt revealed the contact between them is complex. The contact may be at the base of the newly recognized basal marine to marginal marine mudstone and shale unit, the lower sandstone unit, or the carbonaceous mudstone unit depending on which of the lower three units overlies the Cedar Mountain Formation. In each case, the contact separates the typical variegated beds of the Cedar Mountain Formation from organic-rich mudstone or shale beds or a yellow-gray to white coarse-grained sandstone of the Dakota Formation.

Age

The Dakota Formation yields middle to late Albian palynoflora in northeastern Utah. We established this age from samples SV082200-2 (Strike Valley section), and PA060806-1, PA060806-2, and PA060806-3 (Pipeline Access section) collected in the basal mudstone and shale unit, and from samples SKM-1 to SKM-7 (Strike Valley section) collected in the carbonaceous shale unit (figure 3). We recovered a diverse assemblage of spores, pollen, and marine dinoflagellate cysts (table 1; appendices E and F). The taxa that best help to define the age are *Rugubivesiculites rugosus* (appendix F, number 25), which does not range below the late Albian, and *Aptea polymorpha* (appendix E, number 18), *Ovoidinium scabrosum* (appendix E, number 6) and *O. verrucosum* (appendix E, number 7), which do not range above the late Albian. Our taxa that define the age of the Dakota Formation in northeastern

Figure 12. *Contact (white arrow) between the Cedar Mountain Formation and overlying Dakota Formation. Here, the carbonaceous mudstone unit of the Dakota Formation unconformably lies on the Cedar Mountain Formation; the lower two units (mudstone and shale unit and lower sandstone unit) of the Dakota Formation are not preserved. Photograph taken near Island Park in Dinosaur National Monument. View to the south.*

Table 1. *Palynomorph species recovered from the Dakota Formation, northeastern Utah.*

Age	Sample	SPORES AND POLLEN																					
		Apiculatisporis babsae	Apiculatisporis sp.	Appendicisporites potomacensis	Appendicisporites tricornitatus	**Callialasporites dampieri**	Camarozonosporites cerniidites	Cicatricosisporites brevilaesuratus	Cicatricosisporites hallei	Cicatricosisporites hughesii	Cicatricosisporites potomacensis	Cicatricosisporites venustus	Classopollis classoides	**Coronatispora valdensis**	Costatoperforosporites foveolatus	Foveotriletes sp.	Gleicheniidites senonicus	**Klukisporites variegatus**	Laevigatosporites spp.	Lusatisporites circumundulatus	Matonisporites excavatus	Matonisporites sp.	**Neoraistrickia robusta**
Late Albian	SKM-7	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	F	R	R	R	R	R	F
	SKM-6			R	R			R	R		R	R	R		R		F			R			R
	SKM-5																						
Early Late Albian to Middle Albian	SV042605-1			R				R	R		R	R					F		R				
	SKM-4																C						R
	SKM-3																F		R				
	SKM-2																						
	SKM-1																						
	SKM102406-2																						
	SKM102406-1																						
	SV082200-2				R			R					F				A						
	SV060802-2							R	R						R								
	PA060806-3																						R
	PA060806-2																		R				
	PA060806-1					C		R	R			R	F										R

Age	Sample	SPORES AND POLLEN																					
		Nevesisporites semiscalaris	Osmundacidites wellmanii	**Pilosisporites trichopapillosus**	Rouseisporites radiatus	Schizosporis parvus	Sphagnum spp.	**Taurocusporites spackmani**	Taxodiaceae	**Trilobosporites apiverrucatus**	Undifferentiated Bisaccates	Cicatricosisporites australiensis	Concavissimisporites punctatus	Deltoidospora spp.	Exesipollenites tumulus	Gleicheniidites confossus	Lycopodiumsporites sp.	**Trilobosporites crassus**	**Trilobosporites perverulentus**	**Trilobosporites trioreticulosus**	Araucariacites australis	Cyathidites australis	Liliacidites crtassatus
Late Albian	SKM-7	R	R	R	R	R	R	R	R	R	F												
	SKM-6								R	R	R	R	R	R	R	R	R	R	R	R			
	SKM-5																						
Early Late Albian to Middle Albian	SV042605-1			R					R	R	R	R	R	R				R			R	R	R
	SKM-4			R						R	R		R	R	R	R			R	R			
	SKM-3					R	R			F	R			F	R					R			
	SKM-2									R												R	
	SKM-1																						
	SKM102406-2																						
	SKM102406-1																						
	SV082200-2								R		R			A							R		
	SV060802-2								R		R			R		F					F		
	PA060806-3				R	R					R			R			R	R					
	PA060806-2				R						R		R	R							R		
	PA060806-1			R		R			R		R	R	R	F			R	R			A	R	

Age	Sample	SPORES AND POLLEN																												
		Liliacidites peroreticulatus	Liliacidites reticulatus	Peromonolites allensis	Rouseisporites reticulatus	Rouseisporites triangulus	**Trilobosporites marylandensis**	**Trilobosporites tribotrys**	Asteropollis asteroides	Trilobosporites minor	Eucommiidites sp.	Acanthotriletes sp.	Parvisaccites sp.	Camarozonosporites heskimensis	Camarozonosporites insignis	Cerebropolenites mesozoicus	Foraminisporis wonthaggiensis	Klukisporites pseudoreticulatus	Rugubivesiculites rugosus	Appendicisporites cristatus	Cicatricosisporites crassiterminatus	Foraminisporis dailyi	Undulatisporites undulosus	Cicatricosisporites mohrioides	Densoisporites microrugulatus	Endosporites sp.	Lycopodiumsporites austroclavadidites	Lycopodiumsporites sp. A	Reticulatisporites arcuatus	Verrucosisporites sp.
Late Albian	SKM-7																													
	SKM-6																													
	SKM-5																													
Early Late Albian to Middle Albian	SV042605-1	R	R	R	R	R	R	R																						
	SKM-4							R	R	R																				
	SKM-3							R			R																			
	SKM-2											R																		
	SKM-1												R																	
	SKM102406-2																													
	SKM102406-1																													
	SV082200-2													R	R	R	R	R	R											
	SV060802-2														R			R		R	R	R	R							
	PA060806-3																													
	PA060806-2																													
	PA060806-1				R												R							R	R	R	R	R	R	R

Age	Sample	MICROPLANKTON													
		Aptea polymorpha	Canninginopsis colliveri	Chlamydophorella nyei	Cribroperidinium edwardsi	Oligosphaeridium complex	Oligosphaeridium pulcherrimum	Oligosphaeridium totum	Operculodinium sp.	**Ovoidinium verrucosum**	Pseudoceratioum retusum	Spiniferites ramosus	Tasmanaceae	Pterospermella sp.	Impletosphaeridium sp.
Late Albian	SKM-7														
	SKM-6														
	SKM-5														
Early Late Albian to Middle Albian	SV042605-1														
	SKM-4														
	SKM-3														
	SKM-2														
	SKM-1														
	SKM102406-2														
	SKM102406-1														
	SV082200-2	A	R	R	A	F	R	R	R	A	C	R	F		
	SV060802-2		R		A					R			A	A	
	PA060806-3									R			R		
	PA060806-2														
	PA060806-1							R							R

Bold - tops (extinctions) are Late Albian
Red - species that do not range below the Late Albian

R = Rare, less than 6 specimens/slide
F = Frequent, 6 to 15 specimens/slide
C = Common, 16 to 30 specimens/slide
A = Abundant, over 30 specimens/slide

Utah are similar to taxa described from the Dakota Formation and equivalents elsewhere in the Western Interior (Oboh-Ikuenobe and others, 2007; Ludvigson and others, 2010b). We also report a new radiometric age from a thick volcanic ash (bentonite) in the middle carbonaceous interval. Extracted zircons yielded 44 of 50 grains with U-Pb ages between 96 to 109 Ma, and 21 grains with ages between 100 and 104 Ma, giving a final age of 101.4 ± 0.4 Ma at ± 2 sigma (appendices B and D). This radiometric age is compatible with the late Albian age for this interval indicated by palynomorphs.

To the south, the Dakota Formation is Cenomanian based on the contained molluscan assemblage (Eaton and others, 1990; Cobban and others, 2006), radiometric ages (Cifelli and others, 1997; Dyman and others, 2002; Kirschbaum and Schenk, 2010), and palynology (Agasie, 1969; am Ende, 1991; Molenaar and Cobban, 1991).

Mowry Shale

The Mowry Shale is widely distributed in the northern and central Rocky Mountain region but is restricted to the northeastern part of Utah (Byers and Larson, 1979; Molenaar and Cobban, 1991; Ryer, 1993). It was first named by Darton (1904) as the Mowrie beds, a member of the Benton Formation exposed along Mowrie Creek (original spelling) in Johnson County, Wyoming; the spelling was changed to Mowry in 1906 (see Wilmarth, 1957). Since then, this formation has been extensively studied and undergone numerous revisions (see MacLachlan and others, 1996; U.S. Geological Survey, undated).

The Mowry Shale along the south flank of the Uinta Mountains is an easily recognizable formation because it forms silver-gray outcrops that support little vegetation (figures 1, 9, and 11). The Mowry is composed of siliceous shale that contains abundant fossilized scales, bones of teleost fish identified as belonging to the Beryciformes and Aleposaurids (Bilbey and Hamblin, 1992), and shark teeth (*Carcharias amonensis*, Anderson and Kowallis, 2005) in the lower half of the formation. Stewart (1996) described several specimens of the sphenocephalid teleost fish *Xenyllion zonensis* from the *Neogastroplites americanus* ammonite zone from in and around Dinosaur National Monument.

The radiometric age of the Mowry Shale is well constrained from $^{40}Ar/^{39}Ar$ sanidine ages obtained from bentonite beds that bracket the Mowry in Wyoming; the basal Arrow Creek Bentonite is 98.5 ± 0.5 Ma and the capping Clay Spur Bentonite is 97.2 ± 0.7 Ma (Obradovich, 1993). However, the biostratigraphic age of Mowry Shale is controversial because of the continued adjustment to the age of the Albian-Cenomanian boundary based on a shift in ammonite zones associated with new radiometric ages from Japan, and the discrepancy between Western Interior endemic ammonite zones and cosmopolitan dinoflagellates used to correlate to European reference sections (Cobban and Kennedy, 1989; Obradovich, 1993; Gale and others, 1996; Obradovich and others, 2002; Oboh-Ikuenobe and others, 2007; Scott, 2007; Ogg and others, 2008). The Mowry was originally treated as Early Cretaceous (late Albian) in age based on regional work (Cobban and Reeside, 1951; Reeside and Cobban, 1960; Antweiler and others, 1989; Tysdal and others, 1989). However, Cobban and Kennedy (1989) recommended a downward shift of the Albian-Cenomanian boundary from the top of the five neogastroplitid zones to the top of the second zone, thus the making the Mowry Late Cretaceous (Cenomanian) in age (Obradovich, 1993). Numerous researchers (Oboh-Ikuenobe and others, 2007; Scott, 2007; Scott and others, 2009) have challenged their recommendation and made a case, supported by the regional correlation of cosmopolitan dinoflagellates, for the Mowry to remain Albian in age.

DISCUSSION

The Cedar Mountain Formation in northeastern Utah consists of the basal Buckhorn Conglomerate Member or a basal interval of mottled, yellow-orange mudstone with scattered chert pebbles, overlain by a carbonate-rich mudstone that grades upward into a capping noncalcareous mudstone. The basal mottled chert-pebble mudstone beds may represent soil development on floodplain deposits and likely grade laterally to the Buckhorn Conglomerate Member, as has been demonstrated with the Yellow Cat–Buckhorn Members in central Utah (Greenhalgh and Britt, 2007). The bulk of strata exhibited in our sections of the Cedar Mountain Formation best fit the Ruby Ranch Member. The Ruby Ranch Member in its type area (between Crescent Junction and Green River, Utah) is typically drab green and mauve variegated slope-forming mudstone whose most conspicuous features are numerous carbonate nodules that cover the surface and ribbon sandstone lenses (Kirkland and others, 1997; Ludvigson and others, 2010a).

The uppermost part of the Cedar Mountain in northeastern Utah is reminiscent of the Mussentuchit Member of the Cedar Mountain Formation of the western San Rafael Swell, but radiometric data, dinosaur biostratigraphy, and palynomorph assemblages from sections in central Utah indicate these beds are not time equivalent (Tschudy and others, 1984; Cifelli and others, 1997; Kirkland and others, 1997; Kirkland and others, 1999; Sprinkel and others, 1999; Garrison and others, 2007; Kirkland and Madsen, 2007). Radiometric ($^{40}Ar/^{39}Ar$ sanidine) ages obtained from the lower part of the Mussentuchit Member of the Cedar Mountain Formation on the San Rafael Swell are 98.37 ± 0.07 Ma (Cifelli and others, 1997; 1999) and 98.5 ± 0.06 Ma (Garrison and others, 2007). These ages are similar to the radiometric age of the Arrow Creek Bentonite (Obradovich, 1993). A radiometric ($^{40}Ar/^{39}Ar$ sanidine) age of 97.2 ± 0.06 Ma was obtained from near the top of the Mussentuchit Member (Garrison and others, 2007) and is similar to the age of the Clay Spur Bentonite (Obradovich, 1993).

Thus, these dates indicate that the Mussentuchit Member in its type area on the southwest side of the San Rafael Swell is equivalent to the Mowry Shale in Wyoming. In addition, the discontinuous conglomerate that separates the Mussentuchit from the underlying Ruby Ranch member along the west side of the San Rafael Swell (Kirkland and Madsen, 2007; Lawton and others, 2010; Paul Kuehne, Utah Geological Survey, 2010 written communication) may correlate with the Dakota Formation in northeastern Utah, based on late Albian radiometric age and palynomorph assemblage reported here.

Currently, we believe it is unwarranted to use the member names of the Cedar Mountain Formation defined by Kirkland and others (1997) and Kirkland and others (1999) in central Utah for the Cedar Mountain Formation in northeastern Utah because not all members may be represented. However, if the relationship between the Buckhorn Conglomerate Member and the basal mottled chert-pebble mudstone unit can be demonstrated in northeastern Utah, as Greenlaugh and Britt (2007) have shown for the Buckhorn Conglomerate and Yellow Cat Members in central Utah, perhaps the terms Yellow Cat and Ruby Ranch Members can both be applied to the Cedar Mountain Formation in northeastern Utah. If those terms are used, we believe the Mussentuchit Member should not be applied to the uppermost part of the Cedar Mountain Formation in northeastern Utah because the Mussentuchit in central Utah is time equivalent to the Mowry Shale in northeast Utah.

The initial transgression of the Cretaceous Western Interior Seaway in the Rocky Mountain region is recorded in Albian-age marine strata, and the transgressive shoreline approached and possibly encroached into the northeastern corner of Utah by late Albian (Weimer, 1984; Ryer, 1993; Cobban and others, 1994; Dickinson, 2006). Our palynomorph assemblage from the Dakota Formation (table 1) is similar to the assemblage from the Thermopolis Formation of central and southern Wyoming, and the Dakota Formation of Kansas, Nebraska, and Iowa (Oboh-Ikuenobe and others, 2007; Scott, 2007; Scott and others, 2009; Ludvigson and others, 2010b). The middle to late Albian microplankton recovered from the dark-gray, organic-rich shale in the basal Dakota Formation and the irregular thickness of this interval indicate the initial marine incursion into northeastern Utah was likely restricted to incised valleys and other low-lying areas, similar to the Dakota Formation found elsewhere along the Western Interior Seaway (Ludvigson and others, 2010b).

The middle Cretaceous within the Western Interior basin includes the Kiowa–Skull Creek marine depositional cycle (Albian) and Greenhorn marine depositional cycle (Cenomanian) (Brenner and others, 2000). Recently, Ludvigson and others (2010b) proposed a new Muddy-Mowry depositional cycle that separates the Kiowa–Skull Creek and Greenhorn cycles. The Cedar Mountain Formation in northeastern Utah is, in part, the landward time-equivalent of the Kiowa–Skull Creek cycle (figure 13). The basal dinoflagellate-bearing mudstone and shale unit of the Dakota Formation represents peak sea level during the Kiowa–Skull Creek cycle and the initial marine incursion into northeastern Utah (figure 13). The overlying non-marine part of the Dakota Formation and marine Mowry Shale represent the newly recognized Muddy-Mowry cycle (figure 13). Marine environments did not transgress into central Utah until the late Cenomanian (Elder and Kirkland, 1993; Cobban and others, 1994; Elder and Kirkland, 1994).

CONCLUSIONS

The Lower Cretaceous section exposed in northeastern Utah includes the Cedar Mountain and Dakota Formations. The Cedar Mountain Formation consists of fluvial-lacustrine and pedogenic carbonate beds and includes important dinosaur sites. The basal mottled chert-pebble mudstone beds may represent soil development on floodplain deposits and likely grade laterally to the Buckhorn Conglomerate Member, as has been demonstrated with the Yellow Cat–Buckhorn Members in central Utah (Greenhalgh and Britt, 2007). The bulk of strata exhibited in our sections of the Cedar Mountain Formation best fit the Ruby Ranch Member. The uppermost part of the Cedar Mountain in northeastern Utah is reminiscent of the Mussentuchit Member of the Cedar Mountain Formation of the western San Rafael Swell, but radiometric data, dinosaur biostratigraphy, and palynomorph assemblages from sections in central Utah indicate these beds are not time equivalent (Tschudy and others, 1984; Cifelli and others, 1997; Kirkland and others, 1997; Kirkland and others, 1999; Sprinkel and others, 1999; Garrison and others, 2007; Kirkland and Madsen, 2007).

The age of the Cedar Mountain Formation in northeastern Utah is early to late Albian from a radiometric age (detrital U-Pb zircons) of 104.46 ± 0.95 Ma associated with a well-preserved sauropod skull, chemostratigraphic analysis, and palynology in the overlying Dakota Formation. Part of the Cedar Mountain Formation was deposited during the Kiowa–Skull Creek depositional cycle.

The Dakota Formation along the flanks of the Uinta Mountains typically consists of lower and upper light-colored and cross-bedded sandstone ledges separated by dark-colored carbonaceous mudstone and shale. The sandstone and mudstone beds are nonmarine; however, locally the basal Dakota Sandstone includes a thin interval of marine mudstone and shale beds. Our palynomorph assemblage recovered from the basal Dakota Formation is similar to the assemblage from the Thermopolis Formation of central and southern Wyoming, and the Dakota Formation of Kansas, Nebraska, and Iowa (Oboh-Ikuenobe and others, 2007; Scott, 2007; Scott and others, 2009; Ludvigson and others, 2010b). The irregular thickness of this interval indicates that the initial marine incursion into northeastern Utah was likely restricted to incised valleys and other low-lying areas, similar to the Dakota Formation found elsewhere along the Western Interior Seaway (Ludvigson and others, 2010b).

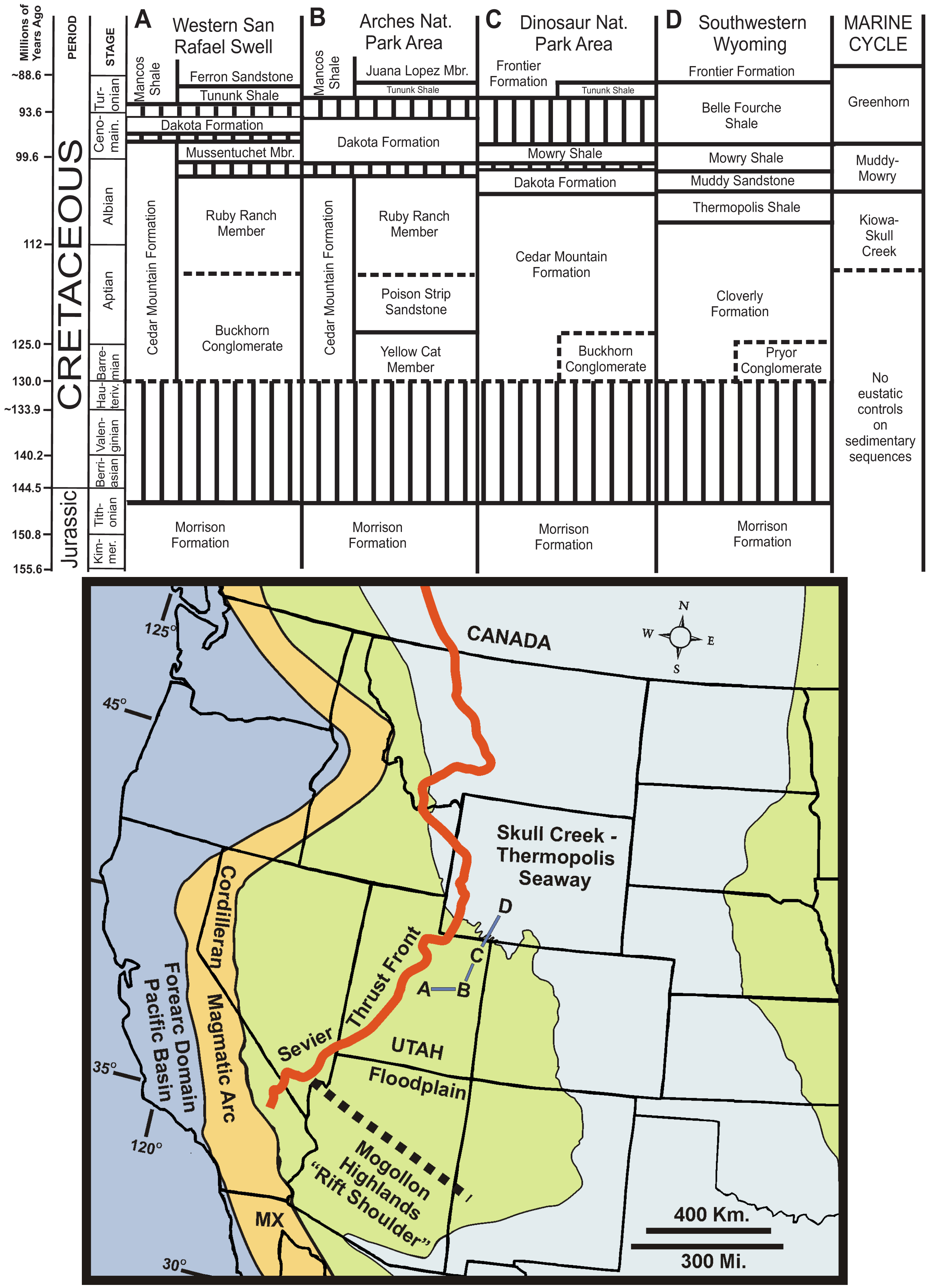

Figure 13. *Correlation chart of Cretaceous formations from the San Rafael Swell in central Utah to southwest Wyoming and associated marine depositional cycles. The paleogeographic map shows the Western Interior Seaway in late Albian time at peak sea level at the end of the Kiowa–Skull Creek marine cycle. The approximate position of the stratigraphic columns A–D is shown on the map, which is modified from Cobban and others (1994) and Dickinson (2006).*

Dinoflagellate cysts recovered from this basal marine interval represent peak sea level during the Kiowa–Skull Creek depositional cycle and the first marine incursion of the Cretaceous Western Interior Seaway into Utah. The age for this event is middle late Albian. An ash bed in the middle Dakota yielded a U-Pb zircon age of 101.4 ± 0.4 Ma, which correlates to the newly defined Muddy-Mowry depositional cycle.

The Mowry Shale consists of siliceous marine shale that represents widespread open-marine conditions for the area. The radiometric age of the Mowry is between 98.5 ± 0.5 Ma and 97.2 ± 0.7 Ma (^{40}Ar/^{39}Ar sanidine) from bentonite beds in Wyoming. However, the biostratigraphic age is controversial because of downward revision to key neogastroplitid ammonite zones, revision of the Albian-Cenomanian boundary age to 99.6 Ma, and recently published palynostratigraphic work.

ACKNOWLEDGMENTS

This project was supported by the Colorado Plateau-Cooperative Ecosystems Studies Unit of the National Park Service and joint funding by the Utah Geological Survey and U.S. Geological Survey through STATEMAP Agreement Nos. 03HQAG0096, 02HQAG055, 01HQAG100, 00HQAG109, and 99HQAG0138. We thank Paul O'Sullivan for the rapid turnaround of the laser ablation data and Apatite to Zircon, Inc. for granting us permission to publish all of the radiometric data tables. We thank Grant Willis, Mike Hylland, Don DeBlieux, and Robert Ressetar (Utah Geological Survey), Brian Currie (Miami University, Ohio), Tim Lawton (New Mexico State University), and Greg Ludvigson (Kansas Geological Survey) for their thoughtful and careful review of the manuscript. We also thank Martha Hayden and Mike Lowe for their editorial reviews of this manuscript.

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APPENDICES

Appendix A. Measured sections

- **on CD:** Sprinkel-etal_CedarMtn-Dakota_Appendix A.pdf
- **online:** geology.utah.gov/online/ss/ss-143/ss-143appx_a.pdf

Appendix B. Detrital zircon U-Pb report on UPbICP and Related Excel Workbooks: Software for Calculating U-Pb Zircon Ages and Presenting U-Pb Data Obtained by LA-ICP-MS

- **on CD:** Sprinkel-etal_CedarMtn-Dakota_Appendix B-UPbICP Report.pdf
- **online:** geology.utah.gov/online/ss/ss-143/ss-143appx_b.pdf

Appendix C. Detrital zircon U-Pb data for the Cedar Mountain Formation

- **on CD:** Sprinkel-etal_CedarMtn-Dakota_Appendix C-CedarMtn UPbICP Data_1131-02.xls
- **on CD:** Sprinkel-etal_CedarMtn-Dakota_Appendix C-CedarMtn UPbICP Data_1131-02.pdf
- **online:** geology.utah.gov/online/ss/ss-143/ss-143appx_c.xls

Appendix D. Detrital zircon U-Pb data for the Dakota Formation

- **on CD:** Sprinkel-etal_CedarMtn-Dakota_Appendix D-Dakota UPbICP-Data_1131-01.xls
- **on CD:** Sprinkel-etal_CedarMtn-Dakota_Appendix D-Dakota UPbICP Data_1131-01.pdf
- **online:** geology.utah.gov/online/ss/ss-143/ss-143appx_d.xls

Appendix E. Photomicrographs and plate descriptions of key marine microplankton from the Dakota Formation.

- **on CD:** Sprinkel-etal_CedarMtn-Dakota_Appendix E.pdf
- **online:** geology.utah.gov/online/ss/ss-143/ss-143appx_e.pdf

Appendix F. Photomicrographs and plate descriptions of key spores and pollen from the Dakota Formation.

- **on CD:** Sprinkel-etal_CedarMtn-Dakota_Appendix F.pdf
- **online:** geology.utah.gov/online/ss/ss-143/ss-143appx_f.pdf