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A Stratigraphic and Geochronologic Analysis of the Morrison Formation/Cedar Mountain Formation Boundary, Utah

Brent W. Greenhalgh
Brigham Young University - Provo

A STRATIGRAPHIC AND GEOCHRONOLOGIC ANALYSIS OF THE MORRISON FORMATION/CEDAR MOUNTAIN FORMATION BOUNDARY, UTAH

by

Brent W. Greenhalgh

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Master of Science

BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

Brent W. Greenhalgh

This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

Date	Brooks B. Britt, Chair
Date	Bart J. Kowallis
Date	Thomas H. Morris
Date	Scott M. Ritter

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Date	Brooks B. Britt Chair, Graduate Committee

Accepted for the Department

Date	Michael J. Dorais Graduate Coordinator

Accepted for the College

Date	Thomas W. Sederberg Associate Dean, College of Physical and Mathematical Sciences

Abstract

A STRATIGRAPHIC AND GEOCHRONOLOGIC ANALYSIS OF THE MORRISON FORMATION/CEDAR MOUNTAIN FORMATION BOUNDARY, UTAH

Brent W. Greenhalgh

Department of Geological Sciences

Master of Science

The Lower Cretaceous Cedar Mountain Formation preserves several vertebrate faunas and has the potential of providing critical timing information pertaining to Early Cretaceous dinosaurs and the Sierran magmatic arc. Historically, the Morrison/Cedar Mountain contact and the duration of the unconformity between them have been difficult or impossible to determine because 1) the formations were deposited in similar environments, 2) the basal Cedar Mountain Formation is composed of reworked Morrison Formation, and 3) there are no radiometric ages for the lower Cedar Mountain Formation. A stratigraphic study through central Utah reveals a diagnostic suite of pedogenic and sedimentologic characters across the previously enigmatic boundary. The

uppermost Morrison Formation is characterized by redoximorphic paleosol features, including iron concentrations, manganese-coated grains, and intense red-purple-green mottling. Upsection increases in chert-pebble lags and channelized conglomerates within the paleosol section indicate a period of reduced accommodation space in the Tithonian. The paleosols are usually capped by a groundwater or pedogenic carbonate. This unit is consistently present from Green River, Utah to the Utah-Colorado border. The lower Cedar Mountain Formation above this package is a poorly sorted mixture of fine-grained material and sand-gravel sized chert grains. Within a sequence stratigraphic framework, these characters record a terrestrial sequence boundary in the uppermost Morrison Formation and degradational-aggradational systems tracts in the Cedar Mountain Formation.

To resolve the lack of age control for the basal Cedar Mountain Formation, a geochronologic zircon study was conducted near the Dalton Wells dinosaur quarry, Moab, Utah. The Dalton Wells quarry, along with numerous other fossil assemblages occurs in the basal Yellowcat Member. Zircons from the Dalton Wells quarry and a correlative eggshell site place the age of this horizon near the Barremian/Aptian boundary at ~124 Ma. Thus, the Yellowcat fauna is time equivalent with the feathered dinosaurs of the Yixian Formation, of Liaoning, China. This age constrains the Morrison/Cedar Mountain unconformity to a period of magmatic quiescence in western North America from 148 Ma-124 Ma. The basal Cedar Mountain age coincides with renewed magmatic activity at ~125 Ma. The Cedar Mountain Formation covers a period of 27 Myr and likely contains numerous small unconformities.

Preface

This thesis contains two chapters each containing a manuscript that will be submitted to a peer-reviewed journal for publication. Each chapter is complete with its own figures, tables, and references. A chapter specific table of contents and figure list occurs at the beginning of each chapter.

Acknowledgements

This work is the culmination of research conducted with the assistance of many people. Without their help, the project would not have been successful. There are many people I would like to thank. I thank my advisor, Brooks Britt for his support of the research project, his enthusiasm for completing it and thoughtful advice and critiques. Brigham Young University and the Geology Department provided financial support for my research. George Gehrels, Victor Valencia and the LaserChron staff at the University of Arizona accommodated my research in their lab and Sam Sorber analyzed zircons while I attended to urgent family business. I thank my committee and Eric Christiansen, Dave Eberth and Greg Retallack for providing direction during the course of my research. Most of all, I thank my wife for her unwavering support of me in completing this project.

Chapter 1
Stratigraphy and Sedimentology of the Morrison/Cedar Mountain Formational Boundary

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Abstract

The Lower Cretaceous Cedar Mountain Formation preserves several vertebrate faunas and has the potential of providing critical timing and deformational information pertaining to the shift from Nevadan to Sevier events in the western North American cordillera. Historically, the contact between the Cedar Mountain Formation and Morrison Formation and the duration of the unconformity between them have been difficult or impossible to determine because 1) the formations were deposited in similar environments, 2) the basal Cedar Mountain Formation is composed of reworked Morrison Formation and 3) there are no radiometric ages for the lower Cedar Mountain Formation. A stratigraphic study through central Utah reveals a diagnostic suite of pedogenic and sedimentologic characters across the previously enigmatic boundary. The uppermost Morrison Formation is characterized by redoximorphic paleosol features, including iron concentrations, manganese-coated grains, and intense red-purple-green mottling. Upsection increases in chert-pebble lags and channelized conglomerates within the paleosol section indicate a period of reduced accommodation space in the Tithonian. The paleosol package is usually capped by a groundwater or pedogenic carbonate. This unit is consistently present from Green River, Utah to the Utah-Colorado border. The lower Cedar Mountain Formation above this package is a poorly sorted mixture of fine-grained material and sand-gravel sized chert grains. These sediments buried the Morrison Formation in response to renewed tectonic activity to the southwest. These characters record a terrestrial sequence boundary in the uppermost Morrison Formation and degradational-aggradational systems tracts through Cedar Mountain time. These

characters provide a method for picking the boundary which will aid in interpreting the stratigraphic relationship of the Morrison and Cedar Mountain Formations.

Introduction

In outcrops extending from central Utah to the Rocky Mountains the Cedar Mountain Formation is one of the few sedimentary rock units deposited during the Early Cretaceous in western North America (Stokes, 1952b). An interval containing uniformly distributed calcareous material was included in the definition of the Morrison Formation (Emmons et al., 1896). This calcareous unit was likely an equivalent of the Cedar Mountain Formation; however it was not differentiated from the Morrison Formation (Emmons et al., 1896). Nearly 50 years later, Stokes (1944) formally separated the Cedar Mountain Formation. Subsequent dinosaur discoveries and other biostratigraphic data have confirmed Stokes' distinction and suggested an Early Cretaceous age for the Cedar Mountain Formation (Tschudy et al., 1984; Kirkland, 1996; Eberth et al., 2006). This places the Cedar Mountain Formation in a unique position to answer critical timing questions pertaining to vertebrate evolution (Kirkland et al., 1999) and the transition from Nevadan to Sevier tectonic events.

Two critical issues make interpretations of the tectonic and paleontologic aspects of the Cedar Mountain Formation difficult. First, the Cedar Mountain Formation and underlying Morrison Formation were deposited in very similar continental fluvial systems, making the boundary between them difficult to recognize. Second, the lack of radiometric ages makes understanding the geochronology of the lower, fossil-rich members of the Cedar Mountain Formation difficult. Correctly placing the boundary has implications for understanding the diverse assemblage of dinosaurs found in the basal

Cedar Mountain Formation and the stratigraphic and tectonic relationship between the Morrison and Cedar Mountain Formations.

Purpose

The purposes of this study are to: (1) Describe and characterize the lithologic and pedogenic features across the Morrison Formation/Cedar Mountain Formation boundary within Utah; and (2) to interpret these features in a sequence stratigraphic and tectonic framework.

Background

Morrison Formation Tectonics & Paleogeography

During the Late Jurassic, the western margin of North America was the site of subduction and arc magmatism (DeCelles, 2004). A fold and thrust belt related to subduction of the Farallon plate propagated as far east as central Nevada (Smith et al., 1993). The Morrison Formation was likely deposited in the backbulge of a foreland basin east of the advancing thrust front (Royse, 1993; Currie, 1997). Morrison Formation isopachs and modern backbulge analogs support this conclusion (Horton and DeCelles, 1997). The Morrison Formation extends from central Utah, where it is ~450 m thick, to a zero edge in western Kansas (Peterson, 1972). Flexural and dynamic subsidence provided the accommodation space (DeCelles, 2004) to preserve ash layers and fine-grained clastic material typical of the Brushy Basin Member of the Morrison Formation. An unconformity marks the top of the Morrison Formation regionally (McGookey et al., 1972), which was likely due to a combination of eastward forebulge migration and dynamic uplift of the basin (Royse, 1993; Currie, 1998).

Cedar Mountain Formation Tectonics & Paleogeography

Similar to the Morrison Formation, the Cedar Mountain Formation is dominantly composed of fluvial overbank silt and mud, channelized sandstone bodies and lacustrine and pedogenic limestone (Stokes, 1944). During the Early Cretaceous, a significant decrease in the volume of arc magmatism and a propagation of thrusting into central Utah and Idaho occurred (Christiansen et al., 1994; DeCelles, 2004). Emplacement of thrust sheets in western Utah shifted the foreland basin into central and eastern Utah, where the Cedar Mountain Formation was deposited in foredeep and backbulge settings (Currie, 1998). Pedogenic carbonate in the basal Cedar Mountain Formation indicates an arid Early Cretaceous climate (e.g. Smith et al., 2001; Ludvigson et al., 2002; Retallack, 2005). A gradual upsection decrease in carbonate and increase in preservation of organic material indicates changing climatic conditions during the deposition of the formation, possibly due to the advancing Cretaceous seaway (Currie, 1998).

Previous Work

Outcrops of fluvial strata overlying the McElmo Formation (equivalent to the Morrison Formation) in southwestern Colorado were first described by Coffin (1921) and named the "Post-McElmo Formation" (Fig. 1). Working in equivalent beds near Cedar Mountain, Emery County, Utah, Stokes (1944) described two stratigraphic units above the Morrison Formation; the Buckhorn Conglomerate and Cedar Mountain Shale. The dramatic increase in grain size from the Brushy Basin Member of the Morrison

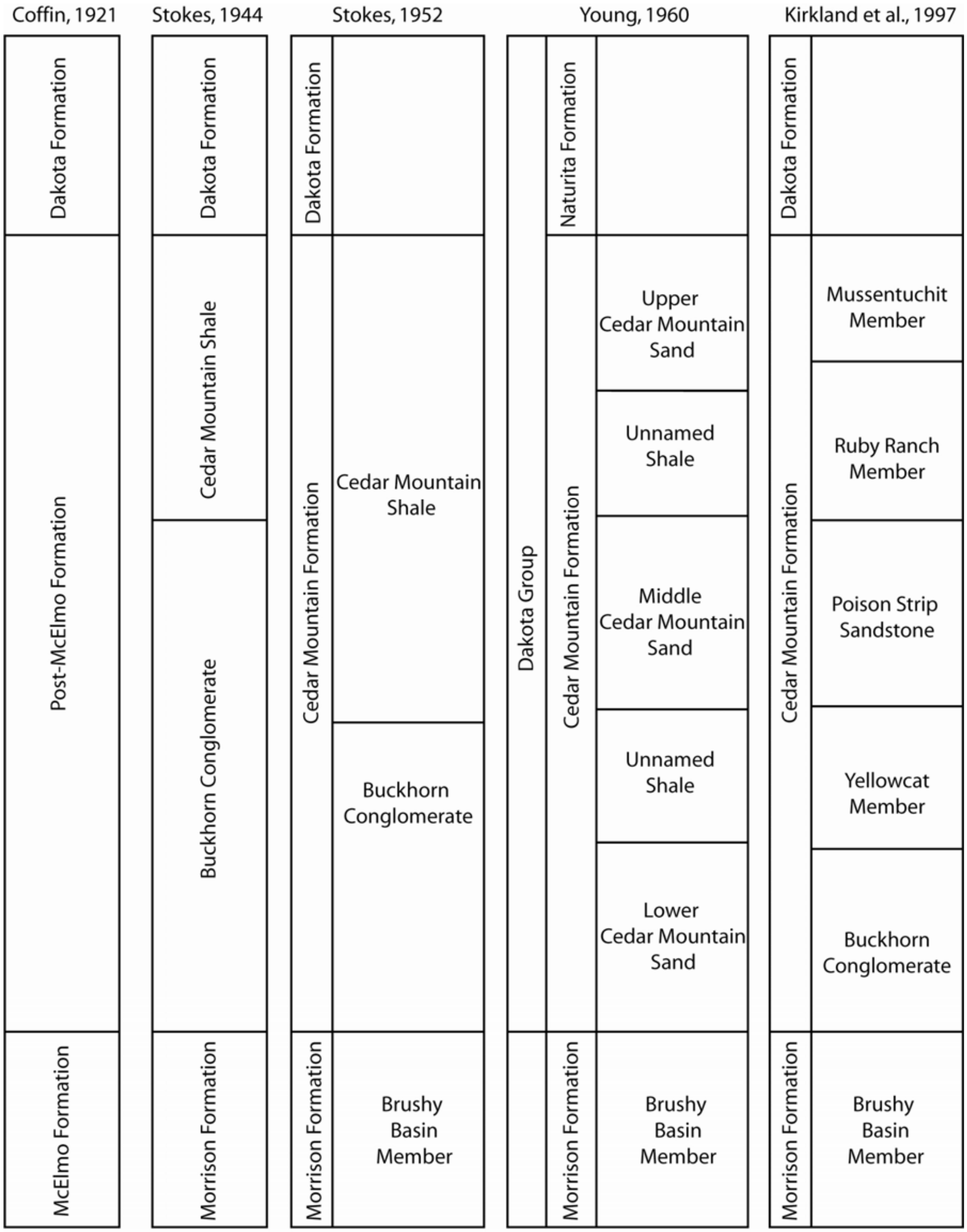

Figure 1.
Progression of Morrison-Dakota stratigraphic nomenclature.

Formation to the Buckhorn Conglomerate was the first evidence of an upper Morrison unconformity and the basis for making the Buckhorn Conglomerate and Cedar Mountain Shale formal stratigraphic units (Stokes, 1944). Further work suggested a close depositional relationship between the conglomerate and shale units and led to their combination as members of the Cedar Mountain Formation (Stokes, 1952a). Despite the coarse-grained conglomeratic material at the boundary throughout much of central Utah, Craig (1955) disagreed with the notion of an unconformity at the top of the Morrison Formation. He stated that the boundary is only identifiable where the conglomeratic material is present and that the two formations were a continuation of the same depositional system. A number of different models have been proposed for dividing the Morrison-Buckhorn-Cedar Mountain interval (Currie, 1997; Kirkland et al., 1997; Aubrey, 1998), however, none have gained widespread acceptance.

Young's and Craig's Studies

Work by Young (1960) demonstrated a possible relationship between the abundant fluvial sandstone bodies in the Cedar Mountain Formation. Young correlated three distinct sandstone packages (lower, middle and upper) and proposed an upsection eastward progression of these sands (Young, 1960). He also proposed an interfingering of the Cedar Mountain Formation with the transitional-marine deposits of the Naturita Formation (equivalent to the Dakota Sandstone/Mancos Shale) indicating that the Cedar Mountain Formation was the alluvial equivalent of the Naturita Formation. Molenaar and Cobban (1991) supported this correlation using outcrop and subsurface data from around the Uinta Basin in northeastern Utah. Craig (1961) challenged Young's proposed correlations because most of the Cedar Mountain Formation sandstone units were channelized and discontinuous. Additionally, he argued that the character of the sands were not distinct enough to distinguish one from another over large distances.

Despite the general dismissal of Young's stratigraphic model for the Cedar Mountain Formation sands (Craig, 1961; Currie, 1997; Kirkland et al., 1997), the details of his observations provided a broad base for subsequent studies.

Kirkland and Others' Study

Kirkland and others (1997) outlined the current, although informal, stratigraphic nomenclature for the Cedar Mountain Formation. Lithologic and paleontological data were used to divide the Cedar Mountain Formation into five members (Fig. 2). Unconformities were conjectured at the base of the Buckhorn and Yellowcat Members and between the Yellowcat Member and Poison Strip Sandstone based primarily on postulated changes in dinosaur faunas (Kirkland et al., 1997). Kirkland and others (1997) nomenclature is adopted for this study in the Green River-Moab area where it can be easily applied. Outside these areas Stokes (1944) original nomenclature is used.

Eberth and Others' Study

Eberth and others (2006) found that the Yellowcat and Poison Strip Sandstone Members interfinger and share a common dinosaur fauna, indicating the units are contemporaneous and that there is no unconformity between them, contrary to Kirkland and others (1997) (Fig. 2). They also found that the Yellowcat Member consists almost entirely of reworked, but minimally transported, Morrison Formation sediments, which explains why it has been so difficult to identify the Morrison/Cedar Mountain contact. They determined that the Yellowcat and Poison Strip Sandstone Members are facies

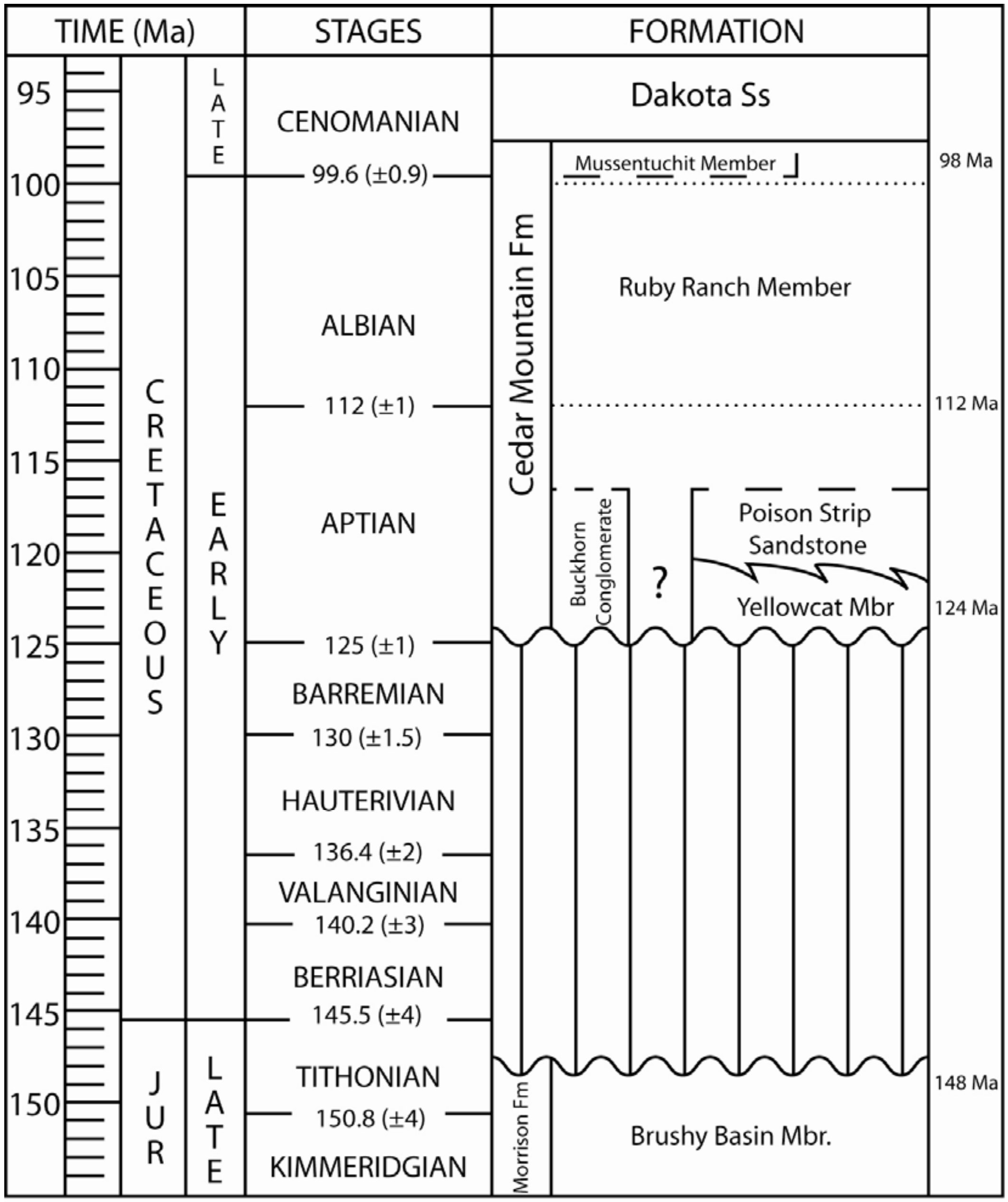

Figure 2.
Revised geochronologic chart for the Morrison-Cedar Mountain interval with informal Cedar Mountain members showing time-span of the Cedar Mountain Formation and the duration of the Morrison /Cedar Mountain unconformity; adapted from Kirkland and others (1997). Timescale from Gradstein and others (2004). Morrison age from Kowallis and others (1998). Basal Cedar Mountain Formation age from chapter 2 of this study. Interfingering of the Poison Strip Sandstone with the Yellowcat Member was demonstrated by Eberth and others (2006). Dashed lines represent uncertain ages. Dotted lines indicate tentative ages based on C-isotope stratigraphy from Lockley and others (2004). Mussentuchit Member age from Cifelli and others (1997).

of a northeastwardly directed fluvial system (Currie, 1997) that buried the Morrison Formation in response to a pulse of tectonic activity to the west.

These studies show that combining paleontologic, stratigraphic and paleogeographic data sets is the key to understanding the Cedar Mountain Formation. As such, in order to understand the Morrison/Cedar Mountain boundary a similar approach of combining multiple data sets is needed. This study presents criteria for distinguishing the Morrison/Cedar Mountain boundary based on sedimentologic, pedogenic and paleontologic characters (Table 1).

Methods

The Morrison/Cedar Mountain boundary was identified at 51 localities covering three distinct areas (Fig. 3); Green River-Moab, San Rafael Swell, and Uinta Mountains. Outcrops in the Green River-Moab area occur south of Interstate 70 from Green River to the Utah-Colorado border and in and around Arches National Park. The San Rafael Swell is defined by outcrops of Morrison and Cedar Mountain strata on the flanks of the San Rafael Swell monocline. The Uinta Mountains area consists of outcrops primarily on the south flank of the Uinta Mountains near Vernal, Utah and Dinosaur National Monument. Lithology, sedimentary facies and pedogenic features were used to identify the boundary. To insure that our observations were not biased toward any particular feature, the starting point for our observations was from the well known, intensely color banded, bentonitic Morrison slopes through strata that were clearly Cedar Mountain Formation, based on the absence of bright color banding and presence of pedogenic carbonate nodules. Fine-grained portions of the section were trenched to expose fresh rock surfaces. Twenty sections were measured using a 1.5 meter survey staff with a top-

TABLE 1. MORRISON/CEDAR MOUNTAIN BOUNDARY CHARACTERS BY AREA

	Feature	Interpretation	Green River/Moab	San Rafael Swell	Uinta Mtns.
Cedar Mountain Formation	Unlithified pebble/cobble conglomerate	Fluvial sheet deposits, overbank splays, avulsion deposits incorporating overbank material		X	X
	Massive to cross stratified conglomerate dominated by dark chert clasts	Ephemeral, high-energy fluvial channel deposits		X	X
	Abundant carbonate nodules in the basal Cedar Mountain Formation	Subsurface Bk horizons of seasonally wet and dry climatic regimes (Retallack, 2001)		X	X
	Cretaceous dinosaur bone and large polished chert clasts (“gastroliths”)	Vertebrate material preserved at the boundary due to an increase in accommodation space (Eberth et al., 2001)	X		X
	Green muddy pebble conglomerate	Debris Flow deposits	X		X
	Non-bentonitic mudstone	Ash-poor fluvial silt and mud	X	X	X
Morrison Formation	Laminated calcrete/silcrete	Well developed (stage V-VI) paleosol Bk horizon, likely marking an unconformity (Retallack, 1998; Retallack, 2001).	X	X	X
	Increase in the abundance of sand-gravel sized reddish chert grains	Deflation surface due to exposure and winnowing of Morrison Formation strata (e.g.(Stokes, 1942))	X		
	Brick red horizon near the top of the Morrison Formation	Alluvial paleosols reddened by burial (e.g. Retallack, 1997).	X		X
	Iron and Manganese nodules and coats, deeply mottled red/purple silt and mudstones	Paleosol complex representing alternating saturated and well-drained soil conditions (Demko et al., 2004)	X		X
	Bentonitic mudstone	Altered volcanic ash	X	X	X

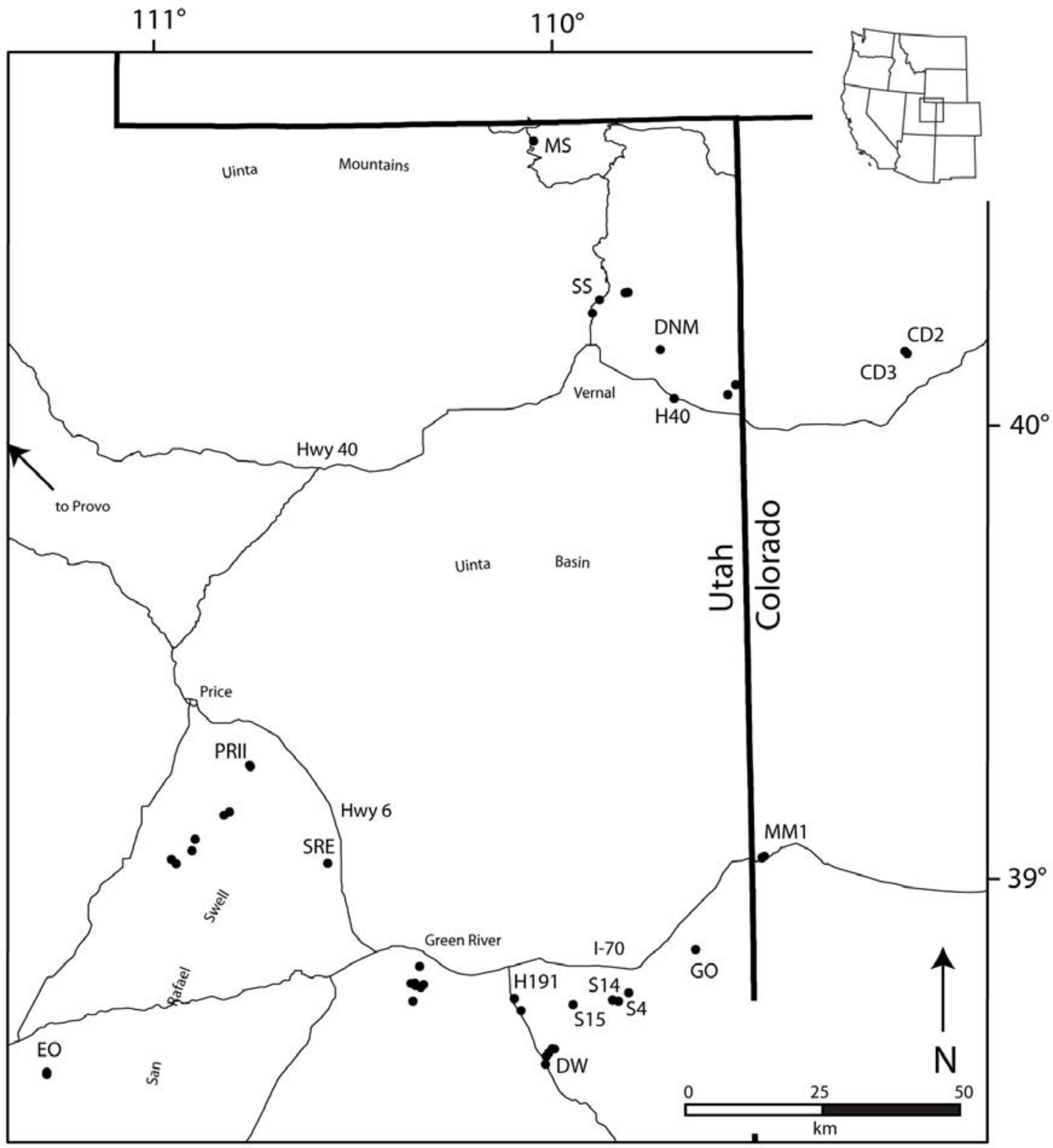

Figure 3.
Morrison Formation/Cedar Mountain Formation boundary study index map. Black dots mark Morrison Formation/Cedar Mountain Formation study locations.

mounted clinometer. Section thicknesses range from 10 to 100 meters. All measured sections cover the uppermost Morrison Formation and lowermost Cedar Mountain Formation. Additionally, many cover the entire Cedar Mountain Formation. Coordinates were taken with a handheld GPS receiver (1983 North American Datum [NAD 83]) and plotted with ArcGIS software.

Results

Green River-Moab

Morrison Formation

The Morrison /Cedar Mountain boundary from Green River, Utah to the Utah-Colorado border has a very consistent, well developed expression (Figs. 4 and 5). The upper 15 m of Morrison Formation is characterized by a significant increase in the abundance of gravel-sized material and in the degree of paleosol development relative to the underlying portions of the Brushy Basin Member (Fig. 4). Isolated channelized conglomerates and sand/gravel sized chert pebble lags are present and increase in abundance up to the boundary. Maximum channel widths vary from a few to tens of meters. Many of the chert pebbles are coated with a metallic gray/blue manganese coating distinctive from chert found in the overlying Cedar Mountain Formation and underlying Morrison Formation. This part of the section also displays intense mottling and iron enrichments in the form of mustard colored (10YR 6/6, GSA Rock Color Chart Value) and blackish red (5R 2/2) stains and concretions. Heavily rooted horizons are apparent primarily in sand-rich intervals. While the Morrison Formation paleosols are not calcareous, in approximately 50% of our sections the paleosols are capped by a 1-3 meter thick carbonate horizon (Fig. 6). This likely represents Early Cretaceous climatic and hydrologic overprinting of the Morrison paleosol sequence (Demko et al., 2004).

Cedar Mountain Formation

The basal Cedar Mountain Formation in the western portion of this area is composed of gray-green (5G 5/2) massive, poorly stratified pebbly mudstone with abundant red chert grains (Figs. 5 and 6). Massive to poorly-defined graded beds and burrows are typical of this unit, as well as vertebrate accumulations, including the Dalton Wells dinosaur quarry. East of Salt Valley Anticline the basal Cedar Mountain Formation changes to a very fine-grained purple silty mudstone. Bone accumulations in this area contain dinosaurs similar to those found throughout the lower Cedar Mountain Formation along with an increase in aquatic forms.

San Rafael Swell

Morrison Formation

On the western slope of the San Rafael Swell the uppermost Morrison Formation is a slightly mottled brownish gray (5YR 4/1) silty mudstone. Pedogenic features are scarce in contrast to the uppermost Morrison Formation in the Green River area. Sand to gravel-sized chert grains are common and increase in abundance up to the Cedar Mountain boundary. These features are common in the uppermost Morrison Formation along the western limb of the San Rafael Swell. Where the Buckhorn Conglomerate is absent, the Morrison Formation is often capped by a one half to two meter thick silcrete or calcrete (Figs. 7 and 8).

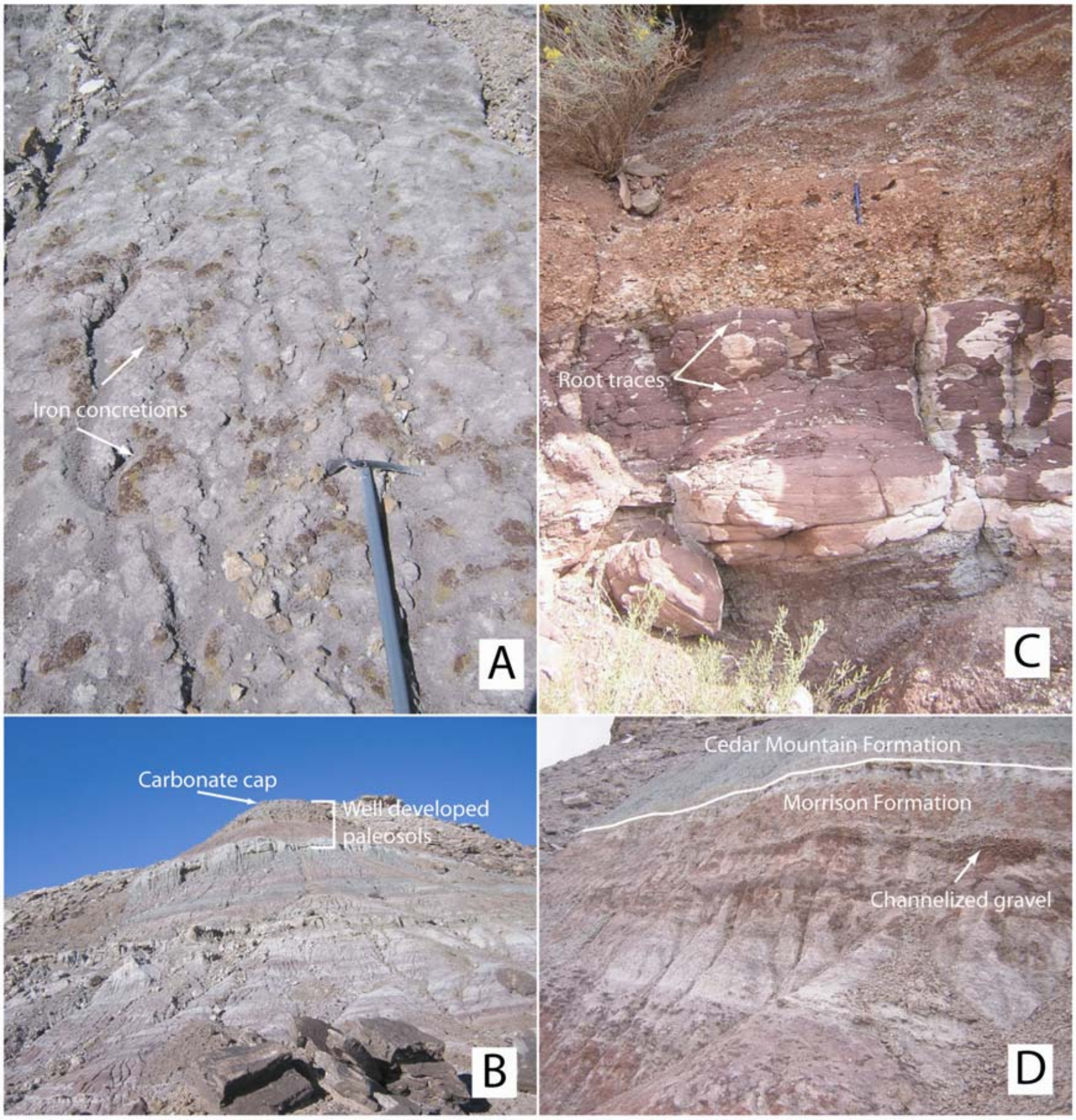

Figure 4.
Uppermost Morrison interval in the Green River-Moab area. A) Yellow and red iron concretions in a mottled purple-green matrix. B) Stacked succession of paleosols capped by carbonate cap. C) Root traces in channelized sandstone overlain by pedogenically overprinted sandstone. D) Small channelized gravel deposits in red paleosol horizons.

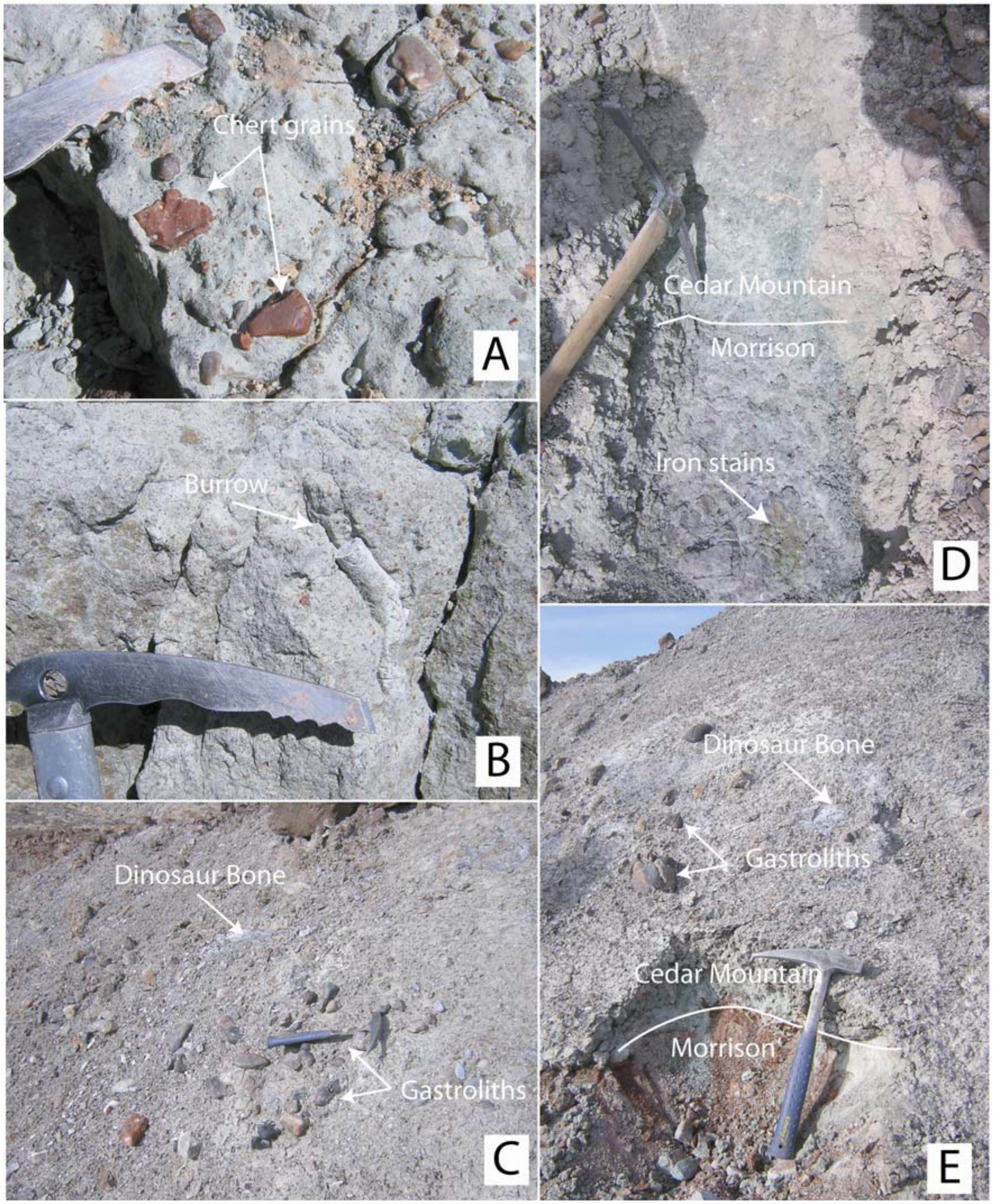

Figure 5.
The basal Cedar Mountain Formation near Green River and Moab, Utah. A) Typical basal Cedar Mountain lithology composed of poorly sorted sand and gravel in a green fine-grained matrix. B) Invertebrate burrow in same matrix as A. C) Basal Cedar Mountain Formation with bones and "gastroliths". D) Fine-grained Cedar Mountain Formation underlain by purple, iron stained Morrison paleosol. E) Bone and "gastrolith" bearing horizon resting on poorly developed Morrison paleosol.

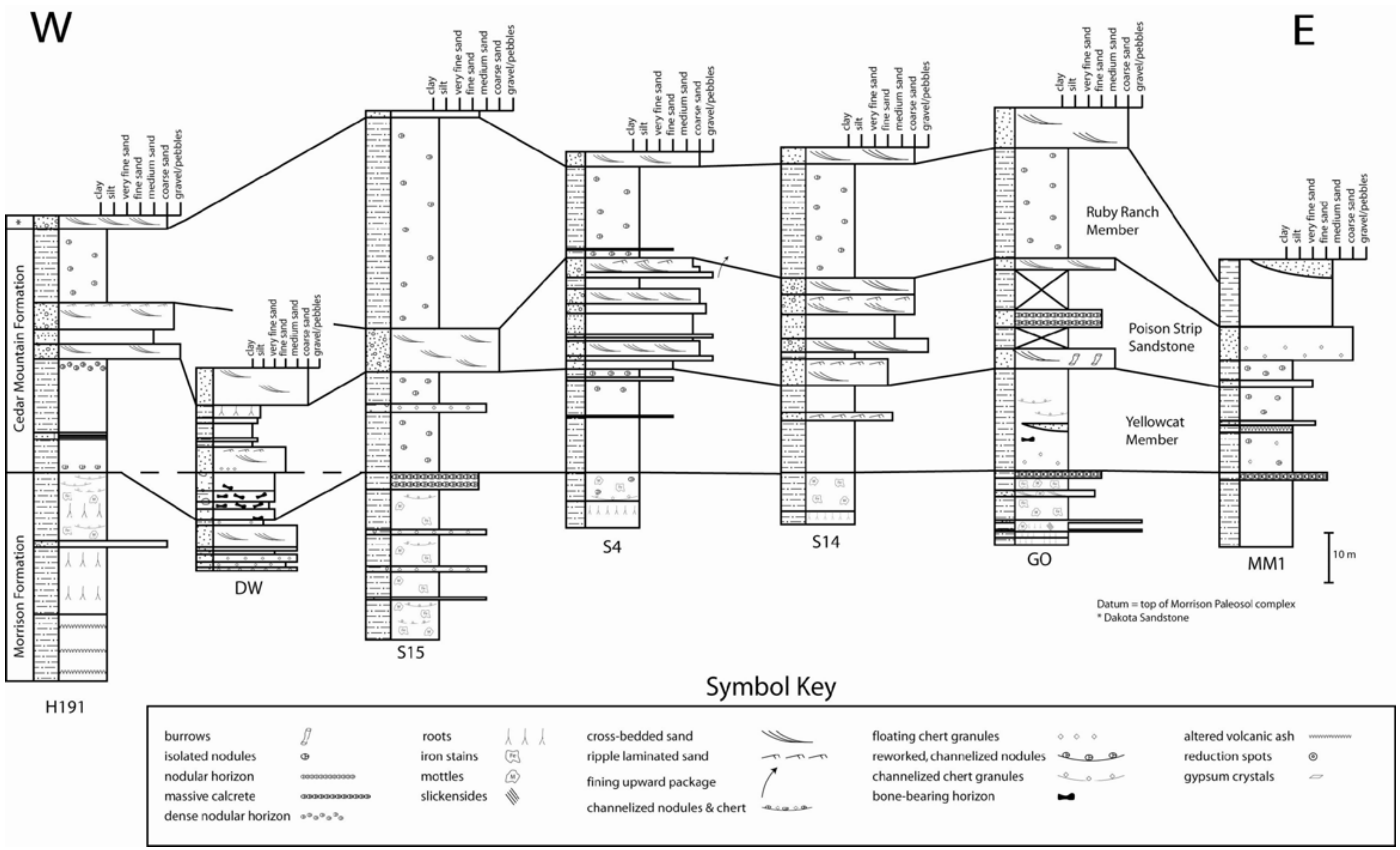

Figure 6.
Measured sections from the Green River to Moab area showing sedimentologic and pedogenic features of the Morrison/Cedar Mountain boundary. Sections S4, S14, and S15 adapted from Stikes (2003).

Cedar Mountain Formation

Throughout this area conglomeratic material is common in the basal Cedar Mountain Formation. The Buckhorn Conglomerate and other conglomeratic units here are characterized by chert clasts in various shades of white, gray and brown. Clast size generally fines upward from ~5 cm pebbles to medium sand. The expression of channelized conglomerates outside of the main Buckhorn Conglomerate trend at the boundary is typical; however the degree to which the conglomerates are cemented varies. The Buckhorn Conglomerate and other clean conglomerates (small amounts of clay) are usually carbonate cemented. Occasionally cementation is so pervasive that the rock has a micritic texture. Channelized conglomerates are not always obvious and many with clay in the interstices readily weather to a slope. Nested, dish-like laminated caliche layers are found toward the top of the Buckhorn Conglomerate together with laminated siliceous horizons similar to those described in the Morrison Formation (Fig. 7 C-F). Above the conglomerates, the Cedar Mountain Formation is dominantly a fine-grained, carbonate nodule-bearing unit with isolated, channelized sandstone bodies (Fig. 8). Carbonate nodules, pastel coloration and, in a general sense, a less bentonitic clay mineralogy distinguish the Cedar Mountain Formation from the Morrison Formation in areas where the Buckhorn Conglomerate is absent.

Uinta Mountains

In the vicinity of the Uinta Mountains the Morrison Formation/Cedar Mountain Formation contact has a character that is similar to the boundary in the Green River-Moab area, but the features are weakly developed (Figs. 9 and 10).

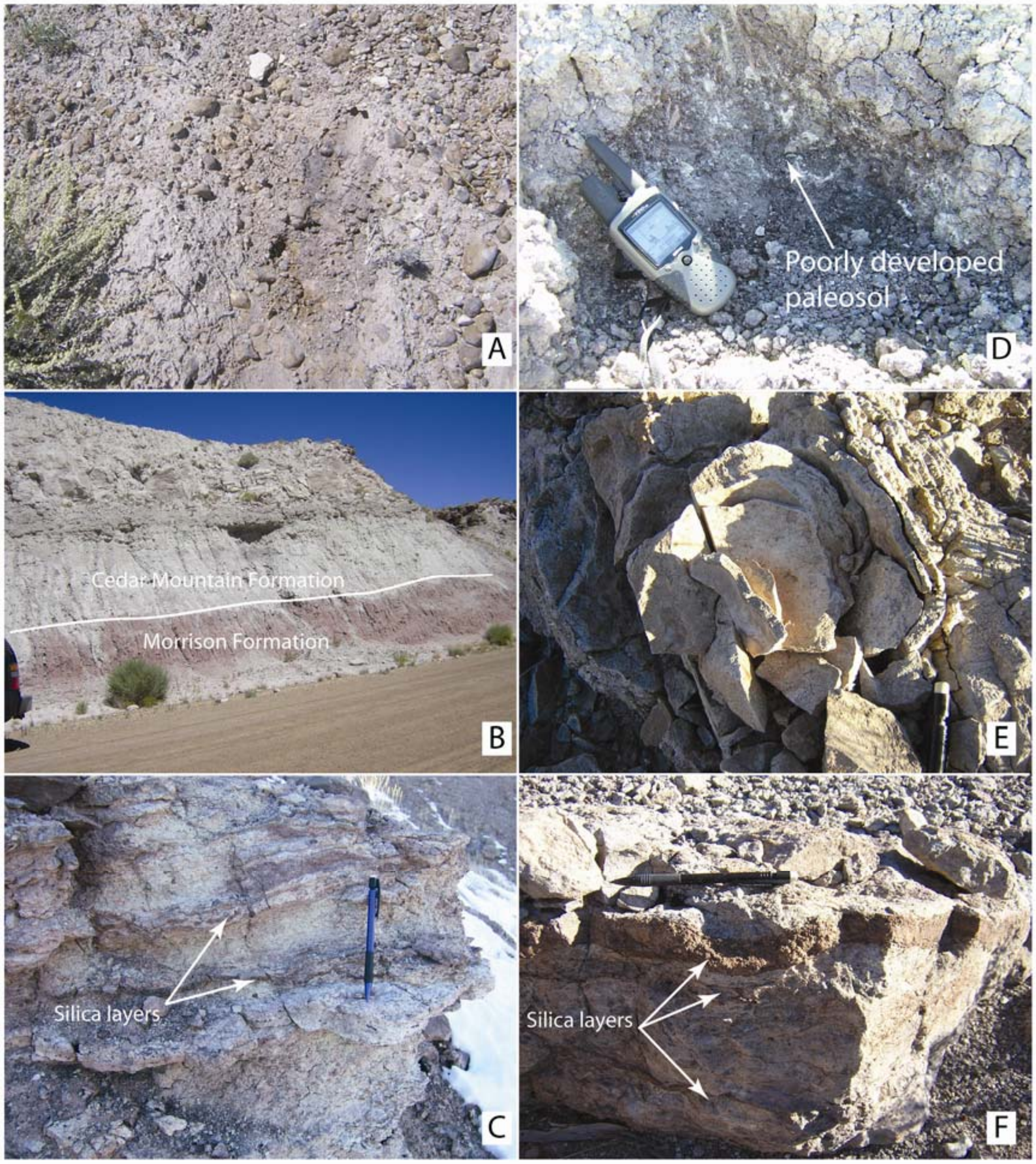

Figure 7.
The Morrison/Cedar Mountain boundary in the San Rafael Swell area. A) Chert pebbles from an isolated, unlithified Buckhorn Conglomerate exposure. B) Fine-on-fine contact with red Morrison Formation and nodular-rich, gray-green Cedar Mountain Formation. C) Silcrete in the uppermost Morrison Formation. D) Poorly developed Morrison paleosol beneath the Buckhorn Conglomerate. E) Caliche in the Buckhorn Conglomerate. F) Silcrete at the top of the Buckhorn Conglomerate.

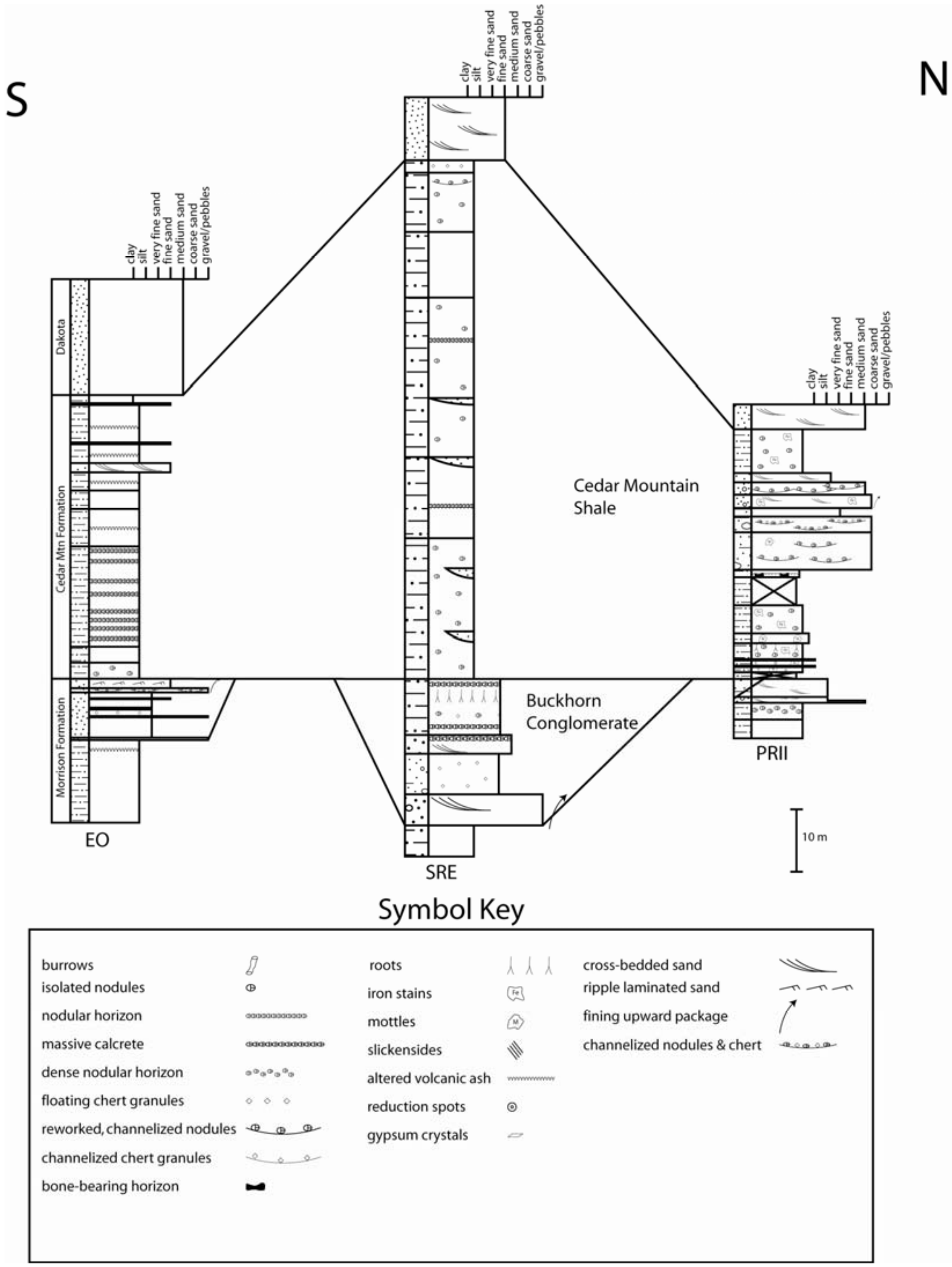

Figure 8.
Measured sections from the San Rafael Swell area showing lithologic and pedogenic features of the Morrison/Cedar Mountain boundary.

Morrison Formation

The uppermost Morrison Formation is dominantly fine-grained and pedogenically overprinted. Pedogenic features are restricted to the upper few meters of the section and include root traces, slickensided peds, mottles, and iron stains. These features are poorly developed in comparison to exposures throughout the Green River-Moab area. Below this horizon the Morrison Formation is primarily fine-grained with abundant, poorly developed paleosols (inceptisols).

Cedar Mountain Formation

The basal Cedar Mountain Formation has a number of expressions ranging from massive gray-green muddy pebble conglomerate with abundant red-black chert grains, to the Buckhorn Conglomerate, to pastel, carbonate nodule-bearing mudstones (Fig. 10). The muddy pebble conglomerates are similar to those found in the Green River-Moab area in many respects (grain size, sorting, sedimentary structures, and burrows). Interestingly, these muddy pebble conglomerates are capped by the resistant calcrete used by Currie (1998) as the Morrison /Cedar Mountain boundary in this same area.

Buckhorn Conglomerate

Here, the Buckhorn Conglomerate is similar in most respects to occurrences in the San Rafael Swell (Currie, 1998). Isolated, Buckhorn-style channelized conglomerates are present on the north slope of the Uinta Mountains, well outside of the thick Buckhorn Conglomerate trend centered on Dinosaur, Colorado. These ancillary conglomerates are similar in clast composition and stratigraphic position to the Buckhorn Conglomerate in the San Rafael Swell (Fig. 8). Where the Buckhorn and other conglomerates are present, the typical suite of paleosol characters in the Morrison Formation is absent and the

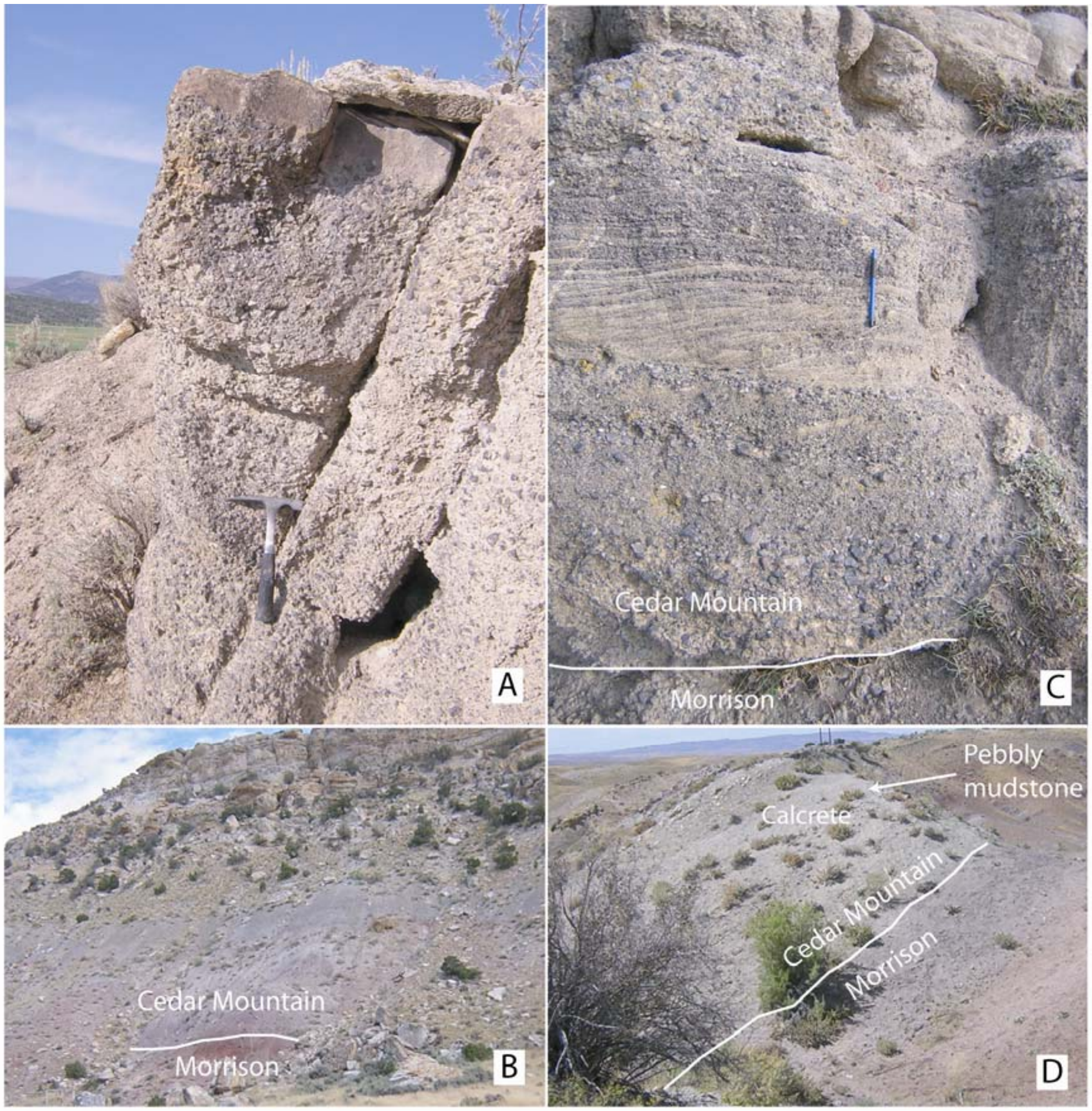

Figure 9.
Images of the Morrison/Cedar Mountain boundary in the Uinta Mountains area. A) Isolated conglomerate at the Morrison/Cedar Mountain boundary. Morrison/Cedar Mountain contact at channel base. B) Morrison/Cedar Mountain contact only identifiable by the transition from a dark red clayey paleosol, indicative of the Late Jurassic climate, to a pastel-colored calcic paleosol, typical of the Early Cretaceous climate. C) Conglomerate at the boundary composed of dark colored chert grains ranging in size from pebbles to medium sand. D) Muddy pebble conglomerate similar to those found in the Green River to Moab area (see Fig. 5A) in the basal Cedar Mountain Formation capped by a calcrete.

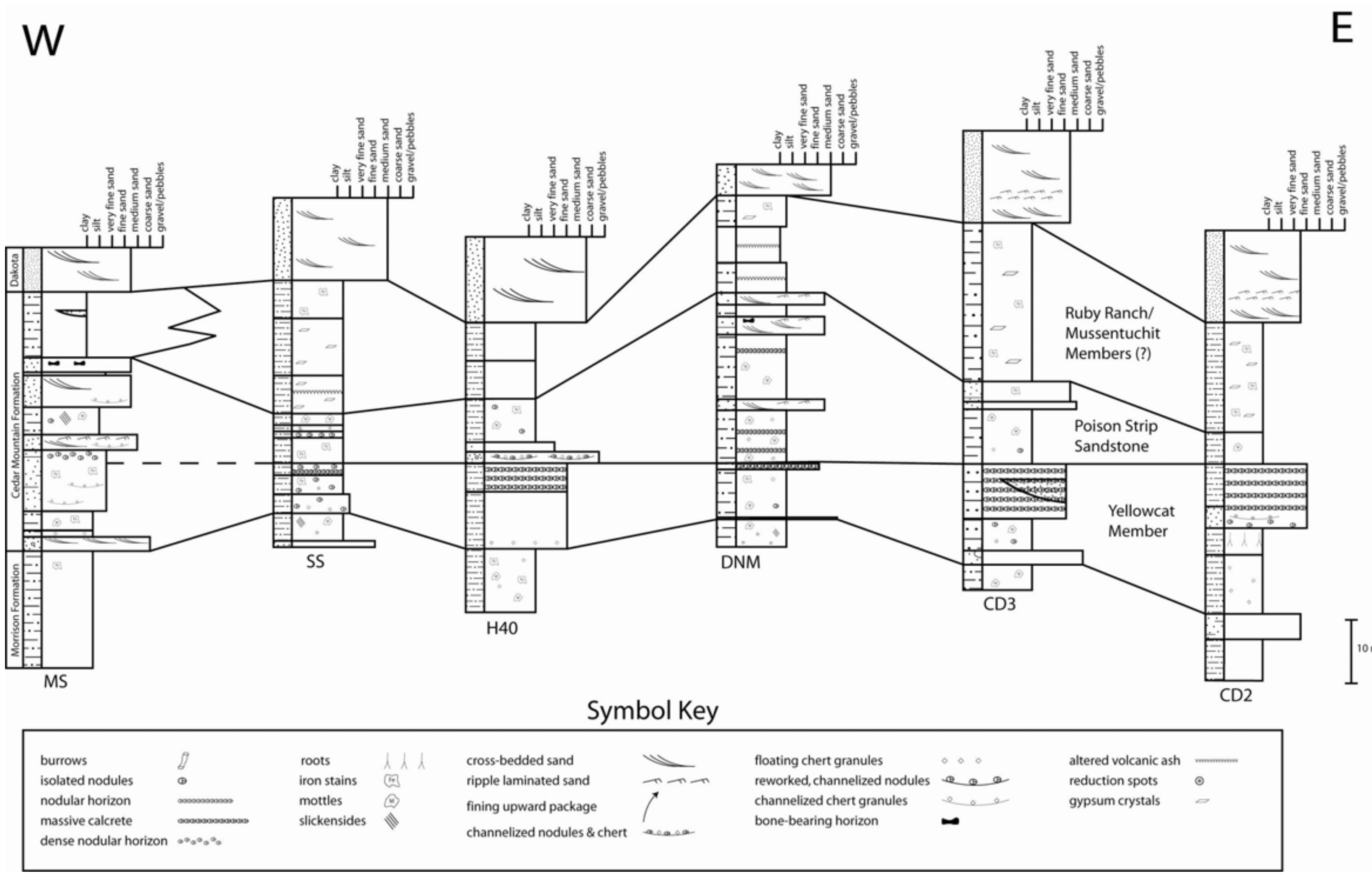

Figure 10.
Measured sections from the Uinta Mountains area showing pedogenic and sedimentologic features of the Morrison/Cedar Mountain boundary.

Morrison Formation is a green-yellow silty mudstone.

Discussion

Upper Morrison Unconformity

The thick interval of interbedded gravel and mudstone overprinted by intense paleosol development at the top of the Morrison Formation suggests that sediment preservation was reduced, but not completely inhibited in the Late Jurassic. A reduction in accommodation space in the Late Jurassic foreland basin could account for both observations.

Gravel Abundance

Sequence stratigraphic models based on changes in base-level have been applied to terrestrial sequences where no influence from sea-level is apparent. In these models, as fluvial systems progressively fill the accommodation space, sediment bypass occurs creating an upsection increase in grain size (Shanley and McCabe, 1994; Shanley and McCabe, 1995; Currie, 1997; Shanley and McCabe, 1998; Eberth et al., 2001). The uppermost Morrison Formation follows this pattern as it transitions from dominantly bentonitic, silty mudstones, to siltstone, sand and gravel at the top (Fig. 4). Winslow and Heller (1987) reported a similar increase in grain-size near the top of the Morrison Formation and into the Cloverly Formation in Wyoming and also attributed it to a reduction in accommodation space.

Paleosol Complex

Reduced accommodation space in the late Morrison Formation basin allowed for little preservation of new sediment. Consequently, the upper Morrison Formation sediments were subject to pedogenic processes for a significant period of time in the Late Jurassic climatic regime (Figs. 11 and 12). Iron stains and intense mottles are extensively developed in the uppermost Morrison Formation (Demko et al., 2004) and are typical of alternating periods of saturated and well-drained soil conditions (e.g. Vepraskas, 1994). The thick carbonate cap at the top of the paleosol complex throughout much of the Green River-Moab area is likely an overprint of the Cretaceous paleoclimatic and paleohydrologic system (Currie, 1998; Demko et al., 2004). The thickness and morphological expression of the carbonate cap is indicative of a period of soil development up to 10^5-10^6 years (e.g. Retallack, 1998). Thus, the time represented by the carbonate cap and the Morrison paleosols combined is likely on the order of millions of years.

Fluvial Incision

While the uppermost Morrison Formation has a consistent expression throughout the Green River-Moab area, these features are absent in outcrops to the north and south. Intense fluvial incision in the Early Cretaceous likely removed much of the paleosol complex on a regional basis, only preserving it in the drainage divides (Demko et al., 2004). The Buckhorn paleovalley was likely the main fluvial system contributing to the erosion of the Morrison Formation paleosol complex. Outside of the main Buckhorn paleovalley, other smaller fluvial/debris flow systems partially or completely removed the paleosols (Fig. 12). An example of this is the Dalton Wells dinosaur quarry, where bone-laden debris flows excised most of the Morrison Formation paleosol complex (Eberth et al., 2006). Similar lithologies to the Dalton Wells quarry in the basal Cedar Mountain Formation are found near Green River, Utah and lack an underlying, well-

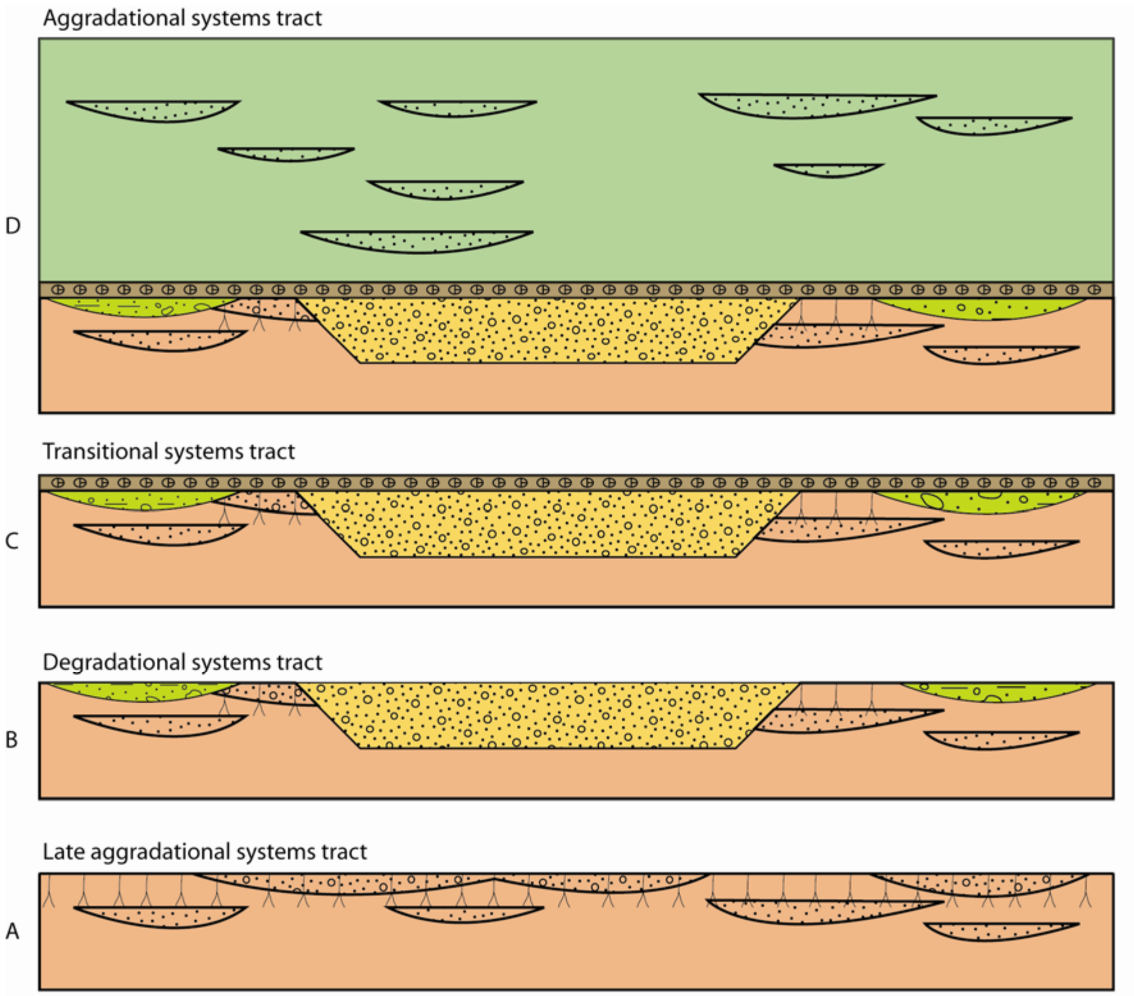

Figure 11.
Generalized Morrison-Cedar Mountain sequence stratigraphic model from Late Jurassic to Early Cretaceous after Currie (1998). A) Late aggradational systems tract in the Morrison characterized by upsection coarsening and paleosol development. B) Degradational systems tract characterized by fluvial incision of the uppermost Morrison by the Buckhorn Conglomerate and Yellowcat Member. C) Transitional systems tract characterized by well-developed calcretes and silcretes. D) Aggradational systems tract of the Cedar Mountain Formation characterized by isolated fluvial sand channels in a fine-grained matrix.

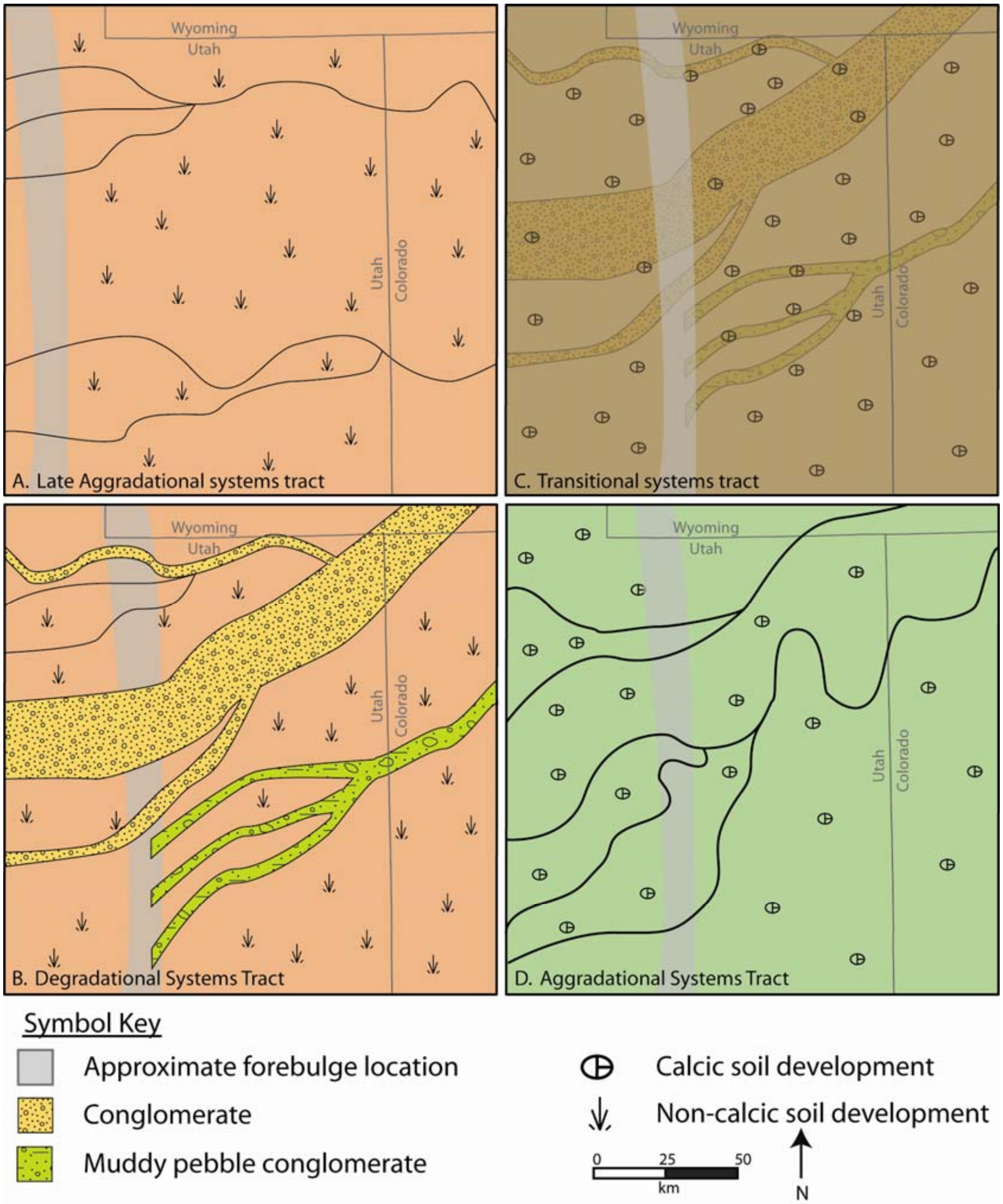

Figure 12.
Schematic paleogeographic reconstruction of Morrison through Cedar Mountain time. A) Late aggradational systems tract. Small-scale uppermost Morrison fluvial systems trending eastward. Widespread non-calcic soil development. B) Degradational systems tract. Buckhorn Conglomerate and Cedar Mountain muddy pebble conglomerate channels incise the non-calcic Morrison paleosols. C) Transitional systems tract. Period of calcic soil development in the Cedar Mountain Formation leading to the formation of widespread calcretes and silcretes. D) Aggradational systems tract. Reestablishment of Cedar Mountain northeast-trending fluvial systems and continuation of calcic soil development.

developed paleosol complex. Thus, the presence of the bone-filled debris flows is indicative of a period of erosion similar to that caused by the Buckhorn fluvial system. Other areas that have lower energy deposits incised the paleosol complex, but did not completely remove it (Fig. 5D).

Salt Tectonics

Salt-tectonics may have played a role in the preservation of the boundary paleosols in the Green River and San Rafael Swell areas. Salt-induced mini-basins have been suggested to explain the abundance of lacustrine facies in the Morrison Formation and the Cedar Mountain Formation near Moab, Utah (Aubrey, 1996; Eberth et al., 2006). These mini-basins could have inhibited the development of the paleosol complex by increasing accommodation space and sediment preservation potential (Aubrey, 1996; Johnson and Aubrey, 1994), thus inhibiting paleosol development. Additionally, lakes formed in the topographic depressions (e.g. Eberth et al., 2006) would have fundamentally inhibited paleosol development.

Soil Features in the Uinta Mountains

In the Uinta Mountains the paleosols are similar to those in the Green River-Moab area, but less well developed suggesting a shorter period of exposure or more intense erosion. In some areas the paleosol features are completely absent, which favors the interpretation that they have been eroded out.

Buckhorn Discussion

The relationship between the Buckhorn Conglomerate and the Morrison/Cedar Mountain Formation has been a topic of debate since its original description (Stokes, 1944). Some authors place it within the Morrison Formation (Aubrey, 1998; Ayers and

Nadon, 2003), others at the base of the Cedar Mountain Formation (Currie, 1997). The Buckhorn Conglomerate is not underlain by the paleosol package found in the uppermost Morrison throughout the Green River-Moab area. This can be accounted for in one of two ways: 1) the Buckhorn depositional system may postdate the Morrison Formation (Currie, 1997), in which case it is likely that the paleosol features were eroded out, or 2) the Buckhorn Conglomerate may be contemporaneous with the Morrison Formation (Aubrey, 1998), in which case, the features would not have been developed in the Morrison Formation because of erosion. In this scenario, some expression of the pedogenic features in the fine-grained sections would be expected in the Buckhorn Conglomerate because they were deposited contemporaneously. The absence of Morrison Formation paleosol features within the Buckhorn Conglomerate supports conclusion (1), that the Buckhorn Conglomerate eroded the paleosols and post-dates the Morrison Formation.

The Buckhorn Conglomerate also displays a thick silica/carbonate cap in the vicinity of the San Rafael Swell (Fig. 7 E and F). This carbonate cap is similar to the carbonate cap found at the top of the paleosol complex throughout the Green River-Moab area (Fig. 4B) and variably within the basal Cedar Mountain Formation. This suggests that the Buckhorn Conglomerate-basal Cedar Mountain Formation records a second unconformity marked by a prolonged period of calcrete development and little-no sedimentation in the Early Cretaceous. The presence of a basal erosional unconformity and the presence of calcretes support the sequence stratigraphic model proposed by (Currie, 1997) as well as our conclusion that the Buckhorn Conglomerate post-dates the Morrison Formation. The variability in the stratigraphic position of the calcretes east of the San Rafael Swell and the presence of a calcrete at the top of the Buckhorn Conglomerate indicate that the Buckhorn Conglomerate and Yellowcat Member are partially time equivalent.

Widespread Buckhorn Paleovalley

Currie (1998) described the Buckhorn paleovalley as a 25-km-wide valley trending NE across central Utah. While it is true that the main Buckhorn Conglomerate is relatively well confined, the Buckhorn depositional system as a whole was not nearly so restricted. Isolated channelized conglomerates persist at least as far south as Capitol Reef National Park. Not all of the incision into the Morrison Formation was filled with coarse-grained material. Near the southern end of the San Rafael Swell there are distinct, channelized incisions into the uppermost bentonitic Morrison Formation sediments. Some of these channels are filled with fine-grained sediment and carbonate nodules typical of the Cedar Mountain Formation (Fig. 13). Channelized conglomerates at the boundary also occur in other outcrops in the Uinta Mountain area (Haddox, 2004) (Fig. 9A). These smaller, more widely spaced fluvial incisions were likely feeder systems into the main Buckhorn paleovalley and show the widespread nature of erosion of the uppermost Morrison Formation during the Early Cretaceous. Fluvial incision of this magnitude also accounts for the small number of Morrison Formation outcrops where the paleosol complex is preserved.

Yellowcat Member Discussion

The preservation of fine-grained sediment and dinosaur bone in the Yellowcat Member (Kirkland, et al., 2005; Eberth et al., 2006) above the unconformity suggest an increase in accommodation space following the Buckhorn Conglomerate (e.g. Rogers and Kidwell, 1998; Eberth et al., 2001). These lines of evidence, together with the intense paleosol development in the uppermost Morrison Formation support the sequence-stratigraphic model for the Cedar Mountain Formation proposed by Currie (1997): the upper Morrison Formation/Buckhorn Conglomerate interval records late aggradational/degradational systems tracts respectively, and the Cedar Mountain Formation records a transitional to aggradational systems tract (Figs. 11 and 12).

Yellowcat Member and Calcretes

The Yellowcat Member in the Green River-Moab area has been interpreted as a mixture of lacustrine sediments and lake-margin debris flows (Eberth et al., 2006). Similar lithologies and sedimentary structures are seen in the lowest Cedar Mountain Formation in the Uinta Mountains area, suggesting that debris flows were common during the initial phases of Cedar Mountain deposition.

Although a precise chronostratigraphic correlation between these units is problematic, a genetic relationship between them is likely. The stratigraphic position of this unit below the calcrete suggests that the current sequence stratigraphic model needs refinement. Currie (1997) proposed two genetically related sequences (LK1 and LK2) for the Cedar Mountain Formation. The Buckhorn Conglomerate comprises the LK1 sequence which is terminated by the well-developed calcrete. The Cedar Mountain Formation above the calcrete comprises the LK2 sequence. Our study suggests that Cedar Mountain Formation deposition during the LK1 sequence was more widespread than Currie’s model suggests and that debritic sedimentation, particularly outside of the main Buckhorn paleovalley, was an integral part of the LK1 depositional system

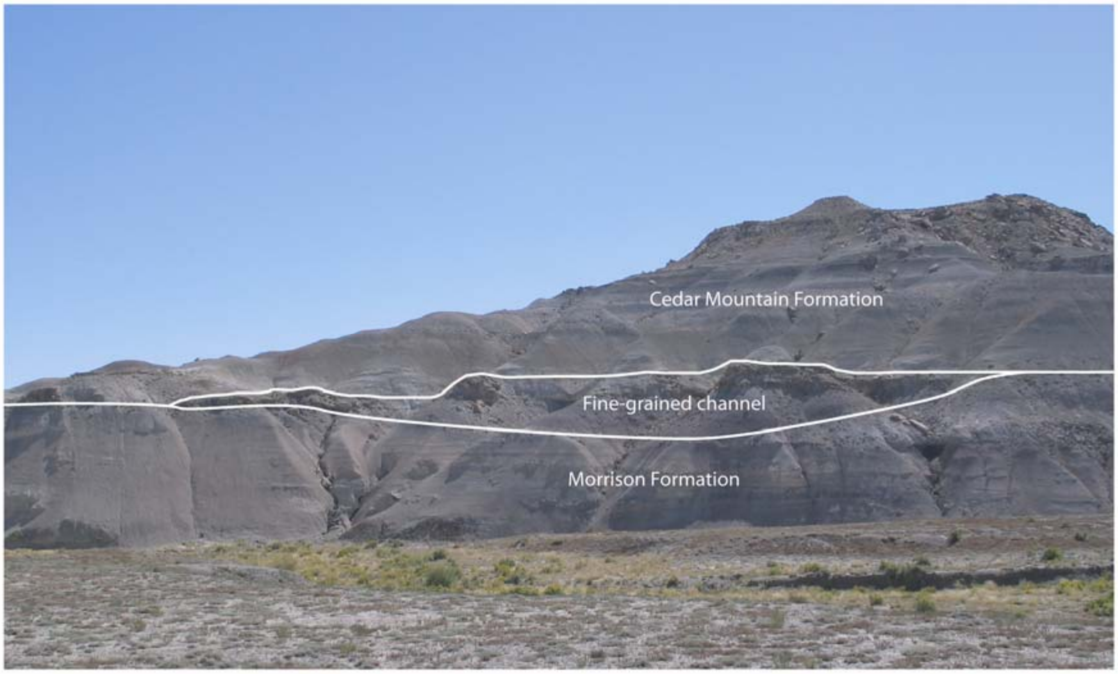

Figure 13.
Fine-grained channel incised into the Morrison Formation near the southern end of the San Rafael Swell. The channel occurs at the Morrison/Cedar Mountain boundary along with other isolated conglomerates, which are correlative with the Buckhorn Conglomerate.

(Figs. 11 and 12). This conclusion is also supported by the presence of debritic lithologies interbedded with the Buckhorn Conglomerate in the San Rafael Swell. We propose that the Buckhorn Conglomerate and the Yellowcat Member are associated facies of the basal Cedar Mountain Formation based on the relationship between a muddy pebble conglomerate associated with a calcrete in the Green River-Moab and Uinta Mountains areas, the presence of similar calcretes in the Buckhorn Conglomerate, and the presence of interbedded muddy pebble conglomerate in the Buckhorn Conglomerate in the San Rafael Swell.

Conclusions

Our study of the Morrison/Cedar Mountain boundary leads us to the following conclusions:

1) A suite of sedimentologic and stratigraphic features characterizes the Morrison /Cedar Mountain boundary for each area. While the features are not identical in each area they are internally consistent and can be accounted for by current sequence stratigraphic models.

2) The uppermost Morrison Formation has features indicative of intense paleosol development in areas not fluvially incised. In areas with high degrees of fluvial incision the paleosol package has been removed and only poorly developed paleosols are preserved at the boundary.

4) The basal Cedar Mountain Formation varies from coarse conglomeratic material of the Buckhorn Conglomerate to muddy pebble conglomerate or carbonate nodule-bearing silty mudstones of the Yellowcat Member.

3) Jurassic paleosol features combined with the Early Cretaceous carbonate cap indicate a period of post Morrison exposure on the order of millions of years.

5) These facies trends indicate an Early Cretaceous progression from degradational to transitional systems tracts in the foreland basin following Morrison Formation deposition.

6) Debritic sedimentation is a characteristic feature of the basal Cedar Mountain Formation and may be the key to deciphering the relationship between the Buckhorn Conglomerate and the Yellowcat Member.

These features provide a framework for deciphering the Morrison/Cedar Mountain contact, which will aid in paleontologic prospecting in the fossil-rich basal

Cedar Mountain Formation. By providing a uniform system for assessing the boundary, this framework will also aid subsequent paleoenvironmental and stratigraphic studies of the Cedar Mountain Formation and its dinosaur fauna. It also shows that despite the sometimes cryptic nature of the Morrison/Cedar Mountain contact, detailed sedimentologic, pedogenic and paleontologic information can be combined to accurately decipher the boundary. This methodology can now be applied to other stratigraphic successions with enigmatic formational boundaries.

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Chapter 2

Zircon Geochronology of the Morrison/Cedar Mountain Formational Boundary, Moab, Utah

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Abstract

The Cedar Mountain Formation has the potential to provide information critical to Early Cretaceous dinosaur evolution in North America. Thus far, radiometric ages for the formation have been available for only the uppermost portions of this 40-100 meter-thick fluvial package. In this paper we present radiometric $^{206}Pb/^{238}U$ zircon ages for the basal Yellowcat Member of the formation, near Moab, Utah. The Dalton Wells dinosaur quarry occurs in the Yellowcat Member along with numerous other fossil assemblages. Zircons collected from the Dalton Wells quarry and a correlative eggshell horizon place the age of the basal Cedar Mountain Formation and its fauna near the Barremian/Aptian boundary at 124 Ma. This permits for the first time a temporal correlation of the Yellowcat fauna and shows that it is time equivalent with the prolific and paleobiologically diverse Yixian Formation, of Liaoning, China. The age of the uppermost Morrison in this area is ~148 Ma, thus constraining the duration of the Morrison/Cedar Mountain unconformity to 24 Myr from 148-124 Ma. This time period correlates with a lull in contractional tectonic activity and magmatism in western North America. This provides more data supporting the fundamental link between magmatism and sediment preservation in western North America and has application to other sedimentary successions associated with magmatic arcs.

Introduction

The Cedar Mountain Formation is a classic example of a terrestrial fluvial succession deposited in a foreland basin (Currie, 1998) and contains an abundance of Early Cretaceous dinosaurs unrivaled in North America (Kirkland et al., 1997; Eberth et al., 2006). Constraining the age of this prolific accumulation of dinosaur material has been difficult because of the paucity of volcanic ash and age diagnostic fossils. Current age assessments for the Cedar Mountain Formation are largely based on biostratigraphic data and biased toward the upper portions of the unit (Young, 1960; Tschudy et al., 1984; Cifelli et al., 1997; Eberth et al., 2006). These data and one radiometric age of 98.0 ± 0.07 Ma at the top of the formation (Cifelli et al., 1997) constrain the upper age of the Cedar Mountain Formation to the Albian-Cenomanian boundary. Vertebrate fossils in the basal Yellowcat Member of the Cedar Mountain Formation (Kirkland et al., 1997) are arguably the earliest Cretaceous dinosaur fossils on the Colorado Plateau (Kirkland et al., 1993) and hold a vital key to understanding the evolution of North American dinosaurs and their connection to other Early Cretaceous dinosaur groups worldwide. The age of the Dalton Wells quarry has been regarded as Barremian based primarily on broad similarities between its dinosaur fauna and the Barremian of Europe (Kirkland et al., 1993; Kirkland et al., 1999), however, the lack of shared genera and absolute age control have left this age assessment tenuous (Eberth et al., 2006). The basal Cedar Mountain Formation has yielded a diverse, dinosaurian fauna that includes relics of Late Jurassic Morrison sauropod lineages (brachiosaurids and a camarasaurid), a basal macronarian, an array of theropods including *Utahraptor*, the largest dromaeosaurid, and a primitive therizinosaur, which demonstrates a transition from carnivory to herbivory within theropoda (Kirkland et al., 1997; Kirkland, 2005; Eberth et al., 2006). The absence of absolute ages has made it impossible to correlate this diverse, sauropod-dominated fauna with time-equivalent faunas. It also hinders biogeographic and times of origin/extinction studies.

In this paper we present radiometric ages from ash-derived zircons collected from the uppermost Morrison Formation and lowermost Cedar Mountain Formation near Moab, Utah. These are the only radiometric ages for the lower Cedar Mountain Formation making it possible for the first time to compare the lower Cedar Mountain Formation with time correlative faunas and to test several proposed dinosaurian evolution hypotheses. These ages also allow us to evaluate causative mechanisms for developing the Morrison/Cedar Mountain unconformity.

Geologic Setting

The Morrison Formation and Cedar Mountain Formation were deposited in the interior foreland basin of western North America and consist primarily of pedogenically altered fluvial and lacustrine sediments and volcanic ash (Emmons et al., 1896; Stokes, 1944; Christiansen et al., 1994; DeCelles, 2004; Demko et al., 2004). The Morrison Formation was most likely deposited in the backbulge of a Late Jurassic foreland basin centered on western Utah and eastern Nevada (Royse, 1993; DeCelles, 2004). Well-preserved volcanic ash layers in the Morrison Formation are abundant and allowed extensive documentation of its age throughout the Colorado Plateau (Kowallis et al., 1998). An uppermost Morrison unconformity likely developed as a result of reduced accommodation space in the foreland basin due to eastward migration of the forebulge, and post-Morrison uplift of the basin (Currie, 1998; Demko et al., 2004). Interior propagation of thrusting shifted the Early Cretaceous foreland basin into central and eastern Utah (Mitra, 1996; Camilleri et al., 1997; Yonkee, 1997; Currie, 1998), where the Cedar Mountain Formation was deposited. A number of dinosaur bonebeds occur within the basal 10 meters of the Cedar Mountain Formation. The rarity of well-preserved ash in the Cedar Mountain Formation, which has hitherto hindered dating this formation, may be a function of an Early Cretaceous lull in volcanic activity in the Sierran magmatic arc (Bateman, 1992; Christiansen et al., 1994), but may be more likely due to a high degree of reworking by Cedar Mountain fluvial systems and/or to destruction of ash due to environmental or diagenetic conditions.

Established Morrison and Cedar Mountain Ages

The age of the Morrison Formation ranges from 155-148 Ma (Kowallis et al., 1998) throughout the Colorado Plateau and is bracketed by 151-145 Ma in southwestern Wyoming (Trujillo, 2003). The Cedar Mountain Formation has been regarded as Early Cretaceous since its original description (Stokes, 1944); however radioisotopic (Cifelli et al., 1997) and palynologically derived ages (Young, 1960; Tschudy et al., 1984) with narrow ranges have been reported for only the upper portions of the formation. This bias is primarily due to an upsection increase in the preservation of ash and age-diagnostic fossils. In contrast, charophytes, pollen and vertebrate faunal comparisons have been used to bracket the age of the lower Cedar Mountain Formation to the Kimmeridgian-Aptian interval (Kirkland et al., 1997; Kirkland et al., 1999; Eberth et al., 2006) and there was no volcanic ages. These ambivalent ages demonstrate the need for precise radiometric age control for the basal Cedar Mountain Formation and its dinosaur assemblage (Eberth et al., 2006).

Zircon Methods and Results

Samples

Eight zircon samples from the Morrison and Cedar Mountain Formations of the Colorado Plateau in Utah were analyzed for this study (Table 1 and Fig. 1). Four of the samples are from the Morrison and Cedar Mountain Formations from the Dalton Wells area near Moab, Utah. Samples M1 and M2 were collected in the Morrison Formation immediately below the Morrison /Cedar Mountain contact (Fig. 1A). Samples CM1 and CM2 are from the Dalton Wells quarry and a correlative eggshell locality, respectively, both of which occur in the basal Cedar Mountain Formation (Fig. 1A). They are lithologically similar and composed of gray-green sandy/silty mudstones with abundant matrix- supported chert grains deposited by debris flows in a lake-margin setting (Eberth et al., 2006) CM1 and CM2 occur 1.5 and 6 m above the Morrison /Cedar Mountain contact respectively and provide ages for the basal Cedar Mountain Formation and its fauna. Together, the Morrison Formation and Cedar Mountain Formation samples provide dates to assess the duration of the unconformity recognized by Stokes (1944) and Young (1960).

The other four samples are archived samples from the Morrison, Carmel, and Temple Cap Formations with published $^{40}Ar/^{39}Ar$ ages. These samples were used to independently verify our zircon methods (Table 1).

Methods

Analytical Methods

U-Pb geochronology of zircons was conducted by laser ablation multicollector inductively coupled plasma mass spectrometry at the University of Arizona LaserChron

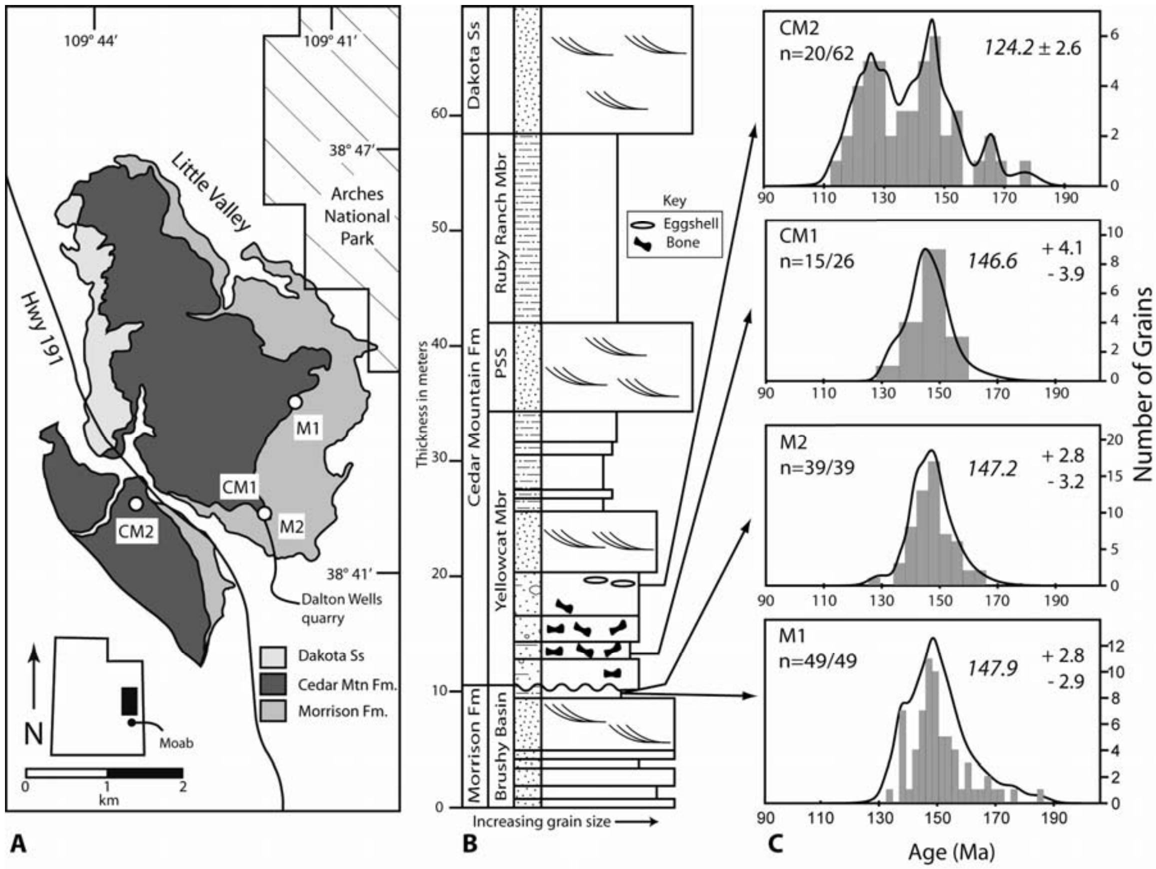

Figure 1.
Locality, stratigraphy, and zircon U-Pb ages. A) Index map and geology of the study area showing sample localities. Samples CM1 and M1 are within and below the Dalton Wells quarry, respectively. B) Stratigraphic section showing positions of samples. C) Histograms of zircon ages with superimposed probability-density plots for all new samples in this study; youngest age for each sample is in italics (asymmetric errors are 95% confidence interval errors); only ages less than 200 Ma are shown; n values are the number of analyses in the youngest age/total number of analyses. Geologic map after Doelling (2001). Stratigraphic column from Eberth and others (2006). Abbreviations: PSS = Poison Strip Sandstone.

TABLE 1. ZIRCON $^{206}Pb/^{238}U$ AND CONTROL SANIDINE $^{40}Ar/^{39}Ar$ AGES

Sample ID	Formation	$^{40}Ar/^{39}Ar$ age (Ma)	$^{206}Pb/^{238}U$ age* (Ma)		n[†]
New Samples					
CM2	Cedar Mountain	N.A.[§]	124.2	± 2.6[#]	20
CM1	Cedar Mountain	N.A.	146.6	+ 4.1 – 3.9	14
M2	Morrison	N.A.	147.2	+ 2.8 – 3.2	39
M1	Morrison	N.A.	147.9	+ 2.8 – 2.9	49
Control Samples**					
DQW-21	Morrison	149.93 ± 0.42	146.5	+ 3.6 – 3.9	23
LCM-1	Morrison	151.15 ± 0.50	147.4	+ 3.5 – 3.3	20
GUN-B	Carmel	169.09 ± 0.50	167.6	+ 4.4 – 3.4	22
MWCB-14	Temple Cap	171.40 ± 0.6	169.4	+ 5.1 – 4.4	21

*Zircon age data reported with asymmetric 95% confidence errors.
[†] n = number of analyses included in zircon age calculations.
[§] N.A. = not applicable
[#] Age calculated using Unmix Ages routine in Isoplot with 2σ error (Ludwig, 2004).
** $^{40}Ar/^{39}Ar$ ages are from Kowallis and others (1998) and Kowallis and others (2001) and are recalibrated against Fish Canyon Tuff at 28.02.

Center. Samples were analyzed during two runs conducted three months apart. Two sets of grains were analyzed for samples M1, M2, and CM2, one during each run, to increase sample size and check for repeatability in our young age. Cathodeluminescence images of zircon grains showed mostly simple, magmatic zonation (Fig. 2). The images were used during the analyses to avoid complex or fractured areas and to target the youngest portions of each grain. Zircon age populations were plotted as histograms with superimposed probability density plots to assess the age distribution of each sample. Reported ages were analyzed using the Tuffzirc routine in Isoplot (Ludwig, 2004) and include all analyses contained in the youngest histogram peak for each sample (Fig. 1). Because of the amount of detrital contamination in sample CM2 and to avoid subjective grain selection, we used the Unmix Ages routine in Isoplot (Ludwig, 2004) to calculate the youngest peak age.

$^{40}Ar/^{39}Ar$ Cross Check

To assess U-Pb zircon methods in this application we determined the U-Pb ages of zircons from samples dated using $^{40}Ar/^{39}Ar$ techniques. Control sample zircon ages were slightly (<2.5%) younger but within analytical error of the $^{40}Ar/^{39}Ar$ ages (Table 1). The discrepancy in ages, which is most apparent in the Morrison samples, is likely due to small zircon crystal sizes and Pb loss below detectable levels. While sanidine crystals are usually preferred for age determinations in tuffaceous units like the Morrison Formation and Cedar Mountain Formation, the close age correlation between both methods verifies the utility of zircon geochronology. Zircons are critical for dating the Cedar Mountain Formation where conditions were apparently not conducive to feldspar preservation.

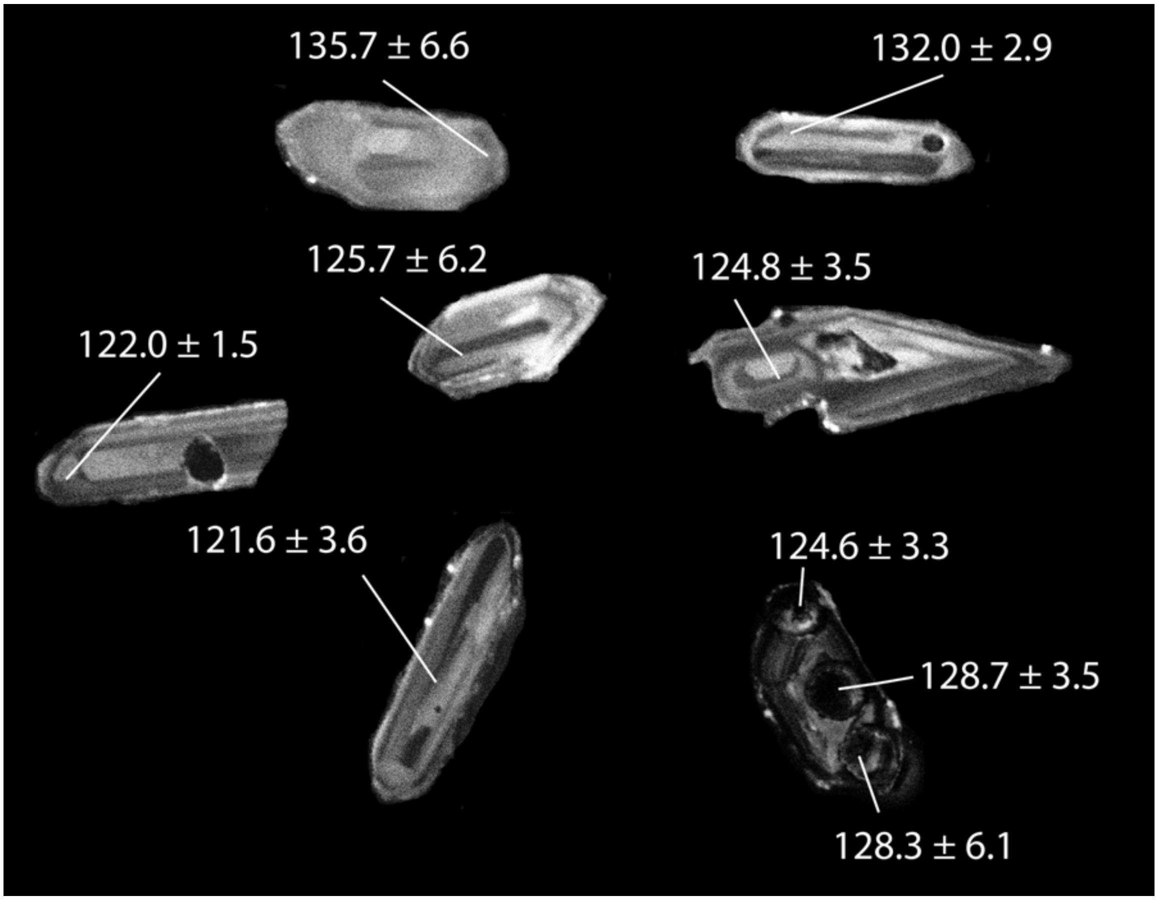

Figure 2.
Cathodluminescence images of zircon grains used in 124 Ma age for sample CM2. Grains show simple magmatic zonation. Young analyses taken from cores and rims of grains indicate that they are primary magmatic grains.

Description of Age Populations

Morrison Ages

Probability density plots for samples M1 and M2 show unimodal age distributions centered on 147 Ma. Ages for these samples are statistically indistinguishable from each other and indicate the samples are from the same ash (Fig. 1). The uppermost Morrison Formation throughout the Colorado Plateau has $^{40}Ar/^{39}Ar$ sanidine ages of ~148 Ma (Kowallis et al., 1998). Given the small offset of ages in control samples, the ~147 Ma age is consistent with other Morrison sections.

Cedar Mountain Ages

Sample CM1, from the Dalton Wells quarry in the basal Cedar Mountain Formation, has a unimodal age peak centered on 146 Ma. A Jurassic peak is expected because 1) the quarry lithosome rests unconformably on the Morrison Formation, 2) the sample is from 1 m above the Morrison Formation/Cedar Mountain Formation contact, and 3) the quarry matrix is composed of slightly reworked Morrison Formation (Eberth et al., 2006).

Sample CM2 is also from the base of the Cedar Mountain Formation, but 6 m above the Morrison /Cedar Mountain contact and 1.5 km distant from the Dalton Wells quarry (Fig. 1). The sample is from a massive, green, silty mudstone that contains eggshell fragments and partial eggs of a theropod dinosaur (based on rugose ornamentation). An identical mudstone, sans eggshell, rests conformably on the Dalton Wells quarry. The Mesozoic age distribution for this sample is more complex than the other samples, with prominent peaks at 124 Ma, and 145 Ma and a minor peak at 166 Ma. Zircon crystals with high U content are known to yield abnormal young ages and many of the analyses in our 124 Ma peak have slightly elevated U concentrations (Fig. 3). The distinct separation between the 124 Ma and 145 Ma peaks (Fig. 1), however, indicate that there are two grain populations. Furthermore, eight of the 20 analyses (40%) have low U concentrations (<500 ppm) and yield a young age. Because our young ages vary only slightly with U concentration, it is unlikely that they have been affected by Pb loss (Fig. 3).

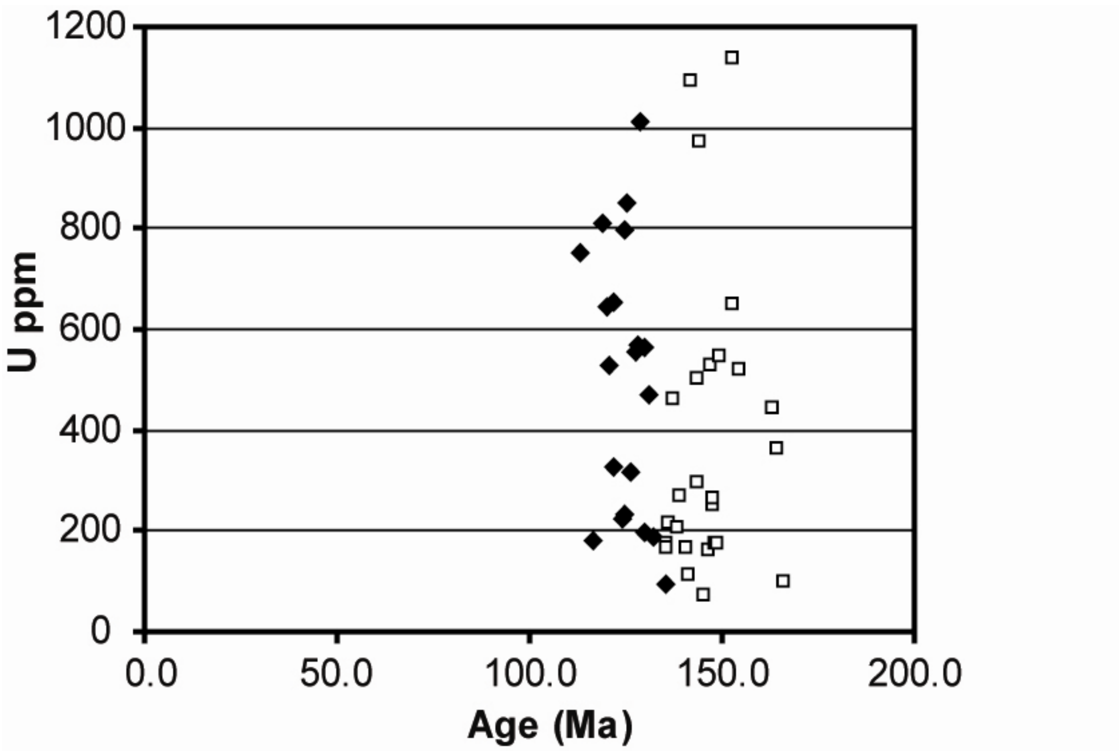

Figure 3.
Uranium concentration vs. age for sample CM2. Black diamonds indicate analyses used for young age; open squares are all other analyses.

Discussion

Basal Cedar Mountain Age

The basal most Cedar Mountain Formation sample, CM1, has a youngest age peak at 146 Ma (Fig. 1). The association of CM1 with Early Cretaceous dinosaur remains indicates that it post-dates the Morrison /Cedar Mountain unconformity and its age is from reworked Morrison Formation zircons. The fine-grained, but detrital nature of CM2 indicates that the 124 Ma zircons were minimally reworked. Thus, 124 Ma can be conservatively regarded as a maximum depositional age for the basal Cedar Mountain Formation (e.g. Riggs, 2003). Because of the sedimentologic similarities between CM1 and CM2 and their stratigraphic and geographic proximity, it is likely that they were deposited contemporaneously (Fig. 1). The absence of the 124 Ma age peak in CM1 indicates that the 124 Ma volcanic event occurred during the deposition of the basal Cedar Mountain Formation package from CM1 to CM2. Thus, the basal Cedar Mountain Formation, including the Dalton Wells quarry, is not significantly younger than 124 Ma. Complicating this interpretation is the fact that CM1 does not duplicate the 166-170 Ma detrital ages present in CM2, however, the overall provenance is congruent (Fig. 4) and the issue would likely be resolved with a larger sample population. This is the first absolute age for the basal Cedar Mountain Formation. The age indicates the Yellowcat Member straddles the Barremian-Aptian boundary (Fig. 5) as defined by Gradstein and others (2004). Other workers have suggested a Barremian age for the Yellowcat Member based on poorly constrained paleontological evidence as summarized by Eberth and others (2006). Our radiometric age is more precise and constrains the fauna to the latest Barremian or earliest Aptian.

Morrison /Cedar Mountain Unconformity

Previous to this age assessment, the duration of the Morrison Formation/Cedar Mountain Formation unconformity could not be resolved with any accuracy. Some authors suggested deposition was essentially continuous (Craig, 1961) while others proposed a hiatus of ~20 million years (Kirkland et al., 1997). Our results indicate a hiatus of some 23 million years (Fig. 4). This indicates that despite the sometimes cryptic nature of the contact, it represents a significant depositional hiatus. A number of authors have speculated on the causative mechanism for the unconformity, namely reduced accommodation space, forebulge migration, and uplift of the basin (Currie, 1997;

Currie, 1998; Demko, Currie and Nicoll, 2004). This age control for the basal Cedar Mountain Formation shows that the unconformity developed during the relatively quiet period of time in the Sierran magmatic arc, from ~145-125 Ma (Christiansen et al., 1994). Tectonically, this period involved mega thrust sheet emplacement concentrated in the eastern portions of the Sevier thrust belt in central Utah and along shear zones within the magmatic arc (Wyld et al., 2001). Emplacement of these thrust sheets at the edge of the Cedar Mountain basin may have contributed to unconformity development. Additionally, our data show that no sedimentary rocks were preserved in this area between 145 Ma and 125 Ma, which supports the conclusion of Christiansen and others (1994) that sedimentary rocks were not well represented during periods of magmatic quiescence in the western interior of North America. Christiansen and others (1994) speculated that increased seafloor spreading rates may have inhibited magmatism in the arc and uplifted the continental margins, which would lead to development of unconformities. This explains the lack of volcanism during this time and fits the hypothesis that uplift of the basin resulted in the development of the Morrison/Cedar Mountain unconformity (Currie, 1998). After 125 Ma, magmatism increased in the Sierran magmatic arc and had a distribution similar to the Late Jurassic (Christiansen et al., 1994). The basal Cedar Mountain age occurs at the beginning of this magmatic flare up and supports the link between volcanism and sediment preservation in the western North American interior.

Intraformational Unconformities

Current age controls indicate that the Cedar Mountain Formation covers about 26 Myr (Fig. 5). This is a large amount of time for a single terrestrial lithosome, considering that the duration of similar formations is usually less than eight Myr (Eberth and

Hamblin, 1993; Kowallis et al., 1998; Ryan et al., 2001; Roberts et al., 2004). For example, the Morrison Formation was deposited over a period of approximately 8 Myr (Kowallis et al., 1998) with an average thickness of 200 m (Currie, 1997), giving an average sedimentation rate of 2.5 cm/kyr. The Cedar Mountain Formation, in contrast, has an average thickness of 40 meters (Currie, 1997) and was deposited over ~26 Myr, giving an average sedimentation rate of 1.5 mm/kyr. With the long duration of the Cedar Mountain Formation, an order of magnitude difference in sedimentation rate and the presence of multiple vertebrate faunas (Kirkland et al., 1999; Eberth et al., 2006) it is likely that significant intraformational unconformities exist. Geochronological studies through the entire Cedar Mountain Formation are necessary to address this issue and constrain the geochronology of the rest of this paleontologically rich package.

Faunal Correlations

The Cedar Mountain Formation, and in particular the Yellowcat Member, were deposited during a critical, but poorly represented period of North American dinosaur evolution when the sauropod-dominated Late Jurassic fauna of the Morrison Formation shifted to the ornithischian-dominated faunas of the Late Cretaceous. The Yellowcat fauna is sauropod dominated, with a diverse fauna of over 11 dinosaurian genera, including the most primitive therizinosaurid theropod, *Falcarius utahensis*; the giant dromaeosaurid theropod, *Utahraptor*; four sauropods – an unnamed basal macronarian, one or two brachiosaurids, and a camarasaurid; plus several iguanodontid ornithopods and *Gastonia*, an ankylosaurid (Kirkland et al., 1997; Kirkland, 2005; Eberth et al., 2006;). The therizinosaur (Kirkland, 2005) and basal macronarian (personal comm. Brooks Britt) represent clades that are otherwise non-North American, facts that when combined with a 124 Ma age make the taxa expecially significant in terms of paleobiogeography and times of origin. It is informative that after a hiatus of some 23 Myr following Morrison times the camarasaurid and brachiosaurid clades survived, while the most diverse Morrison sauropod clade, the Diplodocidae, went extinct in North America (Upchurch et al., 2004). With absolute ages in hand, it is finally possible to temporally compare the Yellowcat fauna to other well known Early Cretaceous faunas (Table 2). There are only two age equivalent faunas, both from members at the base of the Yixian Fm, of Liaoning, China, which are famous for superbly preserved early angiosperms, insects, birds, feathered dinosaurs, and early mammals (Zhou et al., 2003).

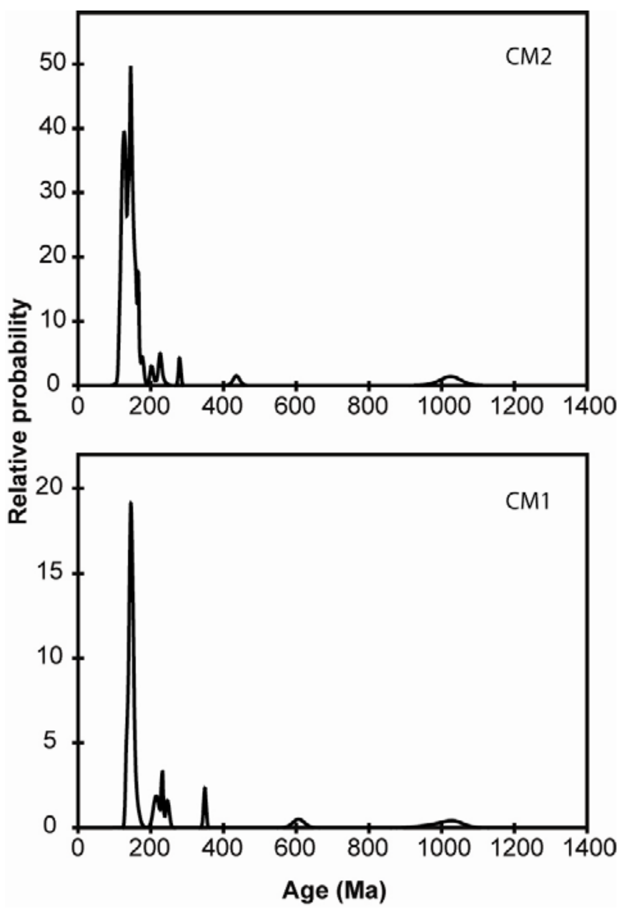

Figure 4.
Detrital zircon populations for both Cedar Mountain samples. Source terrains for both samples were dominantly Mesozoic strata of the Colorado Plateau.

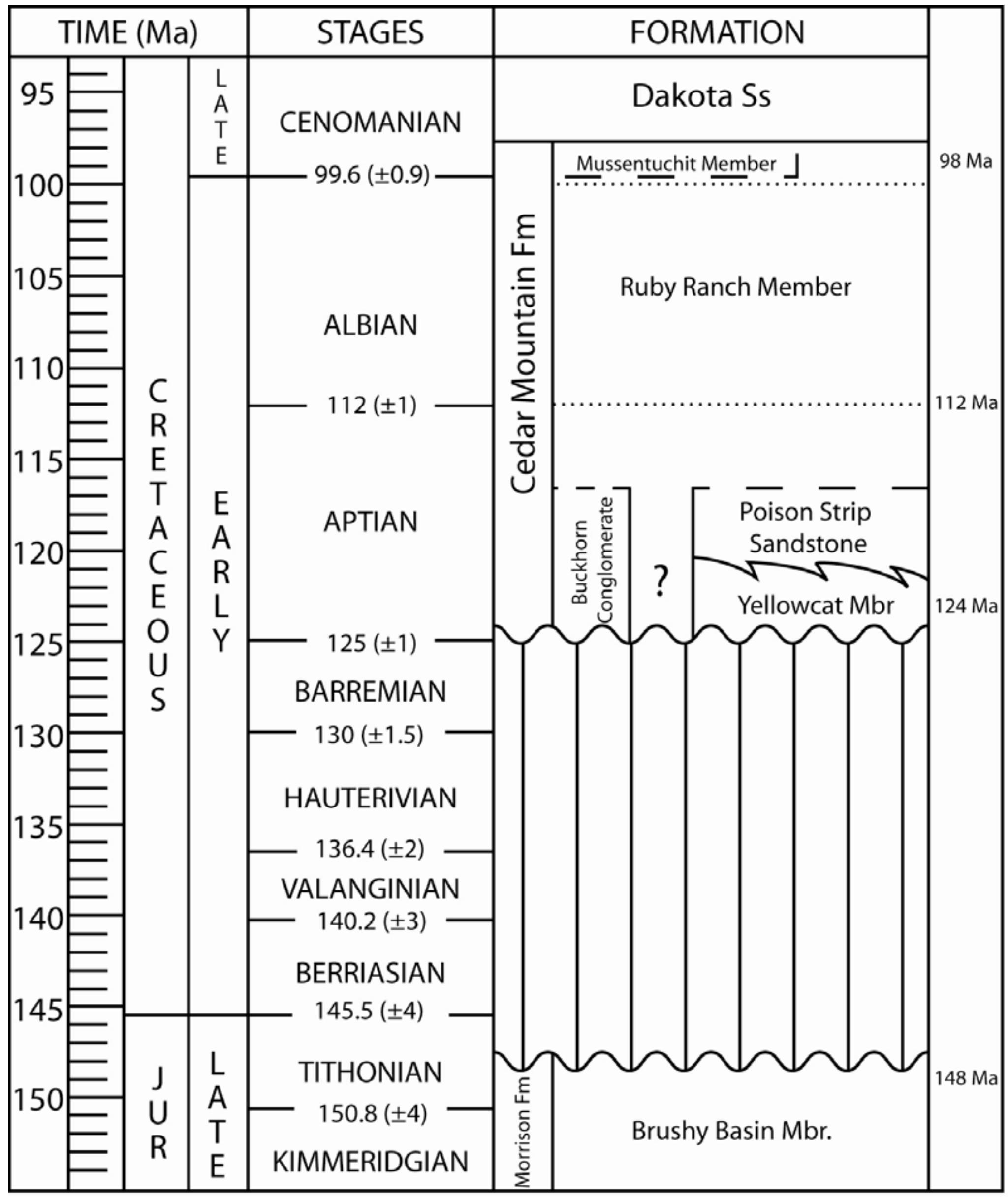

Figure 5.
Proposed geochronologic chart for the uppermost Morrison Formation through the Cedar Mountain Formation interval showing time-span of the Cedar Mountain Formation and the duration of the Morrison /Cedar Mountain unconformity. Aside from Stokes' (1944) Buckhorn Conglomerate, the Cedar Mountain Formation informal members are those proposed by Kirkland and others (1997). Timescale from Gradstein (2004). Morrison age from Kowallis and others (1998) and this study. Mussentuchit Member age from Cifelli and others (1997). Dotted lines represent tentative ages based on C-isotope stratigraphy from Lockley and others (2004). Dashed lines indicate unknown ages. Interfingering of the Poison Strip Sandstone with the Yellowcat Member was demonstrated by Eberth and others (2006).

TABLE 2. AGES OF SELECT EARLY CRETACEOUS DINOSAUR BEARING STRATA

Ages	Basis	Rock Unit	Locality	Country	Citation
Radiometric (Ma)					
98.39 ± 0.07	bulk K feld, $^{40}Ar/^{39}Ar$	Cedar Mtn. Fm., Mussentuchit Mbr.	San Rafael Swell, Utah	U.S.A.	Cifelli et al., 1997
113 ± 8 115 ± 8 129 ± 16	fission track	Cloverly Fm.	Wyoming	U.S.A.	Chen & Lubin, 1997
123.2 ± 1.0	bulk K feld, $^{40}Ar/^{39}Ar$	Lujiatun bed, Yixian Fm., Jehol Grp.	Liaoning	China	He et al., 2006
124.2 ± 2.6	zircon U-Pb	Cedar Mtn. Fm., Yellowcat Mbr.	Moab, Utah	U.S.A.	This study
125.0 ± 0.2	bulk K feld, $^{40}Ar/^{39}Ar$	Jianshangou bed, Yixian Fm., Jehol Grp	Liaoning	China	Swisher et al., 2002
Biostratigraphic					
early-mid Aptian	palynomorphs	Arundel Clay, Patuxent Fm	Maryland	U.S.A.	Doyle, 1992
late Berresian-early Aptian	biocorrelation	Weald-Wessex sub basins,	southern England	U.K.	Allen & Wimbledon, 1991
late Aptian-middle Albian	biocorrelation	Antlers Fm	Texas	U.S.A.	Langston, 1974
post Tithonian, pre Hauterivian	marine palynomorphs	Upper Saurian beds	Tendaguru	Tanzania	Schrank, 2005

Conclusions

The determination of an age of 124 Ma based on U-Pb analyses of ash-derived zircons is significant because it is the first radiometric age for the basal Cedar Mountain Formation. This age leads us to the following conclusions

1) The age of the basal Cedar Mountain Formation is 124 Ma.

2) Thus, the Yellow Cat fauna, which includes the prolific Dalton Wells fauna and other basal Cedar Mountain vertebrate localities, essentially straddles the Barremian/Aptian boundary. The fauna is time correlative with the basal Yixian

Formation of China, which is well known for its exceptionally well-preserved flora and fauna.

3) The duration of the Morrison /Cedar Mountain unconformity is ~23 Myr and is significant because it occurs during a period of tectonic and magmatic quiescence in western North America.

4) The Cedar Mountain Formation was deposited over ~26 Myr. The long duration of this formation compared to other fluvial successions suggests that the Cedar Mountain sedimentation rate was very slow and that the Cedar Mountain Formation may contain other significant unconformities.

The close correlation of our zircon $^{206}Pb/^{238}U$ ages with previously obtained sanidine $^{40}Ar/^{39}Ar$ ages demonstrates the reliability and utility of zircon ages, particularly in sedimentary units where the abundance of ash and/or the preservation of feldspar is low. Future applications of this technique for the Cedar Mountain Formation include obtaining ages for other dinosaur bearing horizons, constraining the duration of the Cedar Mountain Formation as a whole, and addressing the possibility and magnitude of intraformational unconformities.

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