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THE LOWER CRETACEOUS IN EAST-CENTRAL UTAH—THE CEDAR MOUNTAIN FORMATION AND ITS BOUNDING STRATA

James I. Kirkland, Marina Suarez, Celina Suarez, and ReBecca Hunt-Foster

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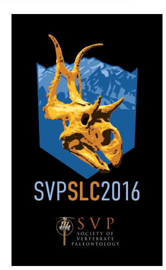

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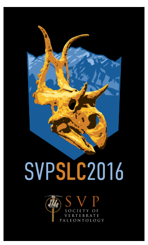

Cover

Cedar Mountain Formation at the Stikes Quarry on Utahraptor Ridge. The Stike Quarry (just below sandstone cliff) is in the upper Yellow Cat Member. The underlying Morrison Formation is the reddish slope at the bottom of photograph and the Naturita Formation caps the ridge.

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The Lower Cretaceous in East-Central Utah—The Cedar Mountain Formation and its Bounding Strata

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ABSTRACT

Although only recognized as a discrete stratigraphic unit since 1944, the Cedar Mountain Formation represents tens of millions of years of geological and biological history on the central Colorado Plateau. This field guide represents an attempt to pull together the results of recent research on the lithostratigraphy, chronostratigraphy, sequence stratigraphy, chemostratigraphy, and biostratigraphy of these medial Mesozoic strata that document the dynamic and complex geological history of this region. Additionally, these data provide a framework by which to examine the history of terrestrial faunas during the final breakup of Pangaea. In fact, the medial Mesozoic faunal record of eastern Utah should be considered a keystone in understanding the history of life across the northern hemisphere.

Following a period of erosion and sediment bypass spanning the Jurassic–Cretaceous boundary, sedimentation across the quiescent Colorado Plateau began during the Early Cretaceous. Thickening of these basal Cretaceous strata across the northern Paradox Basin indicate that salt tectonics may have been the predominant control on deposition in this region leading to the local preservation of fossiliferous strata, while sediment bypass continued elsewhere. Thickening of overlying Aptian strata west across the San Rafael Swell provides direct evidence of the earliest development of a foreland basin with Sevier thrusting that postdates geochemical evidence for the initial development of a rain shadow.

INTRODUCTION

This field trip begins in Salt Lake City and proceeds southeast across Utah. During the morning of Day 1 south of Interstate 70 (I-70) along Yellow Cat Ranch Road on lands managed by the Bureau of Land Management (BLM), northeast of Arches National Park. These stops focus on the eastern exposures of the Cedar Mountain Formation including the definition of its members, their contacts, and how they document active salt tectonics in the northern Paradox Basin during the Early Cretaceous (figure 1). The afternoon of Day 1 will be spent examining the exposures of the Cedar Mountain Formation on lands managed by the State of Utah

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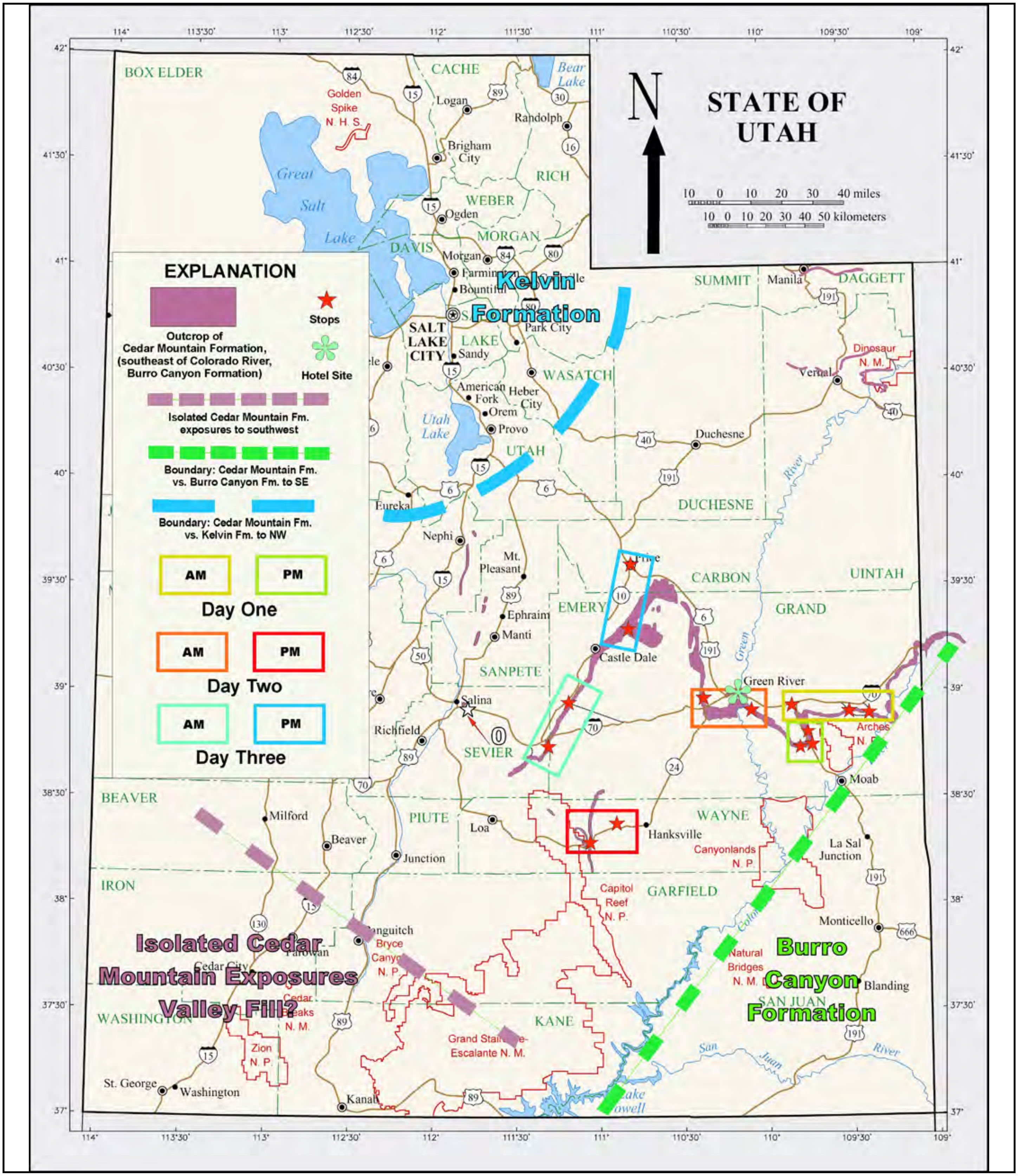

Figure 1. Map of Utah with location of field trip stops and outcrops of Cedar Mountain Formation.

west of Arches National Park where outcrops show contrasting the effects of salt tectonics on either side of the Salt Valley anticline during the Early Cretaceous. Additionally, we will examine the BLM's Mill Canyon Tracksite that has been newly developed as an interpretive site. The first and second nights will be spent in Green River, Utah. The morning of Day 2 will be spent examining the Cedar Mountain south of Green River. The afternoon will be spent examining outcrops of the Cedar Mountain Formation between Hanksville and Capitol Reef National Park where outcrops display lateral changes in the upper and lower contacts of the Cedar Mountain relative to the interface between the Paradox Basin and the forebulge as expressed by the San Rafael Swell. Before returning to Salt Lake City on Day 3, we will proceed west on I-70 to the western side of the San Rafael Swell to examine the effects and relative timing of Early Cretaceous deposition in the Sevier foredeep.

Conventions: Locations of stratigraphic sections and other important sites are given in latitude and longitude in degrees, minutes, and seconds derived from Google Earth™. Locations of fossil sites from lands managed by the BLM are not given, per the 2009 Paleontological Resource Protection Act, but are referred to by their repository location numbers, where the fossils are or will be curated. These data are available to permitted researchers. Important Cedar Mountain repositories referred to herein are as follows where # indicates specimen number:

- Brigham Young University, Paleontological Museum, Provo, Utah; BYU #
- Denver Museum of Nature and Science; DMNH#
- Dinosaur National Monument; DNM#
- Oklahoma Museum of Natural History, Norman, Oklahoma; OMNH#
- Utah Natural History Museum, Salt Lake City, Utah; UMNH#
- Utah State University Eastern, Prehistoric Museum, Price, Utah: uses locality numbers from Utah Paleontological Locality Database (UPLD); Utah (County abbreviation)#
- Utah Geological Survey (UGS): uses numbers from UPLD unless already curated into a recognized Utah repository; Utah (County abbreviation) #

Localities plotted on stratigraphic sections are correlated into the line of section and are located in the same region. All research discussed herein is based on work done under BLM or Utah state permits. Other research groups referred to herein with collections from these strata include: Burpee Museum, Rockford, Illinois; The Field Museum, Chicago, Illinois; and the North Carolina Museum of Natural History, Raleigh, North Carolina.

In discussing driving distances, we only refer to miles in keeping with the distances logged onto odometers in the United States.

OVERVIEW: CEDAR MOUNTAIN FORMATION IN EAST-CENTRAL UTAH

Utah is justifiably famous for its dinosaurs and preserves what may be the most complete and well-dated

Figure 2. Kuang Hang-Wei of the Chinese Geological Survey admires the type area for the Cedar Mountain Formation at Buckhorn Reservoir (39°14'32.15"N, 39°14'32.15"N).

terrestrial Mesozoic record in the world (Kirkland and Farlow, 2012). With historically renowned sites such as the Carnegie Quarry at Dinosaur National Monument and the Cleveland-Lloyd Quarry, Utah's Upper Jurassic Morrison Formation is particularly well known for its dinosaurs. However, Lower Cretaceous strata that overlie the Morrison Formation preserve an even greater number of dinosaur species spanning a much longer time interval. Only over the past two decades have new discoveries revealed the importance of dinosaurs preserved in Utah's Lower Cretaceous Cedar Mountain Formation.

University of Utah's William Lee Stokes can be credited for setting the stage for future research on the Lower Cretaceous of Utah. In 1948, Stokes and Phoenix (1948) described the Burro Canyon Formation as a mappable Lower Cretaceous unit of pebbly channel sandstones and green floodplain mudstones near Slick Rock in west-central Colorado. The following year, Stokes (1944, 1952) applied the name Cedar Mountain Shale to the drab, slope-forming rocks lying between the Buckhorn Conglomerate and Naturita Formation (= Dakota Formation), based on a type section defined on the southwest flank of Cedar Mountain at the north end of the San Rafael Swell by Buckhorn Reservoir (figure 2) in Emery County, Utah. Stokes (1952) renamed the shale the Cedar Mountain Formation and included the Buckhorn Conglomerate Member as its basal member. Where the cliff-forming Buckhorn was not present, the rules of thumb for distinguishing the Cedar Mountain Formation from the underlying Morrison Formation included: (1) a more drably variegated color, (2) more abundant carbonate nodules commonly with a thick carbonate paleosol (ancient soil) at the base, (3) the presence of common, polished chert pebbles identified as gastroliths (Stokes, 1944, 1952), and (4) the absence of dinosaur bones (Kirkland, 2005a). The Cedar Mountain and contiguous Burro Canyon Formations were distinguished based on thickness, pebble size, and paleocurrent directions (Craig, 1981). According to Stokes (1952) and Craig (1981), both units were deposited atop the Upper Jurassic Morrison Formation and formed a broad alluvial plain—rivers flowing from highlands to the south deposited the sediments of the Burro Canyon Formation, and those flowing from the west deposited the material of the Cedar Mountain Formation (Lawton and others, 1997, 2007). The southwest-flowing (modern) Colorado River (figure 1) has served as the arbitrary boundary between the Cedar Mountain (northwest) and Burro Canyon (southeast) Formations (Stokes, 1952; Craig, 1981; Tschudy and others, 1984; Milán and others, 2015).

In the southwestern portion of Utah beyond the contiguous outcrop belt of the Cedar Mountain Formation, the dating of outcrops of pale-green, fine-grained strata below the Naturita Formation (= Dakota Formation) as Early Cretaceous, has led to the recognition of the Cedar Mountain on a number of geological maps in this region (Biek and others, 2009, 2010, 2015; Hylland, 2010). These sites are considered local in extent and radiometric dates indicate that only the late Albian portion of the Cedar Mountain Formation is represent-

Figure 2. Kuang Hang-Wei of the Chinese Geological Survey admires the type area for the Cedar Mountain Formation at Buckhorn Reservoir (39°14'32.15"N, 39°14'32.15"N).

ed (figure 2). Along the Sevier thrust belt in northern Utah, the Cedar Mountain Formation is replaced by the much thicker Kelvin Formation (Mathews, 1931; Granger, 1963; DeCelles and Currie, 1996). Few fossils have been reported from this thick sequence of strata, but it includes microvertebrate remains and dinosaur eggshells (Jensen, 1970; Prothero, 1983; Zelenitsky and others, 2000).

The reported absence of dinosaur bones in the Cedar Mountain Formation limited the interest of paleontologists in these rocks for many years. Because geologists lacked any accepted means of subdividing these rocks, they were long considered a rather monotonous sequence of Lower Cretaceous strata that generally thicken to the west. Young's (1960) report, "Dakota Group of Colorado Plateau," although strongly rebutted (Craig and others, 1961) and largely ignored at the time, has been reinstated as a major contribution to our understanding of these rocks (Kirkland and Madsen, 2007; Sprinkel and others, 2012; Carpenter, 2014). Young's proposal that the correlative Burro Canyon Formation be included as simply an extension of the Cedar Mountain Formation has not been followed, but these correlations have held up well with the recognition of marker sandstones, basically preceding the application of sequence stratigraphic principles (Kirkland and Madsen, 2007; Sprinkel and others, 2012). Currie (1998, 2002), Currie and others (2008, 2012), and McPherson and others (2006), working mainly along the east-west trend of the Uinta Mountains, developed a model for the deposition of the Cedar Mountain Formation within a foreland basin system, but the complexities of preexisting structures and salt tectonics hamper the use of a simplistic foreland basin model.

The recognition of significant vertebrate fossils has provided age control on these rocks, supporting Young's (1960) principal conclusions regarding the Cedar Mountain Formation (Kirkland and others, 1997, 1999; Kirkland and Madsen, 2007; Sprinkel and others, 2012). Young identified regionally extensive sandstone marker beds on which the correlations are based by applying sequence stratigraphic principles to these rocks before the methodology had actually been developed (figure 3). Given Young's limited biostratigraphic and chronostratigraphic tools, the overall accuracy of the correlations is remarkable. The principle disputes between Young (1960) and Craig and others (1961), largely came down to a difference in their conceptual paradigms being applied to the nomenclature.

Up to this time, the Upper Cretaceous strata overlying the Cedar Mountain Formation had often been referred to as "?Dakota" or "so-called" Dakota on the Colorado Plateau. Young (1960, 1965) proposed to reassign these overlying strata to the Naturita Formation but that was met with resistance (Craig and others, 1961). As these strata are Upper Cretaceous and not Lower Cretaceous, and are not contiguous with the Dakota Sandstone in its type area of eastern Nebraska, they are now being more properly referred to the Naturita Formation (Carpenter and others, 2008; Carpenter, 2014; Milán and others, 2015; Cifelli and others, 2016), as they are herein.

New dinosaur species reported in the mid-1990s led to a rush of researchers from many institutions prospecting for dinosaurs in the Cedar Mountain Formation. Brigham Young University, Utah State University Eastern (formally College of Eastern Utah) Prehistoric Museum, Denver Museum of Nature and Science, Dinosaur National Monument, Oklahoma Museum of Natural History, North Carolina Museum of Natural History, The Field Museum (Chicago), and the Utah Geological Survey are just some of the many research groups presently looking for fossils in these rocks. A wealth of new fossil sites (figure 4), along with radiometric ages, have established that this relatively thin layer (normally less than 100 m) of Lower Cretaceous Cedar Mountain Formation, which separates thousands of meters of Jurassic rocks from thousands of meters of Upper Cretaceous rocks, is more complex than previously thought. Additionally, it preserves nearly 30 million years of what may be the most intriguing episode of dinosaur history, apart from their origin and extinction. These studies have in turn spawned additional directions of research in taphonomy, sedimentology, tectonics, geochemistry, radiometric dating, and paleomagnetics.

In addition to dinosaur bones, fossil dinosaur eggshells (Jensen, 1970; Bray, 1998; Zelenitsky and others, 2000) and tracks (DeCourten, 1991; Lockley and others, 1999, 2004, 2014a, 2014b, 2015; Wright and others, 2006) have been identified at several stratigraphic levels

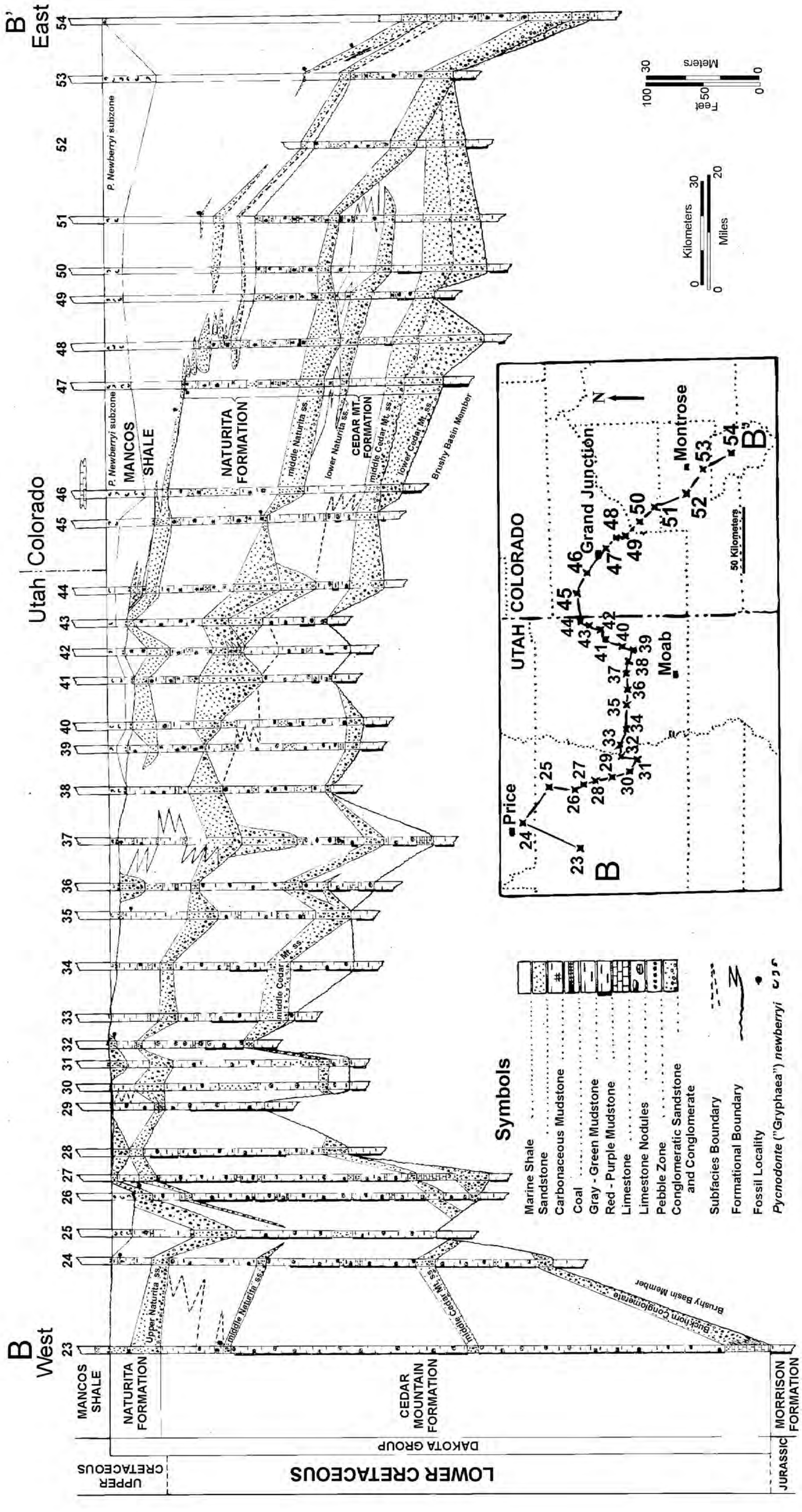

Figure 3. Cross section of the Cedar Mountain and Naturita Formation from Castle Dale, Utah (south of Cedar Mountain Formation type area) to Colona, Colorado. See Young (1960, figure 6) for locality data. From Young (1960).

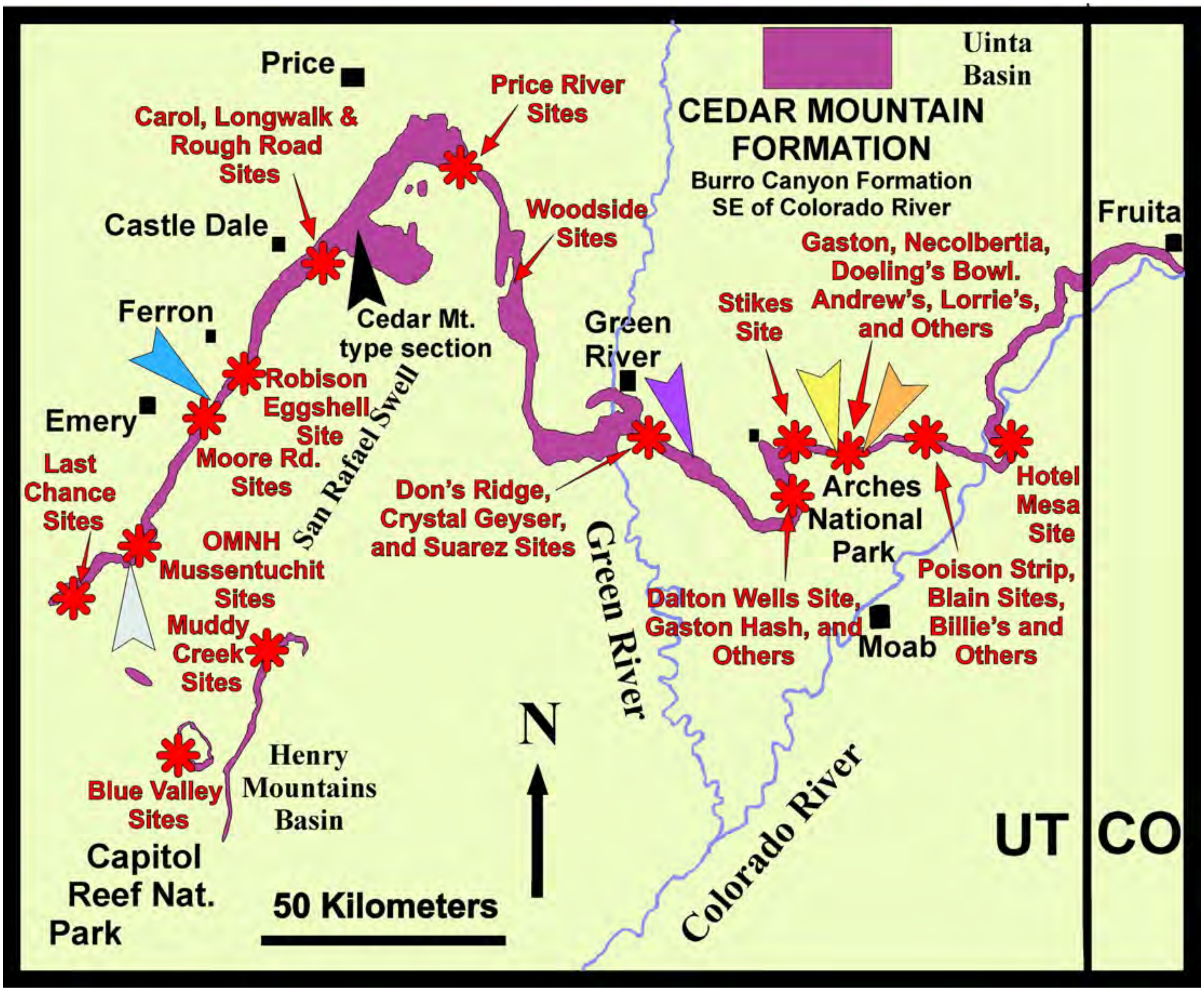

Figure 4. Outcrop map of Cedar Mountain Formation in the central Colorado Plateau area with approximate locations of many of the major fossil sites referred to in the text indicated. Arrows indicate type sections: black – Cedar Mountain Formation and Buckhorn Conglomerate; yellow – Yellow Cat Member; orange – Poison Strip Sandstone; purple – Ruby Ranch Member; gray – Mussentuchit Member; and blue – Short Canyon member.

throughout the Cedar Mountain Formation. While not directly expanding the known diversity of dinosaurs from these rocks, these discoveries are adding considerable ecological and behavioral information concerning Cedar Mountain dinosaurs.

Kirkland and others (1997, 1999) used the distribution of specific dinosaur faunas (groups of dinosaurs living together) and their relationship to distinct rock types to define four additional members of the Cedar Mountain Formation. In ascending order, these are the Yellow Cat Member, Poison Strip Sandstone, Ruby Ranch Member, and Mussentuchit Member. Together with the Buckhorn Conglomerate Member, these rock units and the fossils they contain are shedding light on the previously obscure Early Cretaceous history of Utah (figures 4 and 5). Please note that the Poison Strip Sandstone of Kirkland and others (1997) is herein renamed Poison Strip Member (see the Poison Strip Member section below for details).

Six dinosaur faunas are now recognized within the

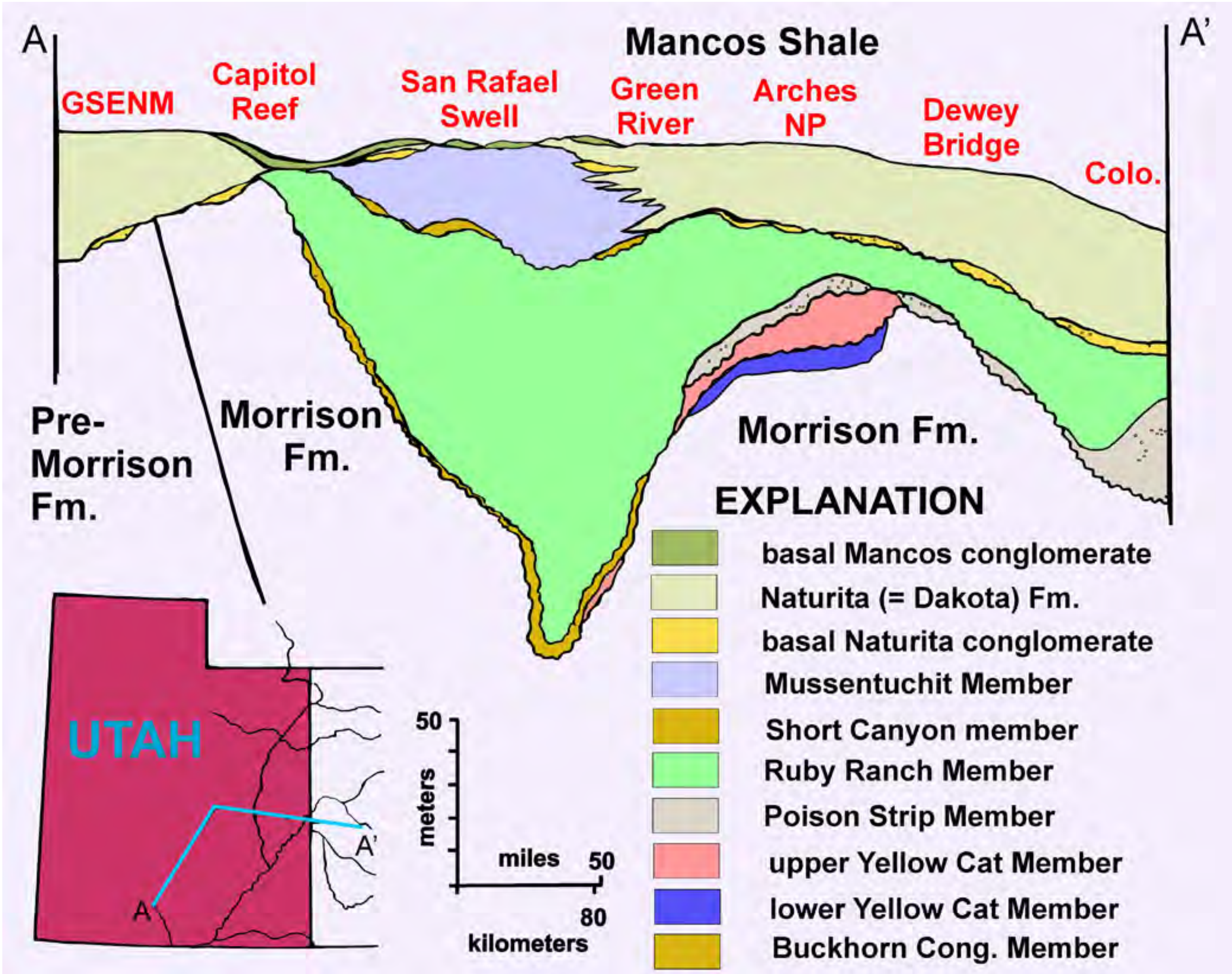

Figure 5. Simplified cross section of Cedar Mountain Formation across eastern Utah showing the relationship of its various members, select dinosaur sites, and adjacent stratigraphic units. Updated after Kirkland and others (1997).

Cedar Mountain Formation on the basis of changes at the genus and species level. More substantial faunal breaks at higher taxonomic levels provide a natural three-fold division that appears to have greater paleogeographic and evolutionary significance (Kirkland and others, 1997, 1999). The lower ("polacanthid") faunal division is grouped together based on presence of polacanthid ankylosaurs, spatulate toothed sauropods, basal styracostern "iguanodonts," and large dromaeosaurine dromaeosaurids, and is recovered from throughout the Yellow Cat and Poison Strip Members. The medial ("tennontosaurid") faunal division is characterized by nodosaurid ankylosaurs, slender-toothed titanotosauriform sauropods, and basal iguanodonian tennontosaurids, and is restricted to the Ruby Ranch Member. The upper ("*Eolambia*") fauna division is restricted to the Mussentuchit Member and is dominated by the hadrosauroid iguanodontian *Eolambia*, having a mix of faunal holdovers from the medial "tennontosaurid" fauna and new faunal elements derived from Asia (Kirkland and others, 1997, 1998, 1999; Kirkland and Madsen, 2007). As described in subsequent sections, the lower fauna appears to be divisible into three sequential faunas and the medial fauna into two sequential faunas.

These three distinct dinosaur faunal divisions match three "chronofacies" based on detrital zircon age distributions from 100 randomly dated zircon grains extracted from sandstones in these intervals (figure 6).

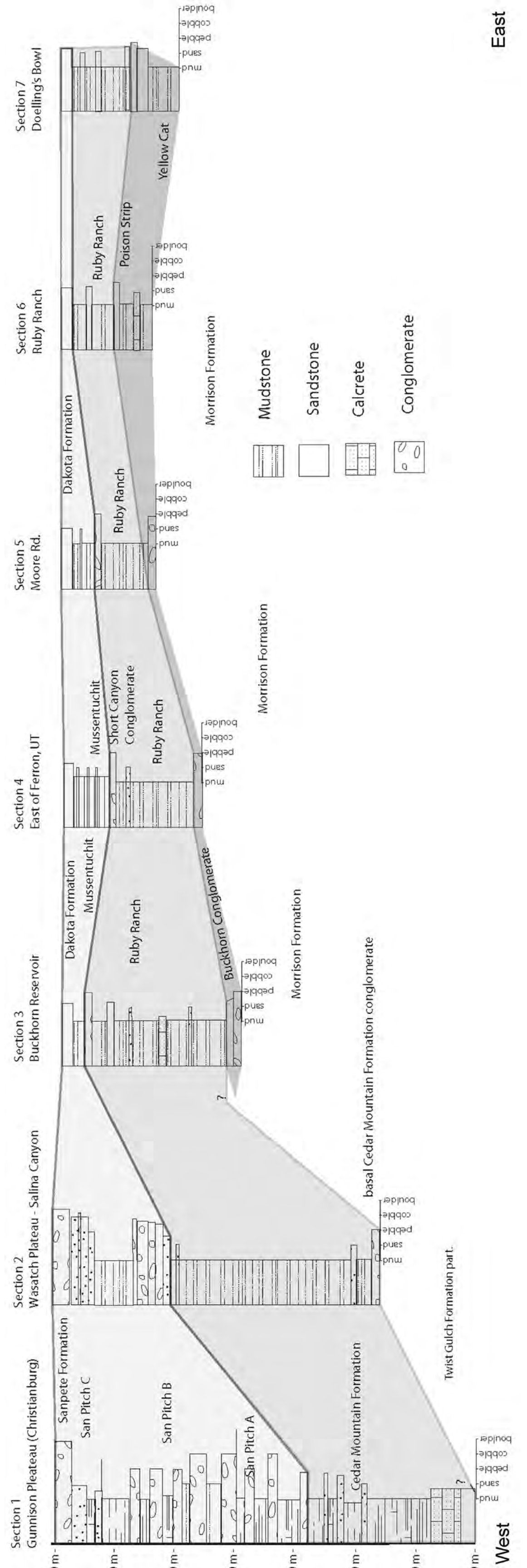

Figure 6. Correlation of Lower Cretaceous chronofacies roughly from west (Sevier thrust belt) to east (Paradox Basin). Dark gray = basal Lower Cretaceous chronofacies; medium gray = upper Lower Cretaceous chronofacies; lightest gray = basal Upper Cretaceous chronofacies. Dakota Formation = Naturita Formation. From Hunt and others (2011).

Following methodologies developed by Dickenson and Gehrels (2008), chronofacies is a proxy for grouping strata based on similar aged source rocks (Lawton and others, 2010; Hunt and others, 2011).

These three dinosaur faunas have a somewhat restricted distribution geographically. The lower polacanthid fauna is only documented in the Yellow Cat and the Poison Strip Members in Grand County, Utah. Of the 496 Cedar Mountain localities recorded for Utah in the UPLD, 302 are in Grand County. The middle "tenontosaurid" fauna is present wherever the Ruby Ranch Member of the Cedar Mountain Formation has been documented, but is only known from a few scattered localities largely due to the difficulty of prospecting for bone fragments amongst the carbonate debris covering many exposures of this member. The upper *Eolambia* fauna is only known from the Mussentuchit Member on the western side of the San Rafael Swell in Emery County and at very limited exposures in Sevier County (three localities). Emery County includes 167 of the known Cedar Mountain fossil localities making Grand and Emery Counties clearly the focal point for Lower Cretaceous paleontological research in Utah.

Buckhorn Conglomerate Member

The basal Buckhorn Conglomerate Member has a type section in the area of Buckhorn Reservoir on the northwest side of the San Rafael Swell. In its type area, the Buckhorn consists largely of a chert-pebble to cobble conglomerate up to 25 meters thick that defines a complex northeast-flowing paleo-river system along the west flank of the San Rafael Swell from the north end of Capitol Reef National Park (Yingling, 1987; Currie, 1998; figure 7). Well-developed Buckhorn Conglomerate extends north of I-70 across the northeast side of the San Rafael Swell and in northeastern Utah at Dinosaur National Monument, Colorado and Utah, and the surrounding area (Currie, 1998; Greenhalgh and Britt, 2007; Currie and others, 2012; Sprinkel and others, 2012). The chert pebbles and cobbles preserve late Paleozoic marine fossils reworked from ancient mountains in northwest Arizona and Nevada.

In recent years, controversy has arisen over the age of the Buckhorn Conglomerate in its type area, as a thick carbonate paleosol locally overlies the Buckhorn and a carbonate paleosol has been used to define the base of the Cretaceous elsewhere (Aubrey, 1996, 1998). Because of the maturity of this paleosol, it has been proposed that it represents an unconformity between the Jurassic and Cretaceous (Aubrey, 1998; Roca, 2002; Ayers, 2004; Roca and Nadon, 2007). However, well-developed paleosols may occur at a number of stratigraphic positions within the Cedar Mountain Formation and it is possible the carbonate paleosol could well post-date the deposition of the Buckhorn Conglomerate (Kirkland and others, 1997; Carpenter and others, 2001; Al-Suwaidi, 2007; Kirkland and Madsen, 2007; Ludvigson and others, 2010a). Recognition of the Buckhorn Conglomerate is also complicated in that it may be poorly or completely uncemented locally and be nearly unrecognizable except by trenching out the section. This is notable just north of the type area above the Cleveland-Lloyd Quarry and on Cedar Mountain on the north end of the San Rafael Swell. The recent discovery of a possible ankylosaur (armored dinosaur) skeleton within the Buckhorn Conglomerate in this area (figure 7D) suggests a Cretaceous age, as these dinosaurs are rare in the Jurassic and are abundant in the Lower Cretaceous (Carpenter and Kirkland, 1998; Kirkland, 2005a; Kirkland and Madsen, 2007). Elsewhere, the sole body fossils identified in the Buckhorn Conglomerate consist of isolated sauropod bones, which unfortunately do not provide any biostratigraphic information.

At the eastern margin of the Buckhorn Conglomerate exposure on the east side of the San Rafael Swell near Green River, Utah, the Buckhorn Conglomerate and Poison Strip Members appear to merge; the Buckhorn Conglomerate Member is used nomenclaturally, where there is no underlying fine-grained Yellow Cat (Kirkland and Madsen, 2007). Good, continuous Buckhorn Conglomerate forms a bench at the base of the Cedar Mountain Formation along the entire northeastern side of the San Rafael Swell, starting approximately 16 km (10 mi) directly north of I-70. Where the Green River Cutoff Road (BLM 401) crosses the Cedar Mountain outcrop belt, Shapiro and others (2009) noted that dinosaur bone-bearing oncolites at the contact between the Buckhorn Conglomerate and the overlying Ruby Ranch Member may best be referred to as a Poison Strip

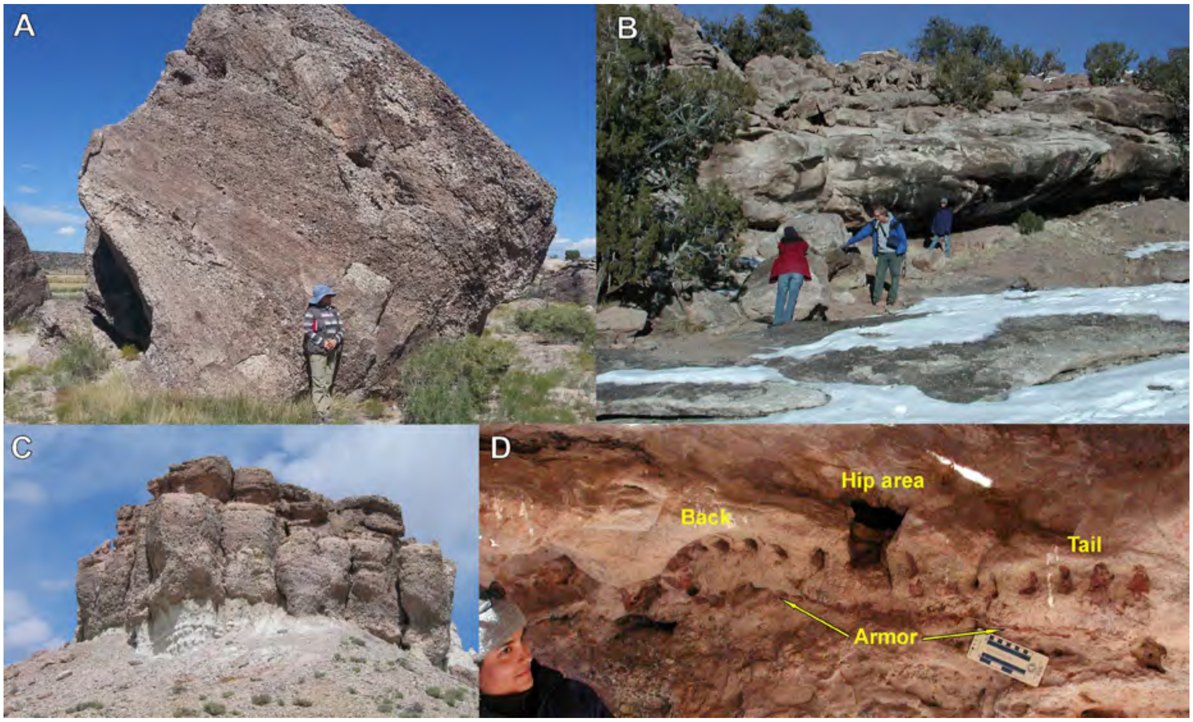

Figure 7. Buckhorn Conglomerate. (A) Boulder of Buckhorn Conglomerate next to road southeast of Buckhorn Reservoir (39°14'23.54"N, 110°48'35.20"W. (B) Outcrop of Buckhorn Conglomerate near Buckhorn Draw. (C) Buckhorn Conglomerate unconformably overlying the Morrison Formation just east of Capitol Reef National Park in the Bentonite Hills (38°21'30.00"N, 111°7'44.53"W). (D) Marina Suarez examining ankylosaur partial skeleton lying on back in middle part of Buckhorn Conglomerate under overhang near Buckhorn Draw Road.

facies that is incorporated into the top of the Buckhorn Conglomerate (R.S. Shapiro, California State University Chico, personal communication, 2008).

Conglomeratic fluvial facies of the Buckhorn have been shown to interfinger with interfluvial facies characteristic of the (at least in part) laterally equivalent Yellow Cat Member of the Cedar Mountain Formation (Greenhalgh, 2006; Greenhalgh and others, 2006; Greenhalgh and Britt, 2007) on the south end of the San Rafael Swell east of Capitol Reef National Park. However, these strata are much sandier than is typical of the Yellow Cat Member in its outcrop belt to the north.

In the San Rafael Swell area, Demko and others (2004) interpreted areas of fine-grained strata with iron enriched paleosols to represent wet climatic conditions at the end of Morrison Formation deposition that were preserved only on drainage divides within the Buckhorn drainage system. We follow Greenhalgh and Britt's (2007) interpretation that these strata interfinger with the Buckhorn Conglomerate Member and argue below (see the section on the lower Yellow Cat) that the wet climatic conditions are represented by iron-stained beds of the lower Yellow Cat Member.

An excellent example of Buckhorn Conglomerate interfingering with Buckhorn interfluvial facies is exposed along of I-70 on the west side of the San Rafael Swell west of the rest area milepost 103.5. Looking west from the rest area, a well-developed ledge of Buckhorn Conglomerate caps the variegated slope formed by the Brushy Basin Member of the Morrison Formation on the skyline (figure 8A). Farther west (5.6 km) and around a bend in the highway at the top of the grade, I-70 cuts through the base of the Cedar Mountain Formation along a well-exposed roadcut where the basal Buckhorn Conglomerate is absent (figure 8D). Over this short distance the Buckhorn is observed interfingering with an interfluvial facies. This interfluvial facies is very similar to lithologies in the lower Yellow

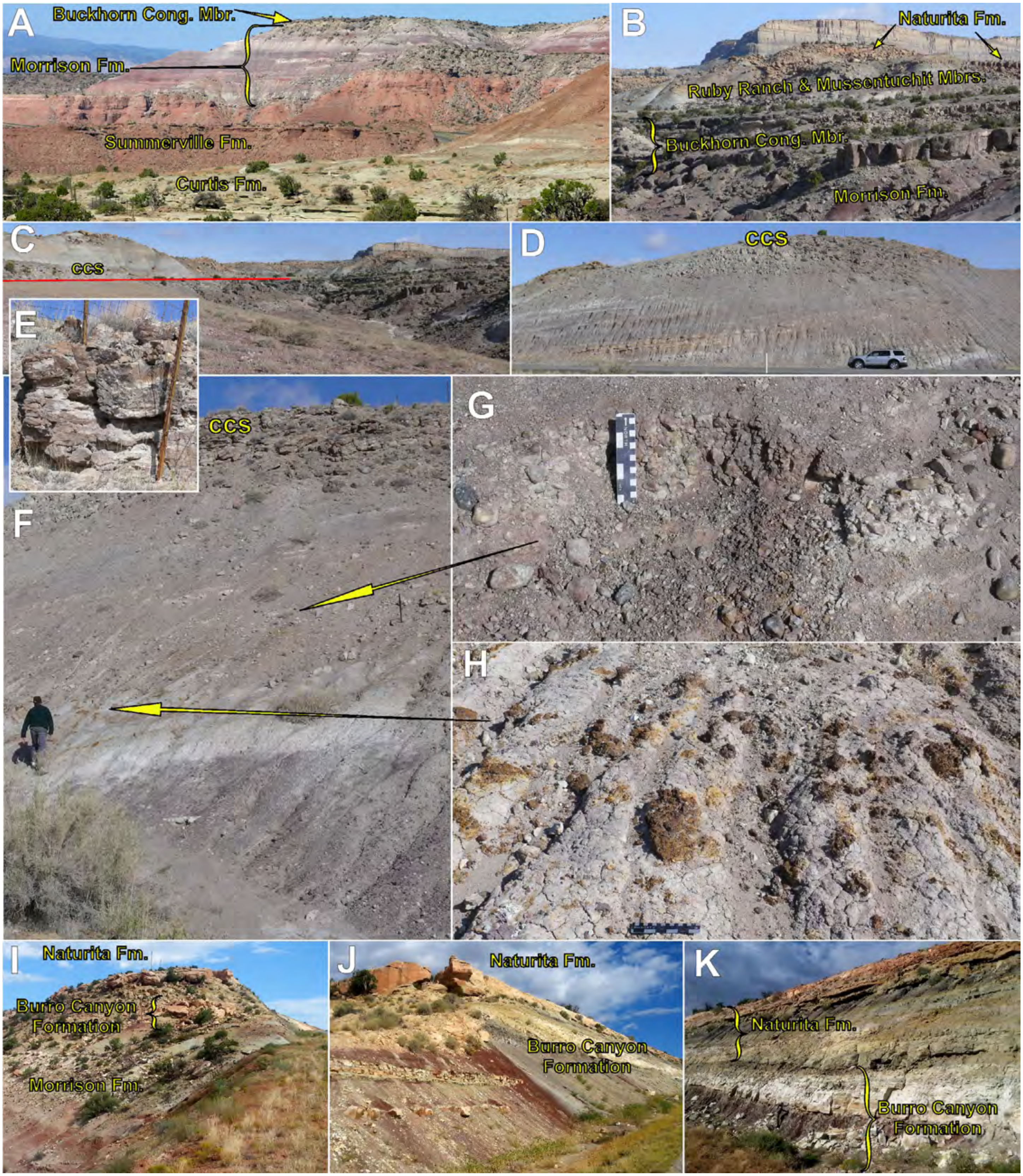

Figure 8. Caption on following page.

Figure 8 (figure on previous page). Exposures of the basal Cedar Mountain Formation between I-70 milepost 104 and 108. (A) Middle Mesozoic strata on north side of I-70 at rest stop on west side of San Rafael Swell (38°49'56.80"N, 111° 6'46.07"W). Note that the smectitic mudstones of the Brushy Basin Member make up most of the Morrison Formation capped by Buckhorn Conglomerate on the skyline. (B) Buckhorn Conglomerate Member with interfingering Yellow Cat interfluvial facies west of outcrop in A. (C) Overview of B showing that the cherty, calcareous sandstone (ccs) capping the road cut in D to F overrides the Buckhorn Conglomerate. Red line shows separation between ccs and underlying tongues of Buckhorn Conglomerate. (D) Overview of road cut exposing Yellow Cat interfluvial facies (38°49'4.22"N, 111°10'16.00"W). (E) Close-up view of cherty, calcareous sandstone (labeled ccs on C, D, and F) capping the road cut. (F) Detail of road cut exposing Yellow Cat interfluvial facies showing position of close up pictures G and H. (G) Lenses of pebble conglomerate. (H) Iron-stained nodules in basal Cedar Mountain Formation. (I) Largely fine-grained facies of the Burro Canyon Formation exposed on west side of US 191 south of Blanding, Utah (37°25'59.62"N, 109°28'13.83"W), viewed from south. (J) Same exposure on south end as viewed from southwest. (K) Contact between Burro Canyon Formation and overlying Naturita Formation on eastern side of US 191 road cut.

Cat Member of the Cedar Mountain Formation in the Paradox Basin as discussed in that section. These fine-grained strata preserve common small lenses and floating pebbles of chert and quartzite. Iron-stained nodules and layers of chert are also present. These strata are capped by cherty, calcareous, fine-grained sandstone that can be traced laterally onto the top of the Buckhorn Conglomerate Member. This bed is in turn overlain by the Ruby Ranch Member of the Cedar Mountain Formation. The Buckhorn Conglomerate represents a large anastomosing river system and these interfingering finer grained strata are herein referred to as the Yellow Cat facies of the Buckhorn Conglomerate. In this way, they are separated nomenclaturally from the carbonate nodule-bearing Ruby Ranch Member, which overlies them. For mapping purposes, it seems logical to map these interfluvial strata within the outcrop belt of the Buckhorn Conglomerate as a Yellow Cat facies of the Buckhorn Conglomerate.

Additionally, it has been documented that gravel floating in fine-grained matrix in the basal Cedar Mountain Formation define the lower Yellow Cat Member across the Paradox Basin east of the Buckhorn outcrop area as discussed in that section. Large chert and quartzite cobbles, associated with sauropod and ankylosaur bones in the lower Yellow Cat on the western margin of the Paradox Basin south of Green River, Utah (Greenhalgh and Britt, 2007; Kirkland and Madsen, 2007; McDonald and others, 2010), are much larger than the pebbles typical of the lower Yellow Cat elsewhere and are thought to represent direct evidence that the lower Yellow Cat is laterally equivalent with the Buckhorn Conglomerate. The facies changes in the basal Cedar Mountain Formation between the Paradox Basin and the San Rafael Swell has the potential to reveal interesting data concerning the onset of Cretaceous deposition following an interval of nondeposition and erosion across the Jurassic-Cretaceous temporal boundary at the interface between two differing tectonic regimes (see Peterson, 1984).

In the southern Paradox Basin of southeastern Utah and to the east of the Paradox Basin in western Colorado, Young (1960) noted a lower Cedar Mountain (conglomeratic) sandstone that may have been equivalent to the Buckhorn Conglomerate, but was not assign these beds to the Buckhorn due to the lack of continuity in deposition. As these exposures are in the Burro Canyon outcrop area, we are in complete agreement with Young's nomenclature. Interestingly, along an extensive road cut along U.S. Highway 191 (US 191) south of Blanding, the entire stratigraphic interval between the underlying Morrison Formation and the overlying Naturita Formation (= Dakota Formation) consists of stacked ferugeneous, pebbly paleosols similar to those present in the Buckhorn interfluvial facies, documenting the presence of the Yellow Cat interfluvial facies in the Burro Canyon Formation in southern Utah (figure 8I to K).

Finally, it is worth noting that Stokes (1950) reported that both the Shinarump Member of the Upper Triassic Chinle Formation and the Buckhorn Conglomerate were broadly similar in being very widespread and relatively thin conglomeratic fluvial units formed on regional unconformities and composed mainly of materials derived from the underling strata. In this, Stokes (1950) referred to the pediment concept, although the term regolith is as applicable. Although our research on the Chinle Formation in Utah is still in its preliminary stages (Martz and others, in review), it is worth noting that Shinarump, interfluvial deposits near the head of Red Canyon in San Juan County in southern Utah, are remarkably similar to those we have noted at the base of the Cedar Mountain Formation on the San Rafael Swell, which suggests that investigating these sequences in comparison to each other may yield interesting results.

Yellow Cat Member

The Yellow Cat Member consists of drab, variegated, illitic mudstone, limestone, and paleosols, with some sandstone lenses. The type section (figures 4 and 9) is west of where the Yellow Cat Road crosses the bench held up by the overlying Poison Strip Member of the Cedar Mountain Formation at the Gaston Quarry (Kirkland and others, 1997). The Yellow Cat is recognized in the area south of I-70 between the Green and Colorado Rivers, where it is thought to reflect the last effects of salt diapirism in the northern Paradox Basin around Arches National Park (Doelling, 1988; Doelling and Kuehne, 2013a).

The Burro Canyon Formation in the central Paradox Basin south of Moab has never been studied paleontologically; however, in the Lisbon Valley area, approximately 40 m of conglomerate and sandstone beds host economically important copper deposits. The copper-bearing beds are overlain by 20 to 40 m of mudstone beds with nodules suggesting that the Yellow Cat Member is not present in this area (Young, 1960; Hahn and Thorson, 2006). A stratigraphic cross section along the outcrop belt (figures 10 and 11) lends considerable support to the hypothesis that the Yellow Cat Member, as used herein, is restricted to the northern Paradox Basin in Grand County, Utah.

The Yellow Cat Member was originally defined as being underlain by a massive carbonate paleosol, reflecting an approximately 25-million-year hiatus in sediment accumulation between the Late Jurassic and middle Early Cretaceous (Aubrey, 1996, 1998; Kirkland and others, 1997, 1999; Skipp, 1997; Demko and others, 2004; Kirkland, 2005a). Early Cretaceous fossils have now been found below the base of this carbonate interval, thus necessitating a redefinition of the lower boundary of the Cedar Mountain Formation at the first occurrence of abundant chert pebbles above typical Morrison swelling clays (Kirkland, 2005b; Kirkland and Madsen, 2007). The Yellow Cat Member is overlain by the Poison Strip Member and pinches out to the east and west (figure 5). It is worth noting that the Yellow Cat is well defined in Young's (1960) cross section below the "middle sandstone unit" between sections 30 and 38 (figure 3).

Figure 9. The Cedar Mountain Formation on the west side of Gastonia Point (east of Yellow Cat Flat), northeast of Arches National Park, with distribution of members labeled. This is the type section of the Yellow Cat Member and Gaston Quarry (Utah Gr 184v) type locality for *Gastonia* and *Utahraptor* (Kirkland and others, 1997).

Jurassic-Cretaceous Boundary and the K-1 Unconformity

Over the past 60 years, the Jurassic-Cretaceous boundary has progressively been pushed stratigraphically lower in the northern Paradox Basin as additional Cretaceous fauna have been discovered. The boundary appears to have stabilized just above the highest smectitic mudstone beds of the Brushy Basin Member of the Morrison Formation (figure 12). With the recognition of Cretaceous strata below the marker calcrete of Aubrey (1996, 1998), a new set of criteria is needed to define the base of the Cedar Mountain Formation in a consistent manner. These criteria also may be applied to those areas in the Buckhorn Conglomerate outcrop belt, where fine-grained interfluvial strata ("Yellow Cat facies") form the base of the Cedar Mountain Formation.

Given the presence of Cretaceous dinosaurs below the marker calcrete, the old rule of thumb that the Cedar Mountain Formation can be distinguished from the underlying Morrison Formation based on its drabber, variegated mudstones (Stokes, 1952; Young, 1960) is problematic, as the basal Yellow Cat Member often includes brightly colored red beds. It is important to note that, whereas the Upper Jurassic Brushy Basin Member of the Morrison Formation is highly smectitic on the Colorado Plateau (Peterson, 1994; Turner and Peterson,

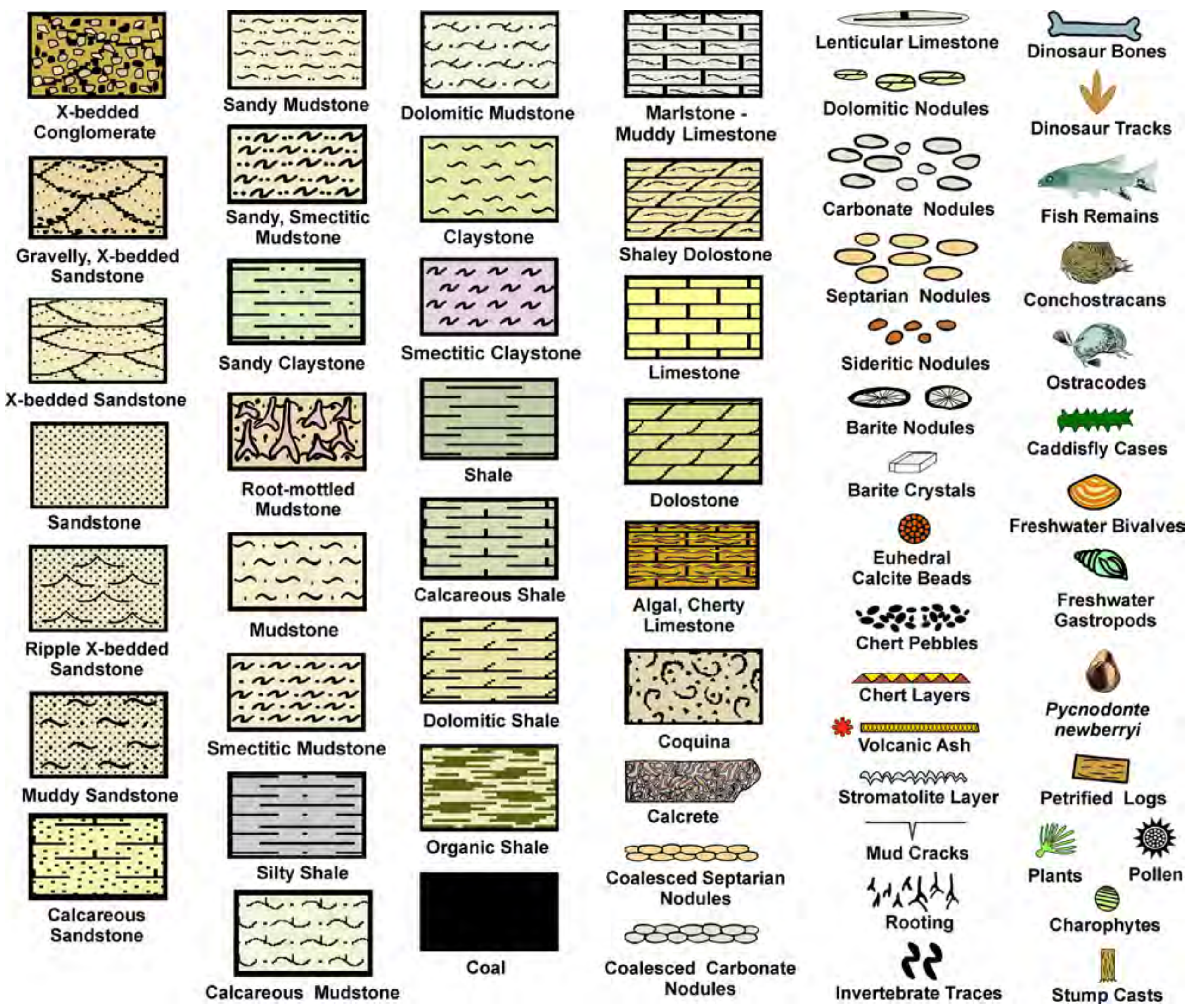

Figure 10. Stratigraphic key for stratigraphic sections presented herein.

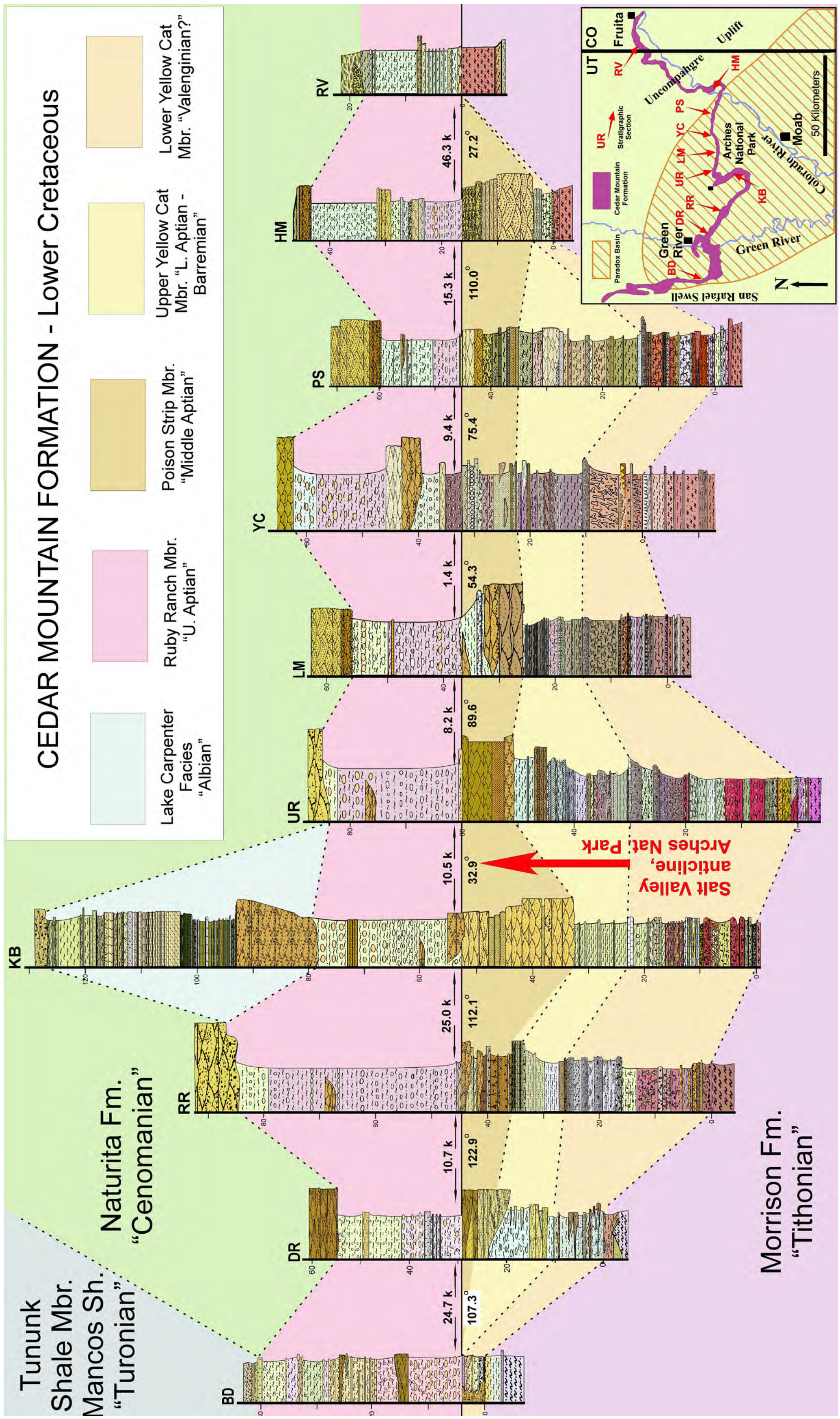

Figure 11. Cross section of Cedar Mountain Formation across the north end of the Paradox Basin, Grand County, Utah. Each section examined in greater detail elsewhere herein. BS=Buckmaster Draw, DR=Don's Ridge, RR= Ruby Ranch Road, KB=Klondike Bluffs Road, UR=Utahraptor Ridge, LM=Lake Madsen section, YC=Yellow Cat Road, PS=Poison Strip section, HM=Hotel Mesa, RV=Rabbit Valley, DB=Doelling's Bowl, PR=Price River section, MW=Mussentuchit Wash, BF=Blue Flats, MC=Muddy Creek (River), and MR=Moore Road. Key to stratigraphic symbols as in figure 10. Vertical scale in m.

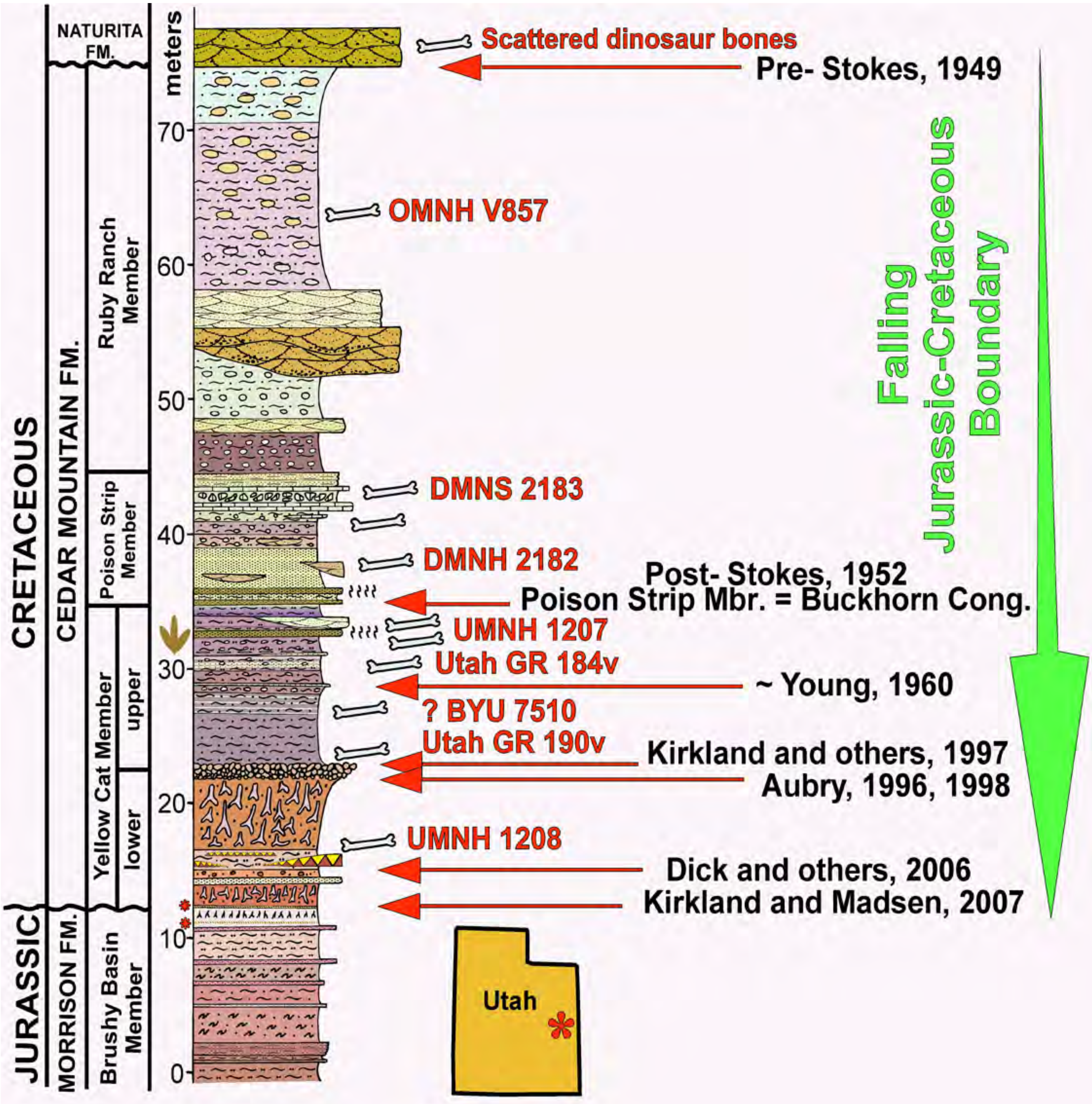

Figure 12. Falling Jurassic-Cretaceous boundary in Paradox Basin plotted against Yellow Cat Road section. BYU 7210 = approximate position of Dalton Wells Quarry (Britt and others, 2009); DMNH 2182 = Tony's bonebed, type locality for *Planocoxa* and *Veneosaurus* (DiCroce and Carpenter, 2001; Tidwell and others, 2001); DMNH 2183 = Lorrie's site, type locality for *Gastonia lorriemcwhinneyae* (Kineer and others, 2016); OMNH v857 = Hotel Mesa site, type locality for *Brontomirus*; UMNH 1207 = Andrew's site, type locality for *Hippodraco*; UMNH 1208 = Doelling's Bowl bonebed, type locality for *Yurgovuchia*; Utah GR 184v = Gaston Quarry, type locality for *Gastonia* and *Utahraptor*; and Utah GR190v = Nedcolbertia site, type locality for *Nedcolbertia*.

1999; Trujillo and Kowallis, 2015), the overlying Yellow Cat Member of the Cedar Mountain Formation is not (Kirkland and others, 1997, 1999; Kirkland and Madsen, 2007). Additionally, the lower Yellow Cat Member is characterized by chert beds and laminae (silcretes?), iron oxide cemented nodules, stacked root-mottled paleosols, and scattered chert pebbles (Dick, 2006; Dick and others, 2006; Kirkland and Madsen, 2007; Toth, 2010). The most consistent sedimentological characteristic found at the base of the Cedar Mountain Formation is the presence of a chert pebble lag or first occurence of chert pebbles "floating" in a mudstone matrix. Workers have suggested that the materials that compose the basal Cedar Mountain Formation are materials winnowed from the underlying Morrison Formation (Eberth and others, 2006; Hunt and others, 2011; Sprinkel and others, 2012).

The methodology now employed in our research to pick the base of the Cedar Mountain Formation in the field is to find the highest smectitic mudstones in the underlying Brushy Basin Member of the Morrison Formation and then trench up through the overlying mudstones into Cedar Mountain strata that clearly preserves matrix-supported or "floating" chert pebbles in root-mottled paleosols with or without chert layers, ferruginous nodules, and iron oxide staining. Then, the strata are carefully examined to find the first occurrence of small chert pebbles, which is then used to mark the base of the Cedar Mountain. Defined by this field proceedure, we have recognized that the uppermost Morrison Formation is typically not smectitic and may exhibit minor root-mottling and iron staining, indicating weathering of the erosion surface prior to initial deposition of the Cedar Mountain Formation. These pebbles may form a distinct horizon that can be readily distinguished, or the contact may only be represented as scattered, very coarse, brightly colored, chert grains within a mudstone matrix.

From a distance and in aerial photography the boundary can be picked based on differences in the weathering profile of the slope. Mudstone beds in the Brushy Basin Member of the Morrison Formation are highly smectitic and generally have a convex profile to their exposed slopes. Mudstone beds in the Yellow Cat Member of the Cedar Mountain Formation are never smectitic and the slope profile is flat to concave. Color is not a good criterion as bright red strata are commonly present in the lower Yellow Cat, although these strata tend to be drabber than those of the underlying Morrison Formation. Combined with field inspection, these have proven to be useful criteria for mapping purposes (Doelling and Kuehne, 2013a).

The contact between the Morrison and Cedar Mountain Formations defined in this way is still identified as representing the K-1 unconformity. The length of time represented by this hiatus is impossible to determine accurately at this time. The youngest ages for Morrison strata in this area are (1) 148.96 +2.54 to -2.21 Ma based on U-Pb ages determined by laser ablation of zircons extracted from a volcanic ash bed about 9 m below the base of the Naturita Formation (= Dakota Formation), which rests directly on the Morrison Formation in these outcrops west of Hanksville, Wayne County, Utah (Kirkland and Madsen, 2007; Kowallis and others, 2007; Hunt and others, 2011) and (2) 150.00 ± 0.52 Ma from near the top of the Brushy Basin Member, near little Cedar Mesa, Emery County, Utah, based on a recalibrated $^{40}Ar/^{39}Ar$ age (Trujillo and Kowallis, 2015). Thus, the top of the Morrison Formation dates to the lower third of the Tithonian Stage near but not to the end of the Jurassic (Cohen and others, 2013).

Dates from the Yellow Cat Member of the Cedar Mountain Formation are limited to U-Pb analysis determined by laser ablation of detrital zircons. The most widely cited age of 124.2 ± 2.6 Ma (Greenhalgh, 2006; Greenlalgh and Britt, 2007; Britt and others, 2009; Ludvigson and others, 2010a) is from the 20 youngest of 62 zircon grains sampled from a sandy green mudstone stratigraphically a few meters higher and two kilometers west of BYU's Dalton Wells Quarry (BYU 7510). A detrital zircon U-Pb age of 146.6 +4.1 to -3.9 Ma from the Dalton Wells Quarry supported the hypothesis that the quarry sediment was derived completely from material reworked from the underlying Morrison Formation (Eberth and others, 2006). The Dalton Wells Quarry preserves a dinosaur fauna consistent with that of the upper part of the Yellow Cat Member (Kirkland and Madsen, 2007; Britt and others, 2009; Kirkland and others, 2012). Mori (2009) reported a number of additional U-Pb ages from detrital zircons at several other sites, but stratigraphic misinterpretations relative to the stratigraphic framework presented herein and limited sample sizes raise some questions as to the accuracy of those results. Of some interest, Mori (2009) reported a maximum age of 121.8 ± 2.2 Ma for a sandy unit just above the Crystal Geyser bonebed in the lower Yellow Cat, and a maximum age of 122.6 ± 0.7 Ma just above the capping sandstone above the Suarez site and below the *Martharaptor* site at the base of the upper Yellow Cat Member as interpreted in that area (Kirkland and others, 2005a, 2005b; Kirkland and Madsen, 2007; Senter and others, 2010, 2012b).

Older ages for the lower Cedar Mountain Formation have recently been proposed based on ostracods and charophytes extracted from the upper Yellow Cat Member. These ages are based largely on the comparison of these microfossils with those known from the Berriassian Purbeck Formation of southern England (Sames and others, 2010; Sames, 2011; Martin-Closas and others, 2013). Furthermore, U-Pb ages from detrital zircons collected from paleosols in which a minimum of 300 zircon grains were dated have suggested dates ranging from 137 to 139 Ma from throughout a section of the Yellow Cat Member at Utahraptor Ridge north of Arches National Park (Hendrix and others, 2015). A 139.7 ± 2.2 Ma age (based on the two youngest zircon grains of 300 dated) occurs in the lowest paleosol in the section and is stratigraphically the lowest non-Jurassic maximum age extracted from the basal Cedar Mountain Formation. Of the 3000 zircons dated in total, not a single Aptian radiometric age has been recovered from this locality (Greg Ludvigson, Kansas Geological Survey, verbal communications, 2016), a surprising result considering many have considered the basal Yellow Cat Member to span the Aptian. Another detrital zircon age from the Doelling's Bowl bonebed in the lower Yellow Cat yielded a maximum age of ~132 Ma (G. Hunt, former Utah Geological Survey intern, verbal communication, 2012).

The disparities of ages for the Yellow Cat Member requires further investigation, but suggest the time missing across the K-1 unconformity in the Paradox Basin ranges from a maximum of 26 million years to as little as 10 million years. With such a significant unconformity, it may not be surprising to observe a wide range of radiometric ages. Numerous periods of pedogenisis are likely to have accumulated a range of zircon populations and "pedoturbation" may have caused mixing of these zircons. Preliminary unpublished paleomagnetic data indicate that deposition of the Yellow Cat at least, in part, preceded the onset of the Middle Cretaceous Long-Normal at the base of the Aptian (Ziegler and others, 2007; Ziegler, 2008). In addition, somewhat ambiguous chemostratigraphic profiles also suggest Barremian to Aptian age (see section of chemostratigraphy).

Lower Yellow Cat Member

The lower Yellow Cat Member is defined as extending from the first "gravelly" beds at the base of the Cedar Mountain Formation to the top of Aubrey's (1996, 1998) marker calcrete bed, which also includes numerous centimeter-scale pebbles scattered within it (figure 13). Essentially, the lower Yellow Cat consists of a stacked sequence of root-mottled paleosols, reflecting the apparent low sediment accumulation rate following the hiatus represented by the K-1 unconformity.

The basal contact locally preserves concentrations of manganese, which were exploited as ore during the early 20th Century in the Little Grand mining district south of Green River, Utah (Baker and others, 1952). Originally noted as being in the upper Morrison Formation, the manganese locally permeates the basal Yellow Cat immediately above the K-1 unconformity, may permineralize bone at Don's Ridge, and forms a patina on some of the best preserved bones at the Crystal Geyser Quarry (figure 13D).

The lower part of the member is often characterized by paleosols with iron oxide nodules that impart a red and yellow appearance. Additionally, the lower part of the Yellow Cat Member includes red bed intervals, which are similar to portions of the underlying Morrison Formation but differentiated based on clay mineralogy and presence of chert as described above. The abundance of iron and the absence of carbonate nodules in the lower part of the lower Yellow Cat indicates wetter paleoclimatic conditions than indicated by paleosols in the underlying Morrison Formation and higher in the Cedar Mountain Formation, from the calcrete marker bed and higher stratigraphically (see section on geo-

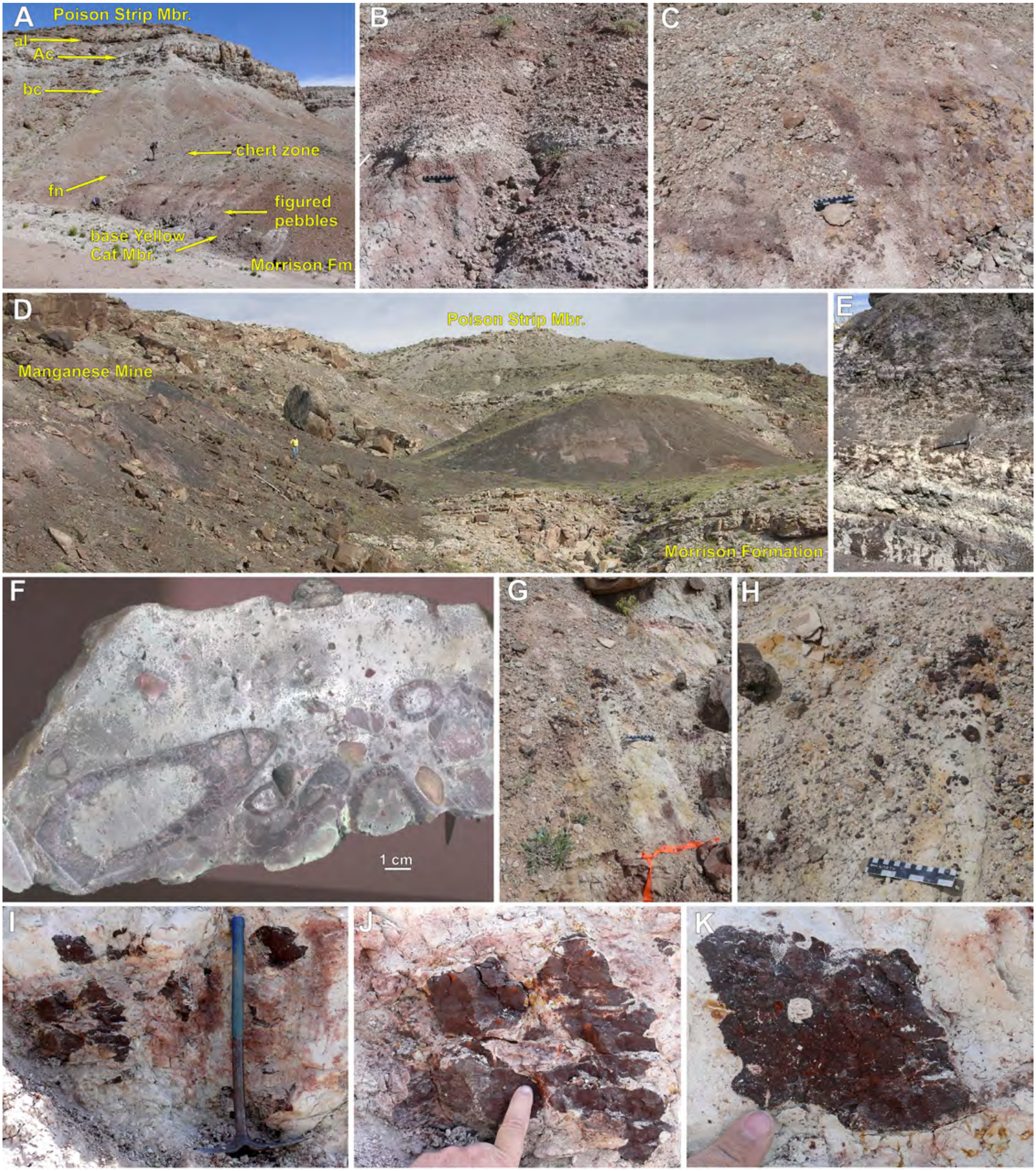

Figure 13. Caption on following page.

Figure 13 (figure on previous page). Features at base of the lower Yellow Cat Member. (A) Newly recognized thick sequence of lower Yellow Cat below type section of the Ruby Ranch Member (figure 11, RR) on the north side of the Ruby Ranch Road (38°51'15.12"N, 109°59'16.24"W). Ac = Aubrey's (1998) massive calcrete bed at top of lower Yellow Cat, al = algal, cherty limestone in upper Yellow Cat Member, bc = basal level of carbonate nodules, fn = ferruginous nodule zone in C. (B) Coarse pebble lenses and pebbles floating in fine-grained mottled strata indicated in A. (C) Ferruginous nodule zone indicated in A. (D) Small manganese mine south of Green River, Utah (109°59'15.35"W, 110° 5'48.54"W). (E) Stacked, pebbly, mottled paleosols in lower Yellow Cat east PS section (figure 11) (38°52'40.51"N, 109°25'3.83"W). (F) Carbonate concretion from base of Crystal Geyser Quarry bonebed form directly upon contact with underlying Morrison Formation, on correct orientation to show pavement of limb bones and floating chert pebbles (UMNH loc. # 157). (G) Ferruginous nodule zone near base section at Utahraptor Ridge (figure 11, UR). (H) Detail from G.(I) Ferruginous nodule zone in fine-grained sandstone at top of Morrison Formation east of section at Utahraptor Ridge (38°50'53.37"N, 109°39'19.73"W). (J) Enlargement of ferruginous nodule from I. (K) Enlargement of another ferruginous nodule from I with cross-cutting burrows and roots.

chemistry). These conclusions were reached relative to this stratigraphic interval by Demko and others (2004) analysis of Morrison paleosols and their paleoclimatic implications. However, in their study, Aubrey's (1998) marker calcrete was identified as the uppermost stratum of the Upper Jurassic Morrison Formation and to quote:

> "…very distinctive, reddish and yellowish color-mottled unit. The coloration is due to extensive redistribution of iron minerals within the paleosol. These features (ferruginous nodules, iron and clay depleted and enriched zones) suggest alternating saturated and well-drained (hydroximorphic and redoximorphic) conditions during soil formation (e.g., Vepraskas, 1994). There is no pedogenic carbonate associated with these paleosols." ….. "The well-developed paleosol complex (redoximorphic Gleysol) at the top the Morrison was formed under wetter conditions than any of the paleosols in the lower portions of the formation. The paleosol complex formed under dominantly saturated soil moisture conditions (with periodic drying out) and low sedimentation rates." (Demko and others, 2004).

These are the only "wetland" paleosols (figure 13C, F, and G) described on the Colorado Plateau anywhere in the interval between and Middle Jurassic and the base of the Upper Cretaceous. Given that, we are redefining the K-1 such that these wet climatic conditions are formed during the Early Cretaceous and not the Late Jurassic, is significant in interpreting the climatic history of the entire region. However, it is important to note that ferruginous nodules may occur at the very top of the Morrison Formation, where they are interpreted to have formed just prior to Cretaceous deposition (figure 13I to K). Demko and others (2004) interpreted the stacking of these paleosols as representing a reduction of sedimentation rates toward the end of the Late Jurassic prior to the development of the K-1 unconformity, whereas we interpret them as representing the gradual increase in accommodation following the erosion surface represented by the K-1 unconformity. Further research on these interesting paleosols is warranted.

Another characteristic feature of the lower Yellow Cat is the presence of chert layers that are often associated with silicified roots. Initially, on discovering that there were Cretaceous dinosaur remains between these prominent cherts and Aubrey's marker calcrete bed, it was assumed that the chert layers represented a silcrete marker bed at the Jurassic-Cretaceous contact (Dick, 2006; Dick and others, 2006). However, with the redefinition of the base of the of the Cedar Mountain Formation using the presence of chert pebbles to separate the Cedar Mountain from the underlying Morrison appearing within the illitic floodplain strata bounding the K-1 unconformity, it has been noted that the chert beds have never been observed at the base of the Cedar Mountain Formation and may in fact appear only above the iron-rich paleosols. Although generally present as thin (1 cm) discontinuous sheets of silica, through less than a meter interval of strata, they may occur in thicker laminated beds that may extend for tens of meters laterally. In the area of the Doelling's Bowl bonebed, chert beds may form mounds as thick as 1 m or occur as amalgamated sheets of horizontal roots (figure 14). These roots only sporadically preserve cell structure. Brigham Young University's famed paleobotanist, the late William Tidwell identified one specimen as the fern *Tempskya,* which builds a pseudo-trunk out of coalesced roots (Tidwell, 1998). However, *Tempskya* are only known from the Mussentuchit Member of Cedar Mountain and Naturita Formations (= Dakota Formation) and thus are exclusively from the basal upper Cretaceous. When I (Kirkland) reported that the thin section was from a horizontal meandering root, Tidwell said, "that this was impossible." As these roots are 25 to 35 Ma older than *Tempskya*, perhaps they represent an ancestral condition. With the passing of Tidwell, additional samples were examined by Brian Axsmith (University of South Alabama, personal communication, 2014), who only committed to the fern root identification. Silicification in this interval occurred near or at the surface as silicified root fragments of the same morphology occur in the Doelling's Bowl bonebed immediately overlying the chert.

A similar occurrence of chert layers and silicified roots is present near the top of the Sonsela Member

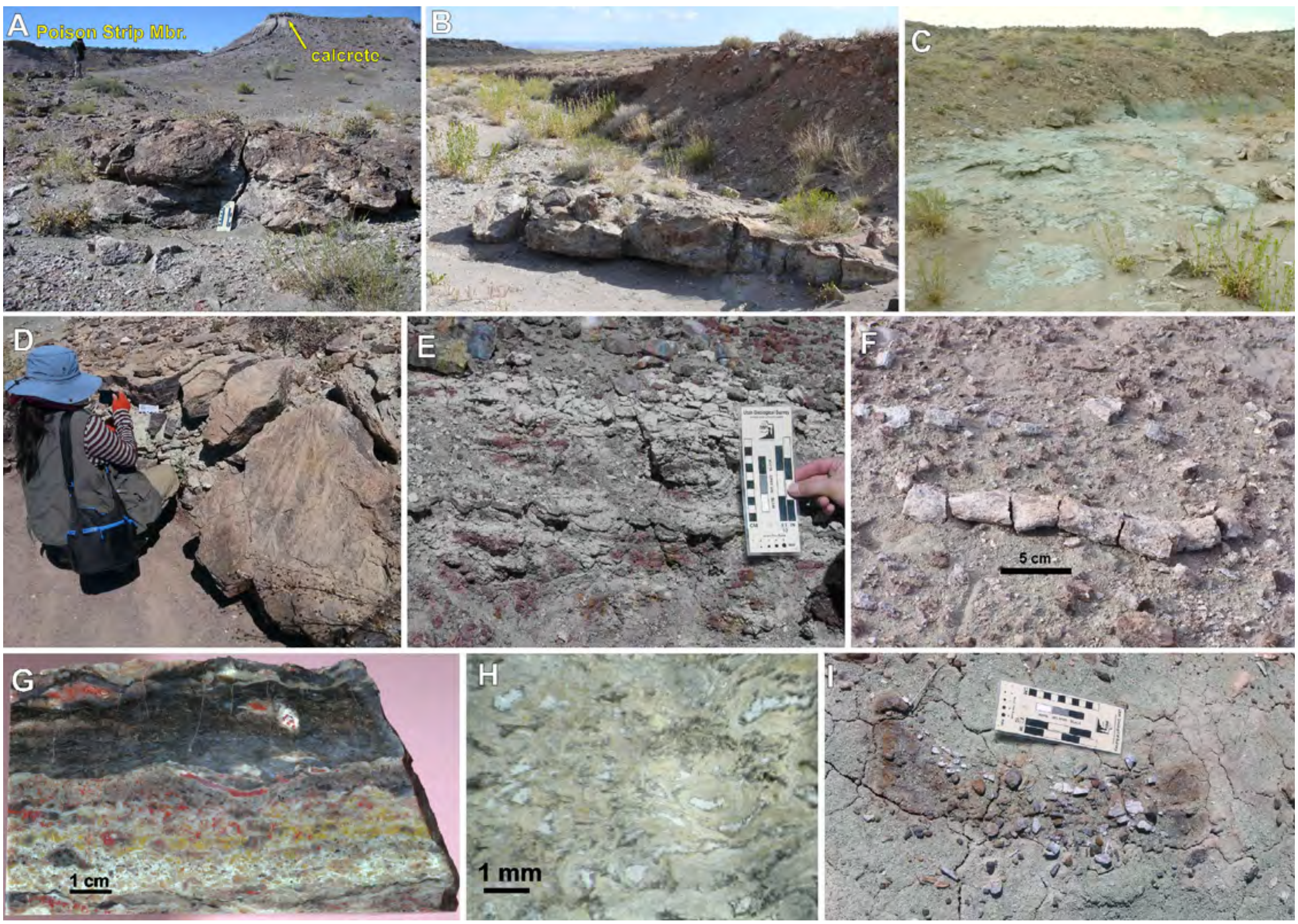

Figure 14. Lower Yellow Cat chert interval as developed at Doelling's Bowl: (A) Chert mound. (B) Laterally extensive chert layer approximately 25 cm thick. (C) Surface expression of laterally extensive chert layer. (D) Fern root mat preserved in top of chert layer. (E) Basal chert interval with pebbles, thin chert layers and silicified roots. (F) Silicified fern roots exposed on surface. (G) Cross section of chert layer. (H) Cross section of rotted root section from Doelling's Bowl bonebed. (I) Weathered iguanodont femur in Doelling's Bowl bonebed immediately above chert zone.

(persistent red silcrete zone) of the Chinle Formation at the Petrified Forest National Park (Martz and Parker, 2010), where it is associated with faunal and floral turnover at the Late Triassic (Norian) Adamanian–Revueltian faunal and floral transition (Parker and Martz, 2011). This silcrete zone is interpreted to represent the silica replacement of peat (histosols) and pedogenetic carbonate in an interval recording a pronounced shift from humid to overall drier climates as indicated by abundant pedogenetic carbonate nodules up section (Driese and others, 2010).

Stacked paleosols continue up section in the lower Yellow Cat Member and the mottling fades in appearance. The overlying calcrete described by Aubrey (1996, 1998) as marking the Jurassic-Cretaceous contact is recognizable in nearly all sections from 5 or more km west of the Poison Strip (PS) section to about 5 km west of the Ruby Ranch Road (RR) section (figure 11). In this area, as noted by Aubrey (1998), this carbonate zone is a honeycomb of nodular and pedotubule calcrete with interstitial matrix and floating pebbles having various amounts of secondary silica. These calcareous units grade upward from the base and may consist of one or several superimposed calcrete sequences with or without interspersed pedogeneic carbonate nodules or sheets. This marker interval typically is from less than 1 m to 10 m or more thick, where it is composed of multiple sequences. It locally forms a massive cliff along the Ruby Ranch Road, where Aubrey (1998, figure 9) refers to it as a hardpan calcrete. Where this cliff of carbonate is well developed, it is always overlain a few meters up section in the upper Yellow Cat Member by an approximately 1-m-thick, dark-brown, algal limestone (figure 15F) that is partially replaced by chert laminae (mistakenly referred to as the marker calcrete in Ludvigson and others [2010a, figure 5C]). We believe that at this particular site, the marker calcrete was enhanced diagenetically, relative to an overlying lacustrine environment. Aubrey (1996, 1998) initially placed the base of the Cedar Mountain Formation at its gradational lower contact, based on the presence of pebbles within it, whereas others placed the contact at the top of this unit with the understanding that it would have been developed on the K-1 unconformity (Kirkland and others, 1997, 1999; Demko and others, 2004). Herein, the top of the "lower" Yellow Cat is placed at the top this calcrete bed as matrix-supported or "floating" pebbles are not characteristic of the Yellow Cat Member higher in the section.

Calcrete of the open morphology described by Aubrey (1998) and illustrated here (figure 15) are not present along the west side the Salt Valley anticline (west side of Arches National Park). Along most of this portion of the outcrop belt the contact between the lower and upper Yellow Cat is placed at a dense carbonate (limestone) bed separating facies typical of the lower Yellow Cat from those typical of the upper Yellow Cat. At the south end of these outcrops at Dalton Wells, there is no carbonate unit in the unusually thin Yellow Cat Member, and the upper Yellow Cat is separated from the underlying Morrison Formation by a "single" mudstone conglomerate bed (Eberth and others, 2006; Kirkland and Madsen, 2007; Britt and others, 2009). A ridge-forming limestone bed has been recognized in the collapsed salt anticline near the Fiery Furnace in Arches National Park but vanishes to the south along this outcrop belt within the park (figure 15L), as the Yellow Cat thins (Stikes, 2006). There does not appear to be a lower Yellow Cat exposed anywhere within Arches National Park. Interestingly, a specimen of *Apatosaurus* at the top of the Morrison Formation (Foster, 2005) south of the pinchout of this limestone bed has a bit of carbonate on the bone and well-indurated bones appears to be have held up a ~5- to 10-m-high paleo-hill at the unconformity just below the overlying Poison Strip Member.

Similarly, there is no carbonate bed as described by Aubrey (1998) in the Yellow Cat outcrops on the west side of the Paradox Basin south of Green River, Utah. There, pebbly facies typical of the lower Yellow Cat are separated from facies of the upper Yellow Cat by a thin, laterally persistent, calcareous, gravelly sandstone bed locally capped by stromatolites that is referred to as the caprock (Kirkland and others, 2005b; Kirkland and Madsen, 2007; Suarez and others, 2007a, 2007b; Senter and others, 2012b). There is a similar unit capping Aubrey's (1998) enhanced calcrete at the Ruby Ranch Road section (figure 15C to E) that adds weight to this potential correlation.

As noted by Demko and others (2004), these carbonate units mark a return to semiarid conditions

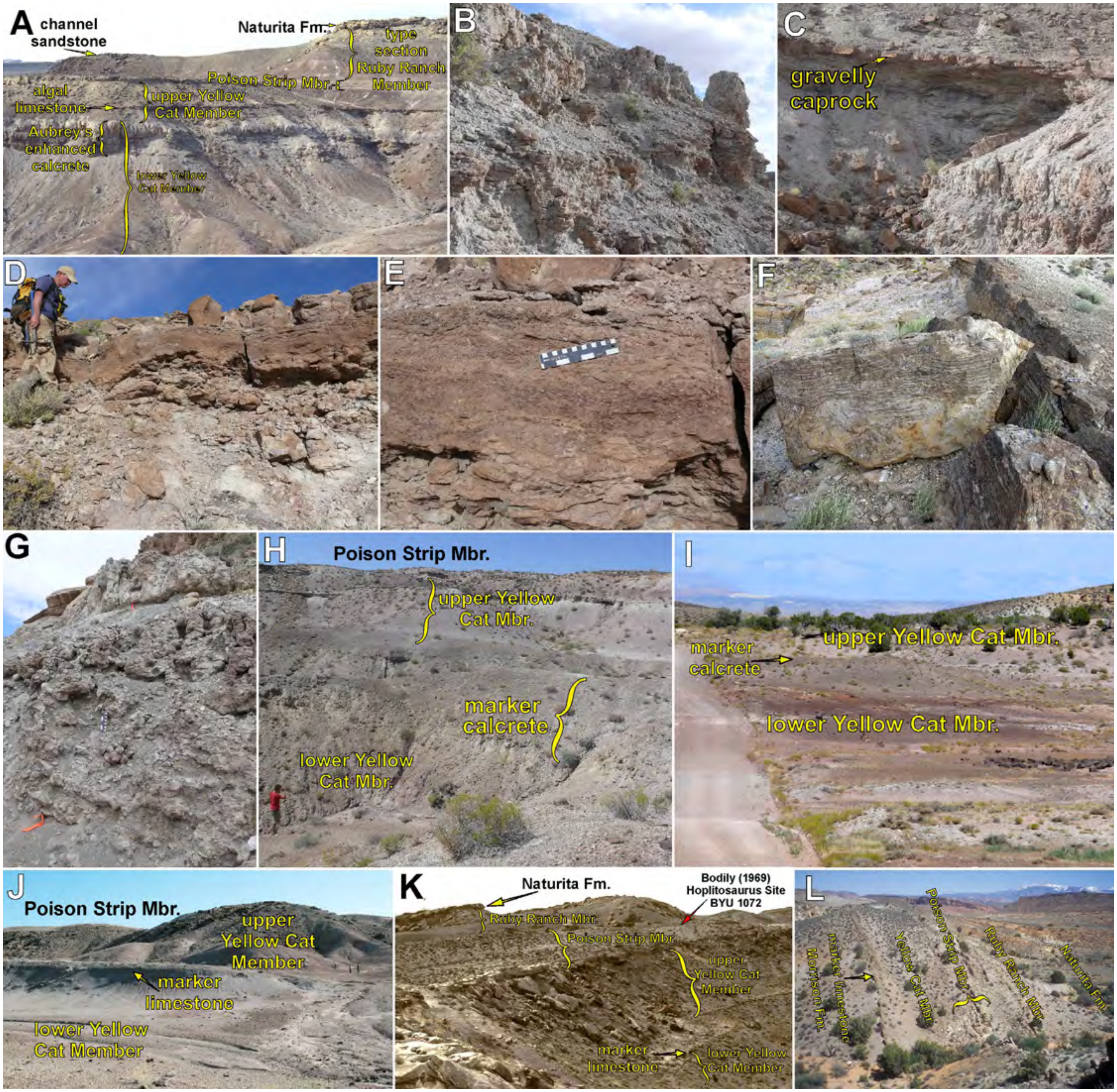

Figure 15. Caption on following page.

with a net evaporative flux. Research on stable isotopes from pedogenetic and paludal carbonates and vertebrate material in the upper Yellow Cat and in the Ruby Ranch Members has shown that this area was in a rain shadow downslope from the Sevier orogenic belt (Ludvigson and others, 2010a, 2015; Suarez and others, 2014). We interpret the formation of these laterally extensive calcretes at the top of the lower Yellow Cat Member as marking the initiation of this rain shadow, reinforcing the need for developing an accurate chronology of these strata.

Figure 15 (figure on previous page). Aubrey's (1998) marker calcrete in the northern Paradox Basin. (A) Aubrey's enhanced calcrete below the type section of the Ruby Ranch Member (109°59'16.24"W, 109°59'10.02"W) of the Cedar Mountain Formation at Ruby Ranch Road section (see below) as viewed from the east. (B) Typical expression of Aubrey's (1998) marker calcrete Ruby Ranch Road section on west side of Canyon in C, where Yellow Cat Member was measured (figure 13A). (C) Typical expression of Aubrey's (1998) marker calcrete Ruby Ranch Road section at head of canyon with capping gravelly unit overlying it (109°59'10.02"W, 109°59'15.35"W). (D) Scott Madsen examining gravelly, calcareous sandstone capping Aubrey's (1998) enhanced calcrete on east wall of canyon in C. (E) Detail of same bed in D. (F) Cherty algal limestone in upper part of Yellow Cat Member on west side of Canyon in C. (G) Multi-tiered calcrete marker bed at Utahraptor Ridge below Stikes Quarry (figure 11). (H) Calcrete marker bed on the west side of the west end of the Yellow Cat Loop Road (38°51'14.86"N, 109°32'56.74"W). (I) Thin calcrete marker bed on the east side of the east end of the Yellow Cat Loop Road (109°32'56.74"W, 109°32'56.74"W); note subtle expression in outcrop. (J) Limestone marker bed on northwest side of Salt Valley anticline (38°49'0.69"N, 109°45'35.54"W). (K) The same limestone marker bed at one of Mori's (2009) sections, for which the author has a very different stratigraphic interpretation, in that there the Mussentuchit Member is below the Naturita Formation (smectitic "Lake Carpenter" facies at top of Ruby Ranch Member) and that the Morrison Formation is below the Poison Strip Member. (L) Cedar Mountain Formation west of the Fiery Furnace in Arches National Park as viewed from the north showing the presence of a "basal carbonate marker bed" here.

Vertebrate Taxa From the Lower Yellow Cat Member

The discovery of a distinct fauna below a medial Yellow Cat 'caprock' near Green River, Utah, characterized by the basal therizinosaur *Falcarius* (Kirkland and others, 2005b; Zanno, 2006, 2010), cf. *Falcarius* n. sp. (Zanno and others, 2014), a primitive troodont *Geminiraptor suarezarum* (Senter and others, 2010), a large basal steracosternid iguanodont *Iguanocolossus fortis* (McDonald and others, 2010), and a giant (nearly double the size of *Gastonia*) polacanthid ankylosaurid (Kirkland and others, 2012) suggests the presence of dinosaur fauna that may be older than that of the upper Yellow Cat fauna. The correlation of this 'caprock' with the calcrete cannot be proven, but appears likely.

Forty-nine km (30 mi) east of Green River, a multitaxic Early Cretaceous dinosaur fauna is preserved below the marker calcrete and immediately above the chert interval in the Doelling's Bowl bonebed (figure 16). The occurrence of these new dinosaur taxa raised the possibility of testing the hypothesis that the calcrete, although not representing the K-1 unconformity, at a minimum represents evolutionary time as dinosaur genera turned over fairly rapidly, on the order of every 1 to 10 million years (Dodson, 1990; Wang and Dodson, 2006; Brusatte, 2012; Bensen and others, 2014; Starrfelt and Liow, 2016). This hypothesis may be tested by examining related species in different dinosaur clades occurring above and below the calcrete (Kirkland and others, 2012). At Doelling's Bowl, the dromaeosaur *Yurgovuchia* has proven close to *Utahraptor* (Senter and others, 2012a). Still under study, the iguanodont material includes many dentaries lacking the distinct shelf of *Hippodraco* and many humerae lacking the well-developed deltopectoral crest present in *Hippodraco* (McDonald and others, 2010) (figure 16). The Doelling's Bowl iguanodont may be assigned to *Iguanocollossus* based on the distinct upturned preacetabular process of the pubis. Additionally, osteohistological analyses indicate the taxon could theoretically reach the large size of *Iguanacolossus* (Sartin and others, 2015). A second iguanodont may be present based on the presence of a more complex ilium, whereas the other ilia are of a simpler morphology, more in keeping with *Iguanacolossus*. The polacathine ankylosaurs at Doelling's Bowl represent a new taxon based on comparisons with the braincases of the Jurassic *Gargoyleosaurus* and *Mymoorapelta* and the 10 known braincases of *Gastonia* (figure 17). Most promising has been the discovery of a juvenile sauropod skeleton, which had been mired in Doelling's Bowl bonebed and is associated with parts of a larger adult animal. Much of the skeleton is preserved, including skull material, pelvic elements, limb bones, an articulated pes and lower leg, and most of the vertebral column including the semi-articulated terminal 10 procoelus vertebrae of the tail. Brigham Young University is researching extensive material from more

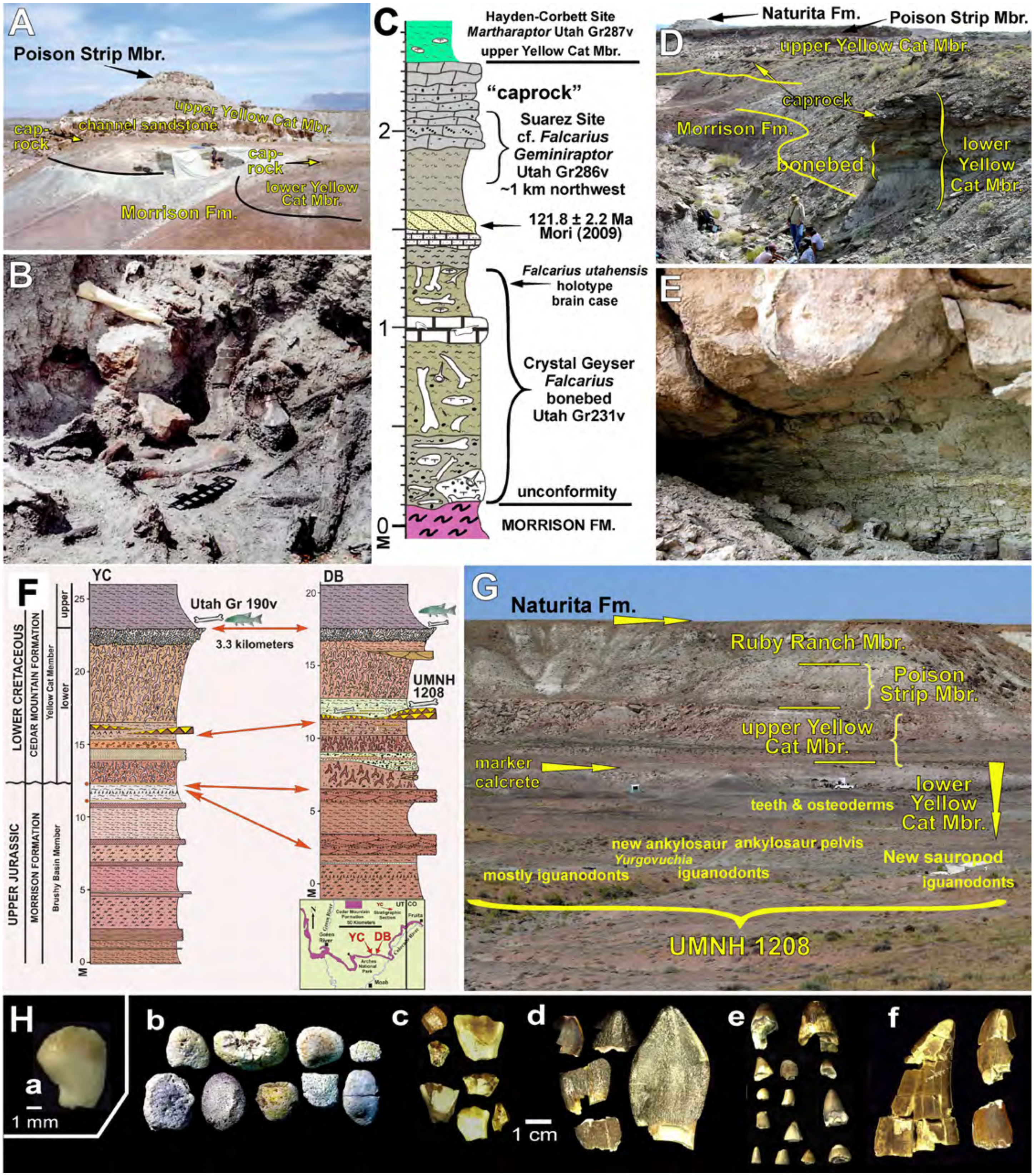

Figure 16. Caption on following page.

Figure 16 (figure on previous page). Important vertebrate localities in the lower Yellow Cat Member. (A) Crystal Geyser Dinosaur Quarry. (B) Bones of *Falcarius utahensis* in Crystal Geyser Dinosaur Quarry. (C) Stratigraphic section at the Crystal Geyser Quarry with positions of important data points in area. (D) Suarez site. (E) Bones as exposed in and just below the caprock. (F) Correlation between the lower Yellow Cat Member on the east side of the Yellow Cat Road (YC in figure 11) and at Doelling's Bowl. (G) Stratigraphic sequence at Doelling's Bowl and the distribution of dinosaurs. (H) Isolated teeth and ossicles characteristic of the Doelling's Bowl bonebed. a) Polacanthid ankylosaur tooth. b) Polacanthid ankylosaur ossicles. c) Iguanodont teeth. d) Sauropod teeth. e) Crocodilian teeth. f) Allosauroid teeth. Section key as in figure 10.

than a dozen individuals of a closely related sauropod found with *Gastonia* and *Utahraptor* at the Dalton Wells Quarry north of Moab, Utah (Britt and others, 2009). Differences in character states between these sauropods provide an additional test of our hypothesis. Probably the most noticible of these is that the medial cervical ribs deepen in the Doelling's Bowl taxon and are divided in the Dalton Wells taxon. Our most recent analysis suggests that it is closest to the turiasaurid sauropods of southern Europe (Royo-Torres and others, 2016).

In addition to these four taxa, the Doelling's Bowl bonebed preserves large shed teeth of an allosauroid theropod. Crocodillian skull fragments and teeth that may pertain to aguatic goniopholid crocodilians occur, as do distinctive shell fragments of the turtle *Naomichelys*.

Just to the east of Utahraptor Ridge (UR; figure 11) scattered dinosaur bones occur even lower in the Yellow Cat in the ferruginous nodular zone below the chert level. These bones include a well-preserved humerus of a polacanthid ankylosaur (figure 17P).

Lower Yellow Cat Fauna

Chelonia:
cf. *Naomichelys* (finely beaded shell surface)

Crocodilia:
aquatic goniopholid crocs.

Dinosauria

Theropoda
Large allosauroid
Falcarius utahensis Kirkland and others (2005b)
Yugovuchia doellingi Senter and others (2012a)
Geminiraptor suarezarum Senter and others (2010)

Sauropoda
brachiosaurid indet.
new turiasaurid (Royo-Torres and others, 2016)

Thyreophora
new polacanthid ankylosaur (Kirkland and others, 2012)
new giant polacanthid ankylosaur (Kirkland and others, 2012)

Ornithopoda
Iguanacolossus fortis (McDonald and others, 2010)
Unstudied second iguanodont taxon (complex ilia)

The Upper Yellow Cat Member

The Yellow Cat Member was originally defined as extending from the top of Aubrey's (1998) marker calcrete to the base of the Poison Strip Member of the Cedar Mountain Formation (Kirkland and others, 1997). New dinosaur taxa (Kirkland and others, 1993, 1998a, 1998b, 1999; Kirkland, 1998a) from these rocks have been critical in stimulating many additional researchers to investigate the Cedar Mountain Formation. It was considered problematic to define another member of the Cedar Mountain Formation below the Yellow Cat Member, as the Yellow Cat was just starting to be mapped as a discrete stratigraphic unit on 7.5-minute geological maps (1:24,000). Given the steep slopes below the capping Poison Strip Member, it was considered simplier to lower the basal contact of the Cedar Mountain Formation at this stage of geologic mapping (Doelling and Kuehne, 2013a). However, using a subdivided Yellow Cat gained traction, especially as it became clear that different dinosaur faunas characterized

Figure 17. Caption on following page.

Figure 17 (figure on previous page). Dinosaurs from the lower Yellow Cat Member. (A) *Falcarius utahensis*. (B) Maxilla of *Gemniraptor suarezarum* from Suarez site in ventral, oblique-medial, and lateral views; top to bottom. (C) Large osteoderms from Suarez site. Photo courtesy of Ken Carpenter, Prehistoric Museum (Utah State University Eastern). (D) Type material of *Iguanocolossus fortis* from McDonald (2010). (E) Partial pubis from cf. *Iguanocolossus* from Doelling's Bowl bonebed (UNMH 1208). (F) Comparison of type *Hippodraco* humerus from upper Yellow Cat (Andrew's site, UMNH 1207) vs. three smaller humerae from cf. *Iguanocolossus* from UMNH 1208. (G) Dromaeosaur (*Yugovuchia*?) pelvis found under ankylosaur pelvis in K from UMNH 1208. (H) Type braincase of *Mymoorapelta maysi* from Mygatt-Moore Quarry, Upper Jurassic Morrison Formation, Rabbit Valley (RV), western Colorado. (I) Basicranium of new polacanthid ankylosaur from UMNH 1208. (J) Basicranium of type of *Gastonia burgei* from the upper Yellow Cat, Gaston Quarry, Utah Gr184. (K) Pelvis of new polacanthid ankylosaur from UMNH 1208. (L) Mired leg of new sauropod in situ at UMNH 1208. (M) Same mired lower leg in ventral view. (N) Large vs. small dentary of new sauropod from UMNH 1208. (O) First mount of new sauropod from upper Yellow Cat, Dalton Wells Quarry (BYU 7510) at Eccles Dinosaur Park, Ogden, Utah, with undivided cervical ribs as in Doelling's Bowl sauropod. (P) Corrected mount of Dalton Wells sauropod with divided cervical ribs. (Q) Polacanthid ankylosaur humerus from ferruginous paleosol interval east of Utahraptor Ridge (UR, figure 11).

strata on either side of the marker calcrete, the boundary used to subdivide the lower and upper Yellow Cat. Thus, biostratigraphic evidence supports defining a lower and upper Yellow Cat Member in the northern Paradox Basin and has expanded our understanding of Utah's geological history during the Early Cretaceous. The lower Yellow Cat Member includes interfluvial facies that is similar to lithofacies of the Buckhorn Conglomerate (figure 8, see above) and locally at the base of the Burro Canyon Formation.The upper Yellow Cat Member, however, appears to be completely restricted to the northern Paradox Basin (figure 11).

West of the Salt Valley anticline on the west side of Arches National Park and running westward to the pinchout of the Yellow Cat Member below the Poison Strip Member south of Green River, Utah (figure 11), the upper Yellow Cat is characterized by fine-grained floodplain facies having common to abundant pedagenic carbonate nodules and isolated ribbon sandstones representing the thalwags of low-sinuosity rivers as discussed below (figure 16A).

The Yellow Cat outcrop belt that runs east–west between the Salt Valley anticline at Arches National Park and the Colorado River (figure 4) includes lacustrine strata east of the Poison Strip section (Kirkland and others, 2016). These strata are an important part of the upper Yellow Cat Member and are informally referred to as Lake Madsen, as Scott Madsen discovered the deepest water-laid facies known near the top of the member (Scott Madsen, formerly with Dinosaur National Monument and Utah Geological Survey, personal communication, 2005). This site consists of organic-rich shale that preserves freshwater hybodont sharks, conchostracans, ostracodes (Sames and others, 2010; Sames, 2011), and the only palynomorph-bearing strata known in the Yellow Cat Member (figure 18). Northeast of Arches Nation Park, it appears that there may be two lacustrine sequences; a lower and an upper sequence separated by an interval of paleosols with dewatering features (Kirkland and others, 2016) (figure 19). It is not clear if these lacustrine sequences are part of one contiguous lake system or if the upper Yellow Cat Member represents an extensive wetlands system resulting from subsidence in the northern Paradox Basin.

The lower lacustrine system immediately overlies the marker calcrete where it is often associated with dispersed vertebrate remains (Kirkland and others, 1998a, 2016). The *Nedcolbertia justinhoffmani* sites at the base of the upper Yellow Cat Member preserve mostly pedal and caudal elements suggesting that these specimens were preserved by miring as lacustrine environments first spread out over the marker calcrete (Kirkland and others, 1998a). The medial hiatus or restriction of lacustrine environments preserves dinosaur tracks locally and at the Stikes Quarry on Utahraptor Ridge (figure 19), the complex bonebed consists of a series of interconnected sandstone masses ("blobs") that encased unfossiliferous floodplain-derived mudstone beds with carbonate nodules. The main upper "blobs" consist of numerous skeletons of Utahraptor that, with only mi-

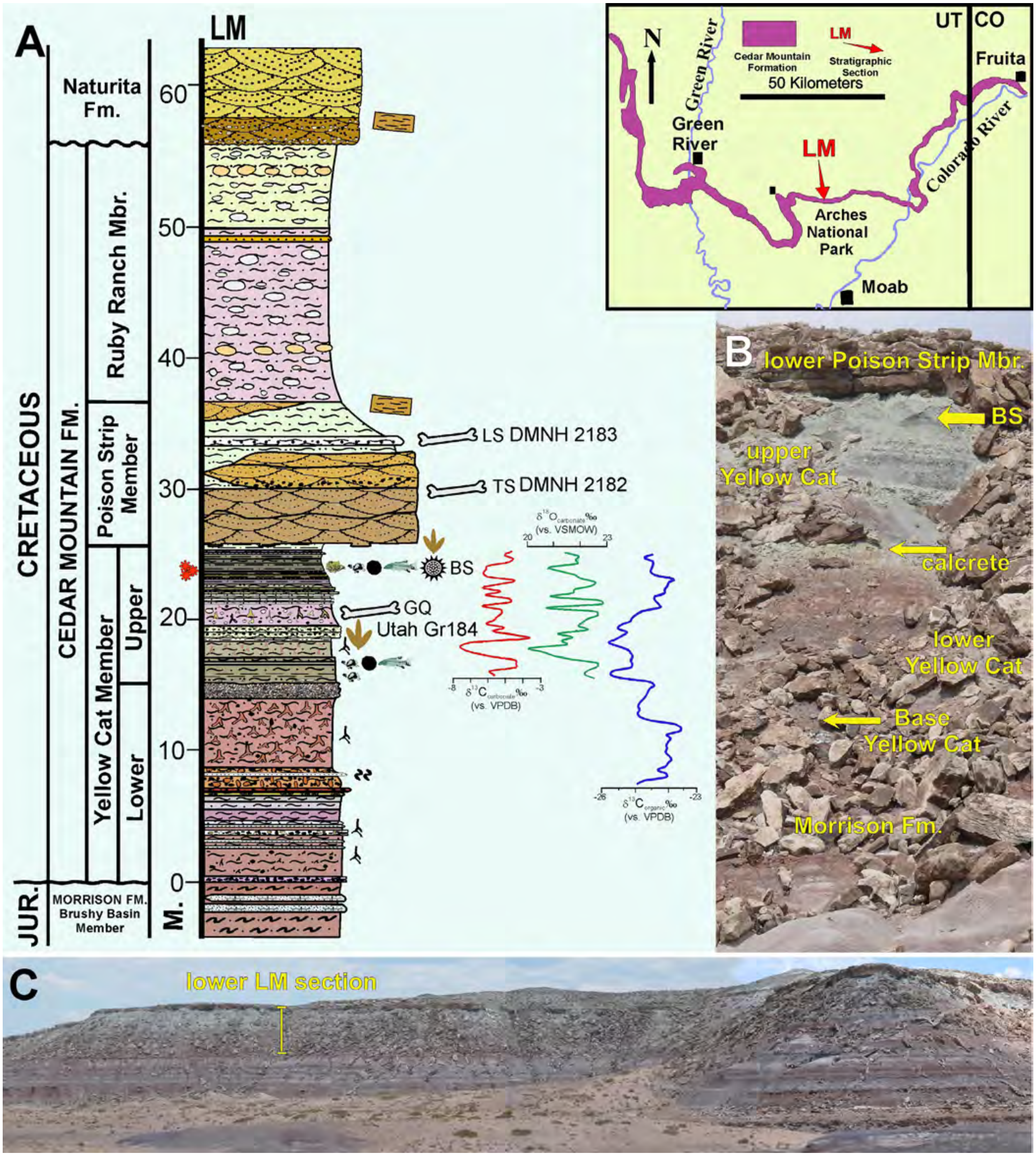

Figure 18. Lake Madsen section. (A) Lake Madsen (LM) section measured from 38°50'50.18"N, 109°33'41.95"W up through 38°51'32.50"N, 109°33'46.52"W with stable isotope geochemistry data from Hatzell (2015). BS = Ben Sames (Sames and others, 2010; Sames 2011) ostracod site. GQ = level of Gaston Quarry relative to upper and lower Lake Madsen sequences. LS = Laurie's site, initially described as in basal Ruby Ranch Member (Carpenter, 2006). TS = Tony's bonebed. Section symbols as in figure 10. (B) Outcrop expression of Yellow Cat Member at discovery site of Lake Madsen facies. (C) Mid-Mesozoic outcrops on the north side of the Yellow Cat Flat with lower Lake Madsen section indicated. Note the entire bench exposed to the north is composed of the Poison Strip Member of the Cedar Mountain Formation (Doelling and Kuehne, 2013a).

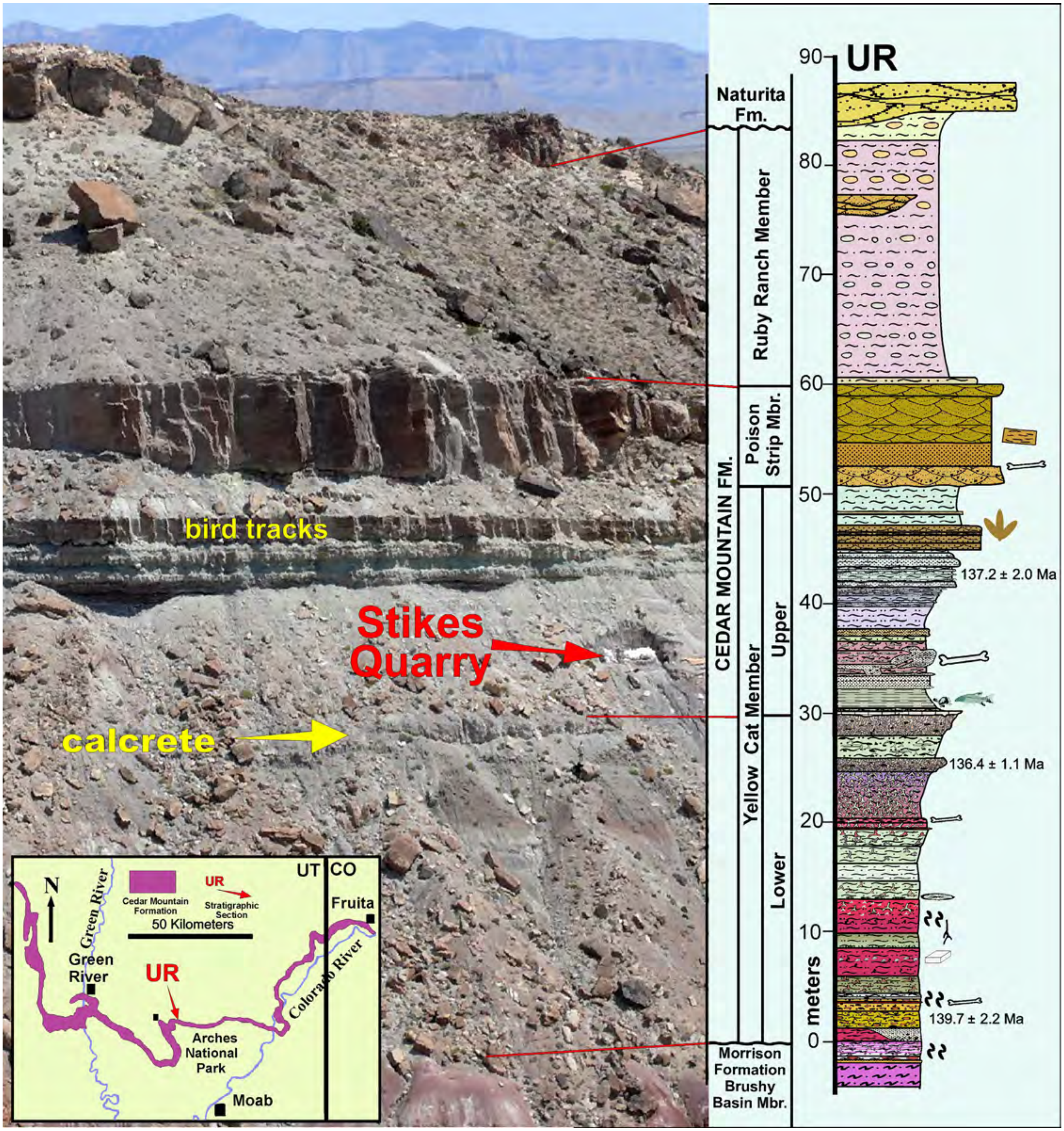

Figure 19. Cedar Mountain section at Utahraptor Ridge (UR) measured from 38°50'51.49"N, 109°39'24.99"W (base) to 38°50'55.46"N (top), 109°39'25.80"W showing the position of the Stike's Quarry (Kirkland and others, 2011, 2016) and bird track locality (Lockley and others, 2015). Detrital zircon U-Pb dates from Hendrix and others (2015). Stratigraphic symbols as in figure 10.

nor preparation of the main plaster jackets to date, include a minimum of three "yearlings" (skull length of ~ 12 cm), five juveniles (skull lengths of ~ 25 cm), and one adult (skull length of about 50 cm), and a juvenile and adult iguanodont (Poole, 2008). This unusual dinosaur locality is interpreted to represent a large collapsed dewatering feature formed on the margin of Lake Madsen and thus is the first dinosaur site ever to be attributed to trapping by "quicksand" (Kirkland and others, 2011, 2016).

Another important site in the medial upper Yellow Cat Member is the Gaston Quarry from which the type specimens of the polacanthid ankylosaur *Gastonia burgei* (Kirkland, 1998a) and *Utahraptor ostromaysorum* (Kirkland and others, 1993) were collected. This site is interpreted to rest on deposits from the shore of Lake Madsen with the bones subjected to a greater degree of subaerial weathering than those preserved in some other major Yellow Cat dinosaur sites (Howard, 2014). The flattened bones at this site (figure 9) rest directly upon a rippled, sandy carbonate preserving dinosaur tracks (Kirkland and others, 2005a; Kirkland and Madsen, 2007) in a pale-green mudstone lense overlain by another sandy carbonate preserving uncrushed bones (). As many as six *Gastonia* are represented at the site by hundreds of skeletal and armor elements with four skulls including the type (Kinneer and others, 2016), one adult *Utahraptor* represented by scattered elements (Kirkland and others, 1993), and a few bones and teeth representing iquanodonts.

The Dalton Wells site is very extensive and located on Utah state land managed by the Utah Division of Forestry, Fire & State Lands along the west side of Arches National Park and at the south end of the Cedar Mountain Formation outcrop belt. Brigham Young University has excavated several thousand dinosaur bones representing a diversity of dinosaur species. The bones at Dalton Wells have been interpreted to represent an accumulation of bones emplaced in a series of four superimposed debris flows (Eberth and others, 2006; Britt and others, 2009). This site preserves the thinnest sequence of the Yellow Cat Member in the central Paradox Basin, and the bonebed rests directly on a pebble lag directly overlying the Morrison Formation as discussed below. Other than, perhaps, this pebble lag, the entire section is interpreted to represent the upper Yellow Cat Member as it preserves many taxa known from only from the upper Yellow Cat from other sites and none of the Dalton Wells dinosaurs are recognized as conspecific with taxa from the lower Yellow Cat Member.

The top of the upper Yellow Cat Member is generally a coarsening upward, regressive lacustrine sequence. The contact with the base of the overlying Poison Strip Member is a sharp break between fine-grained lacustrine strata and overlying cliff-forming, coarse-grained fluvial sandstones. This basal contact is easily picked as seen in the outcrops bounding the Yellow Cat Flat and along the south rim of the Poison Strip escarpment (figures 18, 20, and 21). In areas, where only interfluvial facies are present, the Poison Strip Member does not hold up an escarpment and, almost universally, this is where roads cross the outcrop belt. In these areas, the contact may be difficult to pick without carefully tracking facies from the adjoining fluvial facies capping the escarpment on either side of the road. Such outcrops are limited, however.

A more widespread problem is picking the contact where sandstone units formed by coastal lacustrine processes are preserved in the top of the Yellow Cat Member. A good example of this is the laterally extensive bird track bed (Lockley and others, 2015) at the top of Yellow Cat at Utahraptor Ridge (figure 19). As it is in the base of the cliff formed by the fluvial units of the Poison Strip Member, it is unavoidably mapped as part of the Poison Strip Member (Doelling and Kuehne, 2013a). Stikes (2006) picked this contact correctly in this area (Long Valley Section). A similar difficulty is encountered in the Lower Jurassic of southwestern Utah in picking the contact between the lacustine sequence in the basal Jurassic Whitmore Point Member of the Moenave Formation and the unconformably overlying fluvial Springdale Sandstone Member of the Kayenta Formation (Kirkland and others, 2014).

More research needs to be directed at the contact between these members to determine if it represents a regional unconformity. As discussed below, the upper Yellow Cat fauna and the Poison Strip fauna appear to be completely nonoverlaping, but is this a case of a temporal gap, the effects of different taxa residing in different adjoining environments, or a factor of taphonomic bias?

Fauna from the Upper Yellow Cat Member

Invertebrate fossils from the upper Yellow Cat Member include freshwater ostracods with charophytes (Sames and others, 2010; Sames, 2011; Martin-Closa and others, 2013), conchostracans, and viviparid snails. Fish include ganoid scales and teeth from semionotid fish, high crowned amiid teeth, hybodont shark teeth and spine fragments, with short spiral coprolites containing abundant ganoid scales (figure 22A), and lungfish tooth plates (figure 22B). A new species of mammal is represented by a 7-cm-long cranium (Huttenlocker and others, 2016; figure 22D). Although potential microvertebrate sites are known, it has so far proven impossible to break down the matrix (Scott Madsen, formally with Dinosaur National Monument and Utah Geological Survey, verbal communication, 2005). Bainid turtles are common on the east end of the Yellow Cat Loop Road, and one site has yielded a number of skulls assigned to a new species of *Trinitichelys* (Brinkman and others, 2015). A large eilenodontid sphenodont, similar to *Toxolophosaurus*, is represented by isolated jaws, and a partial skeleton. Given the abundance of this taxon, it probably was an important small terrestrial herbivore during the deposition of the upper Yellow Cat Member. A small proximal femur from the Dalton Wells Quarry has been identified as a primitive neochoristodere (Britt and others, 2006). A variety of aquatic crocodilians are represented by teeth. A small, possibly terrestrial, basal mesoeusuchian crocodilian, represented by a complete skull and articulated osteoderms, is currently under study. Britt and others (2009) have recovered an isolated pterosaur bone from Dalton Wells.

Dinosaurs identified in the upper Yellow Cat Member include numerous skeletons of the polacanthine ankylosaur, *Gastonia burgei* (Kirkland, 1998a), from several sites making it the best-characterized polacanthid known (Blows, 2015). Basal steracosternid iguanodonts (bipedal plant eaters with thumb spikes) are diverse represented by a minimum of three taxa (A. Scheetz, Brigham Young University, Paleontology Museum, verbal communication, 2015). *"Iguanodon" ottingeri* (Galton and Jensen, 1979) is represented by an undiagnostic maxilla fragment with two teeth. *Hippodraco scutidens* is represented by a significant portion of a juvenile skeleton with a skull (figure 22O and P), which was found at Andrew's site (UMNH 1207; figure 12) with a large adult iguanodon that lacks diagnostic overlapping skeletal elements (McDonald and others, 2010). *Hippodraco scutidens* is closest to *Theiophytalia kerri* from the Lytle Member of the Purgatory Formation of the Colorado Front Range (Brill and Carpenter, 2007; McDonald, 2011). Scheetz and others (2010b) have described a partial skeleton of a large iguanodont with elongate neural spines, quite unlike the short, squared-off, proximal caudal, neural spines on the large specimen from Andrew's site (figure 22Q). Iguanodontian tracks are relatively abundant in the upper Yellow Cat Member (figure 22K), but it is noteworthy that none have yet approached the size of the large iguanodontian tracks known from the Wealden of England (Sarjeant and others, 1998; Martill and Naish, 2001b). Hypsilophodont grade ornithopods are represented by a foot and a scapula (figure 22N). There are several sauropod families present, represented by the brachiosaurid *Cedarosaurus weiskopfae* (Tidwell and others, 1999; Sanders and others, 2001) and a possible camarasaurid (Eberth and others, 2006; Britt and others, 2009) (figures 17P and 22M). One unusual sauropod is present in large numbers at the Dalton Wells Quarry and is represented by a minimum of 17 individuals based on braincases (Brooks Britt, Brigham Young University, personal communication, 2007). This sauropod is convergent on titanosaurs in many characters and was thought to represent a primitive new titanosaurid for many years (Britt and others, 1997; Britt and Stadtman, 1997). Primitive vertebral development has suggested that it represented a primitive macranarian (Britt and others, 2009). However, recent comparisons with taxa from the Upper Jurassic of Spain suggest that like the new sauropod from the Doelling's Bowl site (figure 17O), it represents a turiasaurid sauropod; a basal eusauropod group not identified previously in North America (Royo-Torres and others, 2016).

Theropod dinosaurs include the small coelurosaur, *Nedcolbertia justinhoffmani* (Kirkland and others, 1998a), which is represented by several partial juvenile specimens, may be a primitive ornithomimid, and would have left tracks like those in figure 22J. A larger ornithomimid partial skeleton with skull material was reported by Scheetz and others (2010a). The

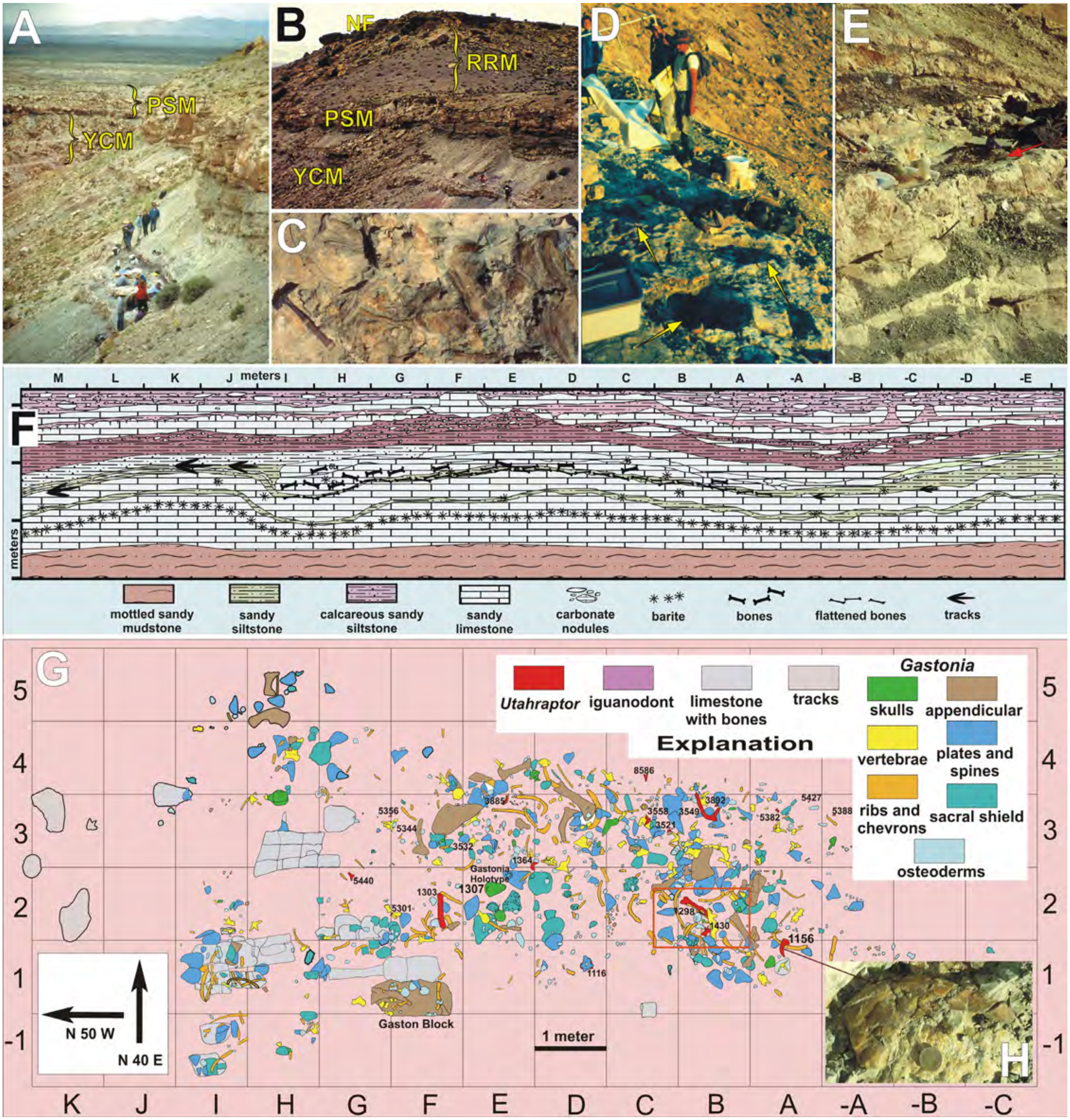

Figure 20. Gaston Quarry. (A) Overview of Gaston Quarry from south. B) Overview of Gaston Quarry from southwest. (C) Detail of portion of the bonebed approximately matching red box in figure G. (D) Rob Gaston (white shirt on right) and Don Burge (behind holding quarry map) overseeing work on sauropod tracks exposed at base of bonebed in foreground indicated by yellow arrows. (E) Quarry profile with red arrow indicating base of bonebed impressed into surface of limestone. (F) Schematic profile of Gaston Quarry highwall. (G) Quarry map of Gaston Quarry excavation. (H) Second pedal ungula (sickle-claw) of *Utahraptor* holotype in situ.

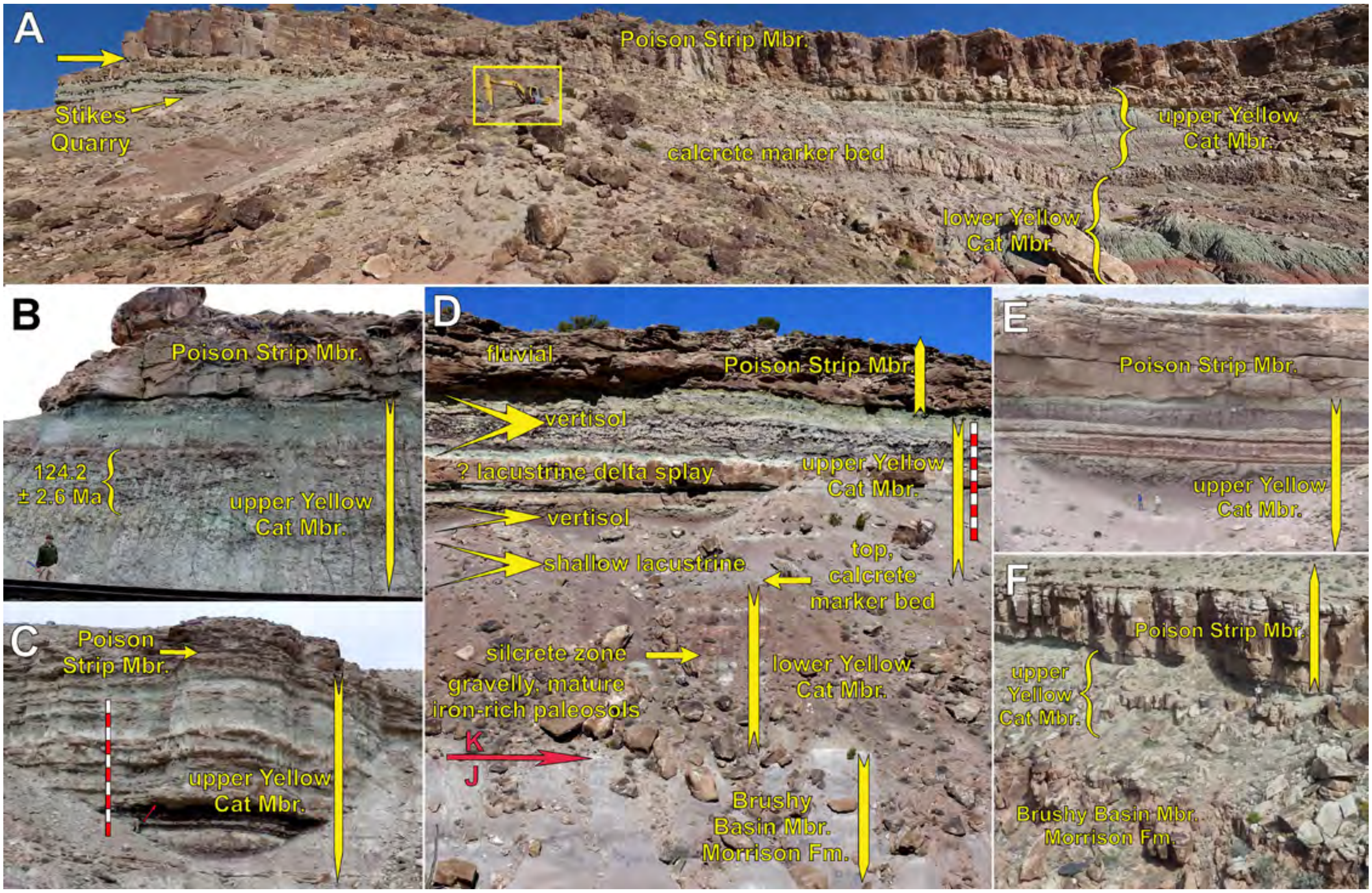

Figure 21. Uppermost Yellow Cat Member and its contact with Poison Strip Member. (A) South escarpment below Utahraptor Ridge (figures 11 and 19). Note trackhoe near center of image; broad yellow arrow designates base of Poison Strip Member. (B) Upper Yellow Cat contact on west side of US 191 in railroad cut (38°43'15.16"N, 109°42'51.37"W) with approximate position of detrital zircon date (Greenhalgh, 2006; Greehaulgh and others, 2007; Britt and others, 2009); Matt Joeckel (Nebraska State Geologist) for scale. (C) Uppermost Yellow Cat on the southwest side of Doelling's Bowl with Matt Joeckel (right of red and white bar) examining underside of a sauropod trampolite surface, which rests on the dark-colored beds as indicated by red arrow; broad yellow arrow designates base of Poison Strip Member; red- and white-banded bar equals 10 m. (D) Steep exposure of Yellow Cat Member exposed on west side of small canyon on the southwest corner of Gaston's Bowl (38°51'54.67"N, 109°29'3.99"W) with paleoenvironmental interpretation; red- and white-banded bar equals 10 m. (E) Matt Joeckel and Greg Ludvigson looking at coastal vertisol on west side of Gaston's Bowl near top of Yellow Cat Member (38°52'30.72"N,109°28'30.78"W). (F) Thin interval of Yellow Cat Member exposed on west side of Hotel Mesa on east side of Colorado River (38°49'58.79"N, 109°16'32.28"W).

giant dromaeosauriid or "raptor," *Utahraptor ostrommaysorum* (Kirkland and others, 1993), is now known from four major sites and bone scraps from other sites. It was the sixth and still most massive dromaeosaurid ever discovered and although initially described from a scattering of bone, new discoveries (Kirkland and others, 2011; Kirkland and others, 2016) indicate that eventually it may become one of the best-known dromaeosaurids. While *Utahraptor* is a dromaeosaurine, a small velociraptorine (Senter and others, 2012a) also appears to be represented in these strata (figure 22G). *Martharaptor greenriverensis* was initially identified as a therizinosaurid and its poorly represented skeletal remains were collected a short distance above the caprock

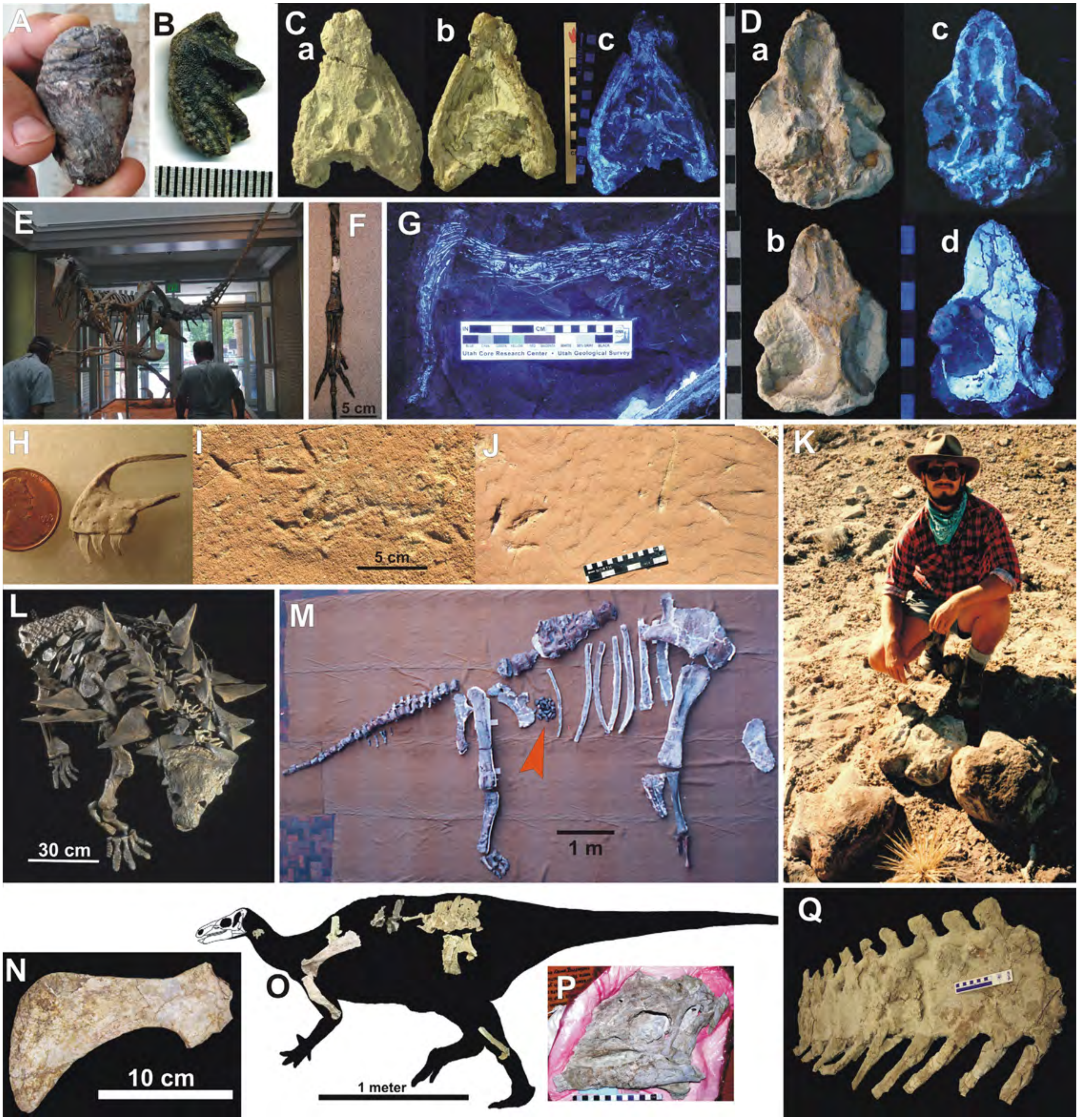

Figure 22. Caption on following page.

Figure 22 (figure on previous page). Characteristic faunal elements from the upper Yellow Cat Member of Cedar Mountain Formation. (A) Spiral coprolite embedded with small ganoid scales from *Nedcolbertia* site Utah Gr190v (figure 12). (B) Lower Ceratodus tooth plate from *Nedcolbertia* site Utah Gr190v (figure 12). (C) Basal mesoeusuchia crocodilian skull from Andrew's site UMNH 1207 (figure 12) in a) dorsal, b) ventral, and c) ventral view in UV light. (D) Skull of new mammal from Andrew's site UMNH 1207 (figure 12) in a) ventral, b) dorsal, ventral in UV light, and d) dorsal view in UV light. (E) Mount of *Utahraptor* as exhibited at Utah State University Eastern's Prehistoric Museum in Price. (F) Lower leg of holotype of *Nedcolbertia* as exhibited at Utah State University Eastern's Prehistoric Museum in Price. (G) Tail of *veloceraptorine* dromaeosaur from Andrew's site UMNH 1207 (figure 12) in UV light. (H) Premaxilla of "baby" *Utahraptor* from Stikes Quarry at Utahraptor Ridge. (I) Bird tracks (*Aquatilavipes*) from Utahraptor Ridge (figure 19) (Lockley and others, 2015). (J) Theropod tracks from same site as I. (K) Randy Nydam with iguanodont tracks from just below Andrew's site (figure 12) (Lockley and others, 1998). (L) Skeletal reconstruction of Gastonia based on material from Gaston Quarry. Scale bar for holotype skull, given perspective. Photo of Gaston Design reconstruction courtesy of Francois Gohier. (M) Holotype skeleton of brachiosaurid sauropod *Cedarosaurus* laid out on floor of the Denver Museum of Nature and Science. Note arrow pointing to gastroliths found within rib cage (Sanders and others, 2001). Photo courtesy of Ken Carpenter, Prehistoric Musem (Utah State University Eastern). (N) Hypsilophadont scapula from Andrew's site UMNH 1207 (figure 12) (McDonald and others, 2010). (O) Postcranial skeletal reconstruction of holotype of *Hippodraco* from Andrew's site UMNH 1207 (figure 12) (McDonald and others, 2010). (P) Skull of holotype of *Hippodraco* from Andrew's site UMNH 1207 (figure 12) (McDonald and others, 2010). (Q) Proximal tail of large iguanodont from Andrew's site UMNH 1207 (figure 12) (McDonald and others, 2010); note very short neural spines.

south of Green River, Utah (Senter and others, 2012b). Other undescribed theropod species have been identified from Dalton Wells Quarry west of Arches National Park (Britt and Stadtman, 1997; Eberth and others, 2006). There have been no teeth or bones indicating the presence of a large allosauroid in the upper Yellow Cat fauna, although they are represented in faunas above and below.

Upper Yellow Cat Fauna

Chondrichthyes
Polyacrodontidae
?*Polyacrodus* sp. Teeth and fine spines, coprolites?

Osteichthyes
Semionitidae
n. gen. n. sp. Scales and ridge scales Amiidae
High-crowned tooth crowns

Dipnoi
Neoceratodontidae
Ceratodus sp.

Chelonia
Baenidae
Trinitichelys n. sp. (fine reticulate shell) (Brinkman and others, 2015)

Rhynchocephalia
cf. *Toxolophosaurus*, large eilenodontid

Choristodera
Small neochoristodere indet. (Britt and others, 2006)

Crocodilia
New medium-sized (20 cm skull) basal mesosuchian terrestrial crocodilian
Aquatic goniopholid crocs.

Pterosauria
?pterosaur (Britt and others, 2009)

Dinosauria
Theropoda
Small slender teeth similar to *Richardestesia* ?
Nedcolbertia justinhoffmani (Kirkland and others, 1998a)
Ornithomimid n. sp. ? (Scheetz and others, 2010a)
Martharaptor greenriverensis Senter and others (2012b) poorly resolved oviraptorisaur or therizinosaur
Utahraptor ostrommayorum Kirkland and others (1993)

Velociraptorine dromaeosaurid indet. (Senter and others, 2012a)
Assorted theropod tracks (Lockley and others, 2015)
Bird tracks (Lockley and others, 2015)

Sauropoda
Cedarosaurus weiskopfae Tidwell and others (1999)
New turiasaurid (Royo-Torres and others, 2016, by reference to Kirkland and others, 2012)
Camarasaurimorph (Britt and others, 2009)

Thyreophora
Gastonia burgei Kirkland (1998a), polacanthid ankylosaur

Ornithopoda
Hypsilophodont grade ornithischian (McDonald and others, 2010)
Hippodraco scutodens McDonald and others (2010)
Sail-backed iguanodont (Scheetz and others, 2010b)
Third styracosternid iguanodont n. gen. n. sp. (A. Scheetz, BYU, personal communication, 2014)

Mammalia
n. gen. n. sp. large 7 cm long skull (Huttenlocker and others, 2016)

The dinosaurs, together with pollen and charophytes (green algae), and various isotopic dating methodologies suggest that the Yellow Cat Member rocks are anywhere from 137 to 120 million years old (Kirkland and others, 1997, 1998b, 1999; Eberth and others, 2006; Britt and others 2009; Ludvigson and others, 2010a; Hendrix and others, 2015). In Europe, similar types of dinosaurs are also known from rocks of this age (Martill and Naish, 2001a), a time when the northernmost Atlantic Ocean had not yet opened, thereby permitting the exchange of animals between these two regions prior to the formation of an Alaskan land bridge (Cifelli and others, 1997; Kirkland and others, 1997, 1998b, 1999, 2013a, 2015; Kirkland and Madsen, 2007; Brikiatis, 2016). However, Britt and others (2006) dispute this interpretation based on a small proximal femur identified as a primitive neochoristodere (an extinct semiaquatic lizard-like group) from the Dalton Wells Quarry west of Arches National Park. It is related to taxa known only from Asia in the Early Cretaceous. Britt and others' (2006) interpretation does not take into account that this group may be tied to Asia through Europe as suggested for Falcarius (Kirkland and others, 2005b) given that no land connection to Asia existed at this time (Plafker and Berg, 1994; Brikiatis, 2016). Brikiatis (2016) suggests that the last direct land connection between North America and Europe was early in the Barremian around 131 Ma after which North America would have been an isolated island continent.

Poison Strip Member

The Poison Strip Member is a complex of well-cemented sandstone beds that indicate deposition in amalgamated low-sinuosity anastomosing and meandering river systems, and coeval interfluvial deposits (Kirkland and others, 1997, 1999; Kirkland, 2005a; Kirkland and Madsen, 2007; Stikes, 2003, 2006). The type section (figure 23A) is up section to the north of the Ringtail mine on the west end of the Poison Strip, and is 5.4-m-thick, trough cross-bedded, medium- to coarse-grained sandstone with chert-pebble lenses in the lower part, fining upward to medium-grained sandstone with mudstone partings at the top (Kirkland and others, 1997). Unfortunately, the type section did not have a clear contact with the overlying Ruby Ranch Member given that the upper contact is picked at a dramatic change to floodplain deposition with abundant pedogenetic carbonates. Although initially described as the Poison Strip Sandstone (Kirkland and others, 1997), the variety of strata other than sandstone, necessitates renaming it to the Poison Strip Member to avoid misinterpretation. In the Arches National Park area, Stikes (2006) found the Poison Strip Member to represent an amalgam of river channels as much as 15 m thick due to decreased subsidence rates dominated by low- to moderate-sinuosity channels with lateral bars and distal braided channels (Miall, 1996). As Kirkland and others (1997) noted, as many as three sandstone beds may define the Poison Strip Member, although one prominent ledge is the norm and locally may have no sandstone beds.

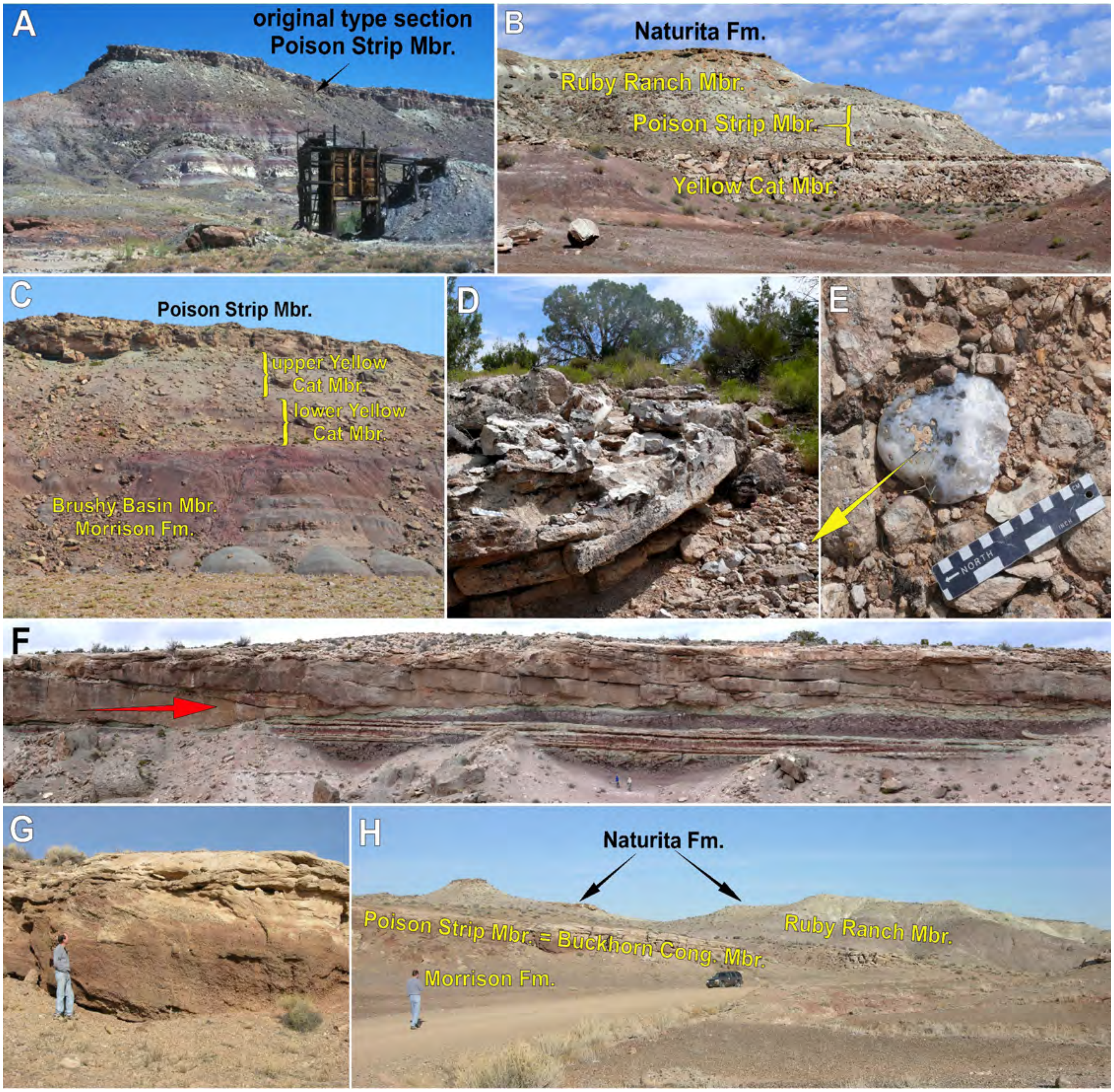

Figure 23. Poison Strip Member of the Cedar Mountain Formation. (A) Type section on the west end of Poison Strip escarpment above Ringtail mine of Yellow Cat mining district (38°51'11.56"N, 109°31'36.02"W). (B) Northeastern rim of Doelling's Bowl, where there are no major cliff forming sandstone benches in the member and it is mostly an interfluvial floodplain sequence. (C) Exposures toward eastern end of the Poison Strip escarpment (38°51'16.30"N, 109°28'33.78"W). (D) One of many small quartzite sites on top of the Poison Strip escarpment utilized for lithic material by native people. (E) Chert hammerstone with arrow pointing to it in D. (F) Panel diagram Poison Strip channel sandstone above vertisol in figure 21E to show large scale lateral accretion bedding. Arrow indicates direction of lateral migration of channel. (G) Poison Strip Member resting on Morrison Formation south of Green River, Utah (38°56'57.58"N, 110° 5'41.84"W), whereby UGS convention, it would be mapped as Buckhorn Conglomerate. (H) Overview of same locality as in G as viewed from east.

The Cisco gas field northeast of Arches National Park is hosted within sandstones of this member. Stikes (2006) reported that these sandstones are more porous than the sandstones in the underlying Morrison Formation. Young (1960) referred to these resistant sandstones as the middle Cedar Mountain sandstone and noted that they form the most continuous marker bed in the Cedar Mountain Formation. These resistant sandstone beds hold up an extensive cliff of lower Cedar Mountain and upper Morrison Formation extending across much of east-central Utah from the eastern San Rafael Swell to western Colorado.

The term Poison Strip Member is only used in the northern Paradox Basin in Grand County, Utah, where the Yellow Cat Member separates these strata from the underling Morrison Formation (figure 11). Even in the Dewey Bridge area (figures 21F and 24A) on the western boundary of the Paradox Basin, a thin interval of Yellow Cat Member is present below the Poison Strip Member, and farther east in Rabbit Valley, Colorado, the Ruby Ranch Member rests directly on the Morrison Formation (figure 24B and D). Elsewhere in western Colorado and southwestern Utah, Young (1960) recognized the middle sandstone of the Cedar Mountain Formation. Our own research has not extended into this region and the extention of the Poison Strip Member in the Burro Canyon Formation remains a decision for future researchers.

To the west the Poison Strip Member rests directly upon the Morrison Formation and, following Utah Geological Survey (UGS) convention, these strata should be referred to as the Buckhorn Conglomerate Member, which we hypothesize are the youngest Buckhorn Conglomerate strata. Shapiro and others (2009; personal communication, 2007) have suggested that the lacustrine units preserving the dinosaur bone shard, bearing oncoids that they described from immediately above the Buckhorn Conglomerate along the Green River Cutoff Road on the northeastern side of the San Rafael Swell around the Woodside anticline area (39°12'4.43"N,110°22'36.31"W) may be correlative with the Poison Strip Member.

Stikes (2006) reported that the generally northeasterly trending Poison Strip channel sandstones contained bedforms characterizing both vertical and lateral accretion (figure 23F) and noted that Paradox Basin salt tectonics do not appear to have played a role in Poison Strip depositional patterns, instead, it records an interval of reduced accommodation reflecting low net sedimentation. The lack of accommodation space allowed for fluvial systems to migrate laterally across one level, and Stikes (2006) concluded that the Poison Strip Member represented a degradational systems tract controlled more by Sevier tectonics from distal areas to the foreland basin. Hunt and others (2011) and Hunt (2016) have noted that an analysis of detrital zircons indicate that there is an increasing proportion of material derived from the Morrison Formation in the Poison Strip Member from west to east across the Paradox Basin.

In the few areas in the northern Paradox Basin where well-indurated sandstone beds are absent, the Poison Strip Member does not cap a steep escarpment and roads cross the outcrop belt at these "paleo-water-gaps" making these the most accessible outcrops of the Poison Strip and Yellow Cat Members of the Cedar Mountain Formation (Kirkland and Madsen, 2007). The only way to calibrate the thickness of the Poison Strip is to trace the crevasse splays and lacustrine limestone beds from areas in the fluvial systems holding up the escarpments on either side of these roads into the outcrops along the roads. A good example of this is in the access point to Doelling's Bowl on its northeast side (figure 23B). A prominent sandstone channel system forms the south rim of the bowl that can be traced into the base of the interfluvial Poison Strip Member. To the northeast, the Poison Strip fluvial system can be traced into the top of this interval of interbedded crevasse splays, mudstone, and lacustrine limestones. The interrelationships between large channel systems and their interfluvial deposits occur en echelon over distances of kilometers and are not easily documented. Although they are recognized in the field, they are difficult to photographically record at a scale appropriate to this volume.

This broadly en echelon pattern of fluvial deposition led several workers to interpret Lorrie's site as having a "Yellow Cat fauna" extending upward into the Ruby Ranch Member (Shaw, 2003; Kirkland and others, 2005a; Carpenter, 2006; Lee, 2014; Kinneer and others, 2016). Given our earlier interpretations of Poison Strip deposition, this is a logical conclusion as site DMNH

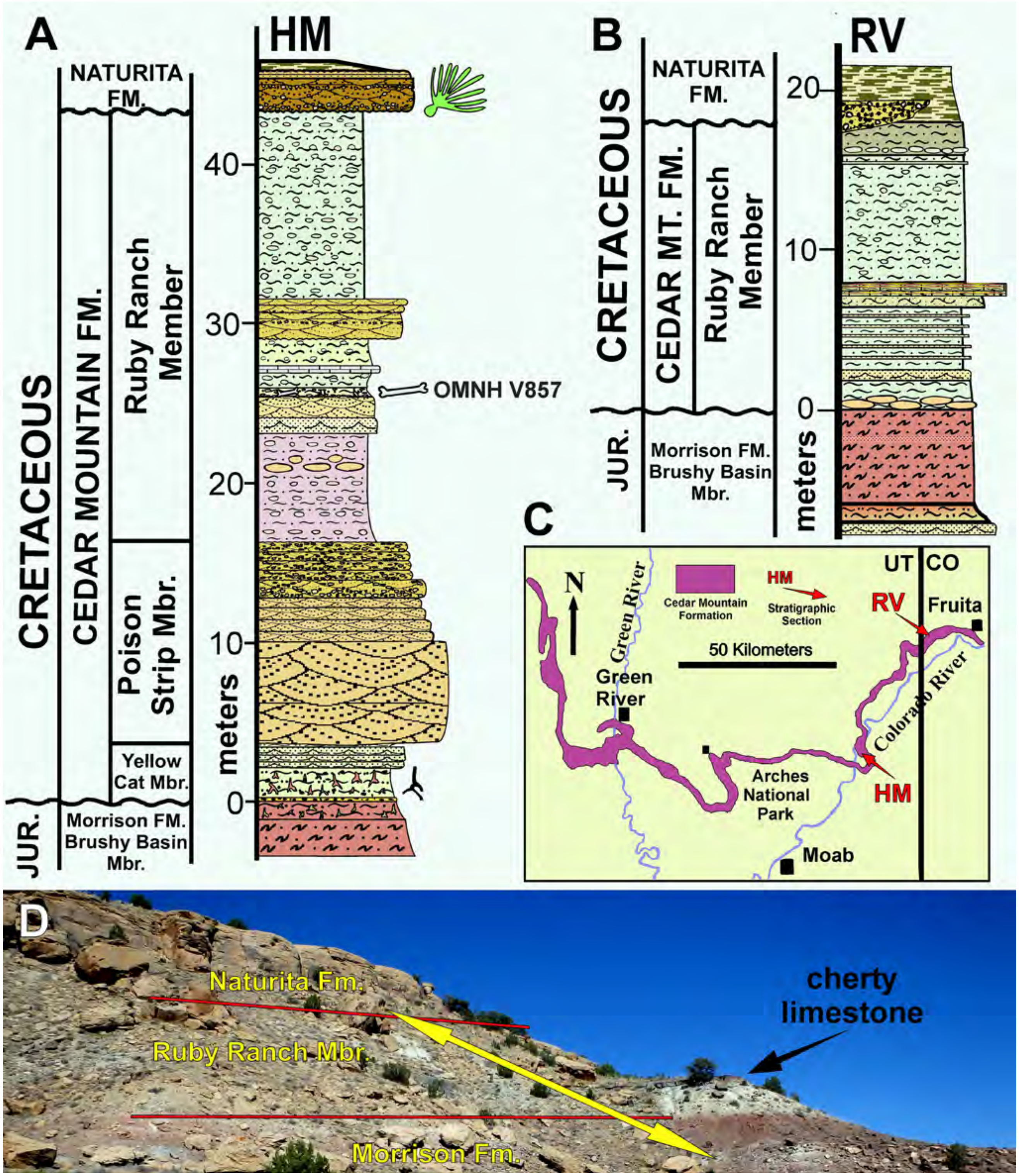

Figure 24. Cedar Mountain sections on the east side of the Paradox Basin. (A) Hotel Mesa (HM) section measure from 38°49'51.36"N, 109°16'29.82"W up to 38°49'57.95"N, 109°16'28.54"W. OMNH v857 is the type locality of *Brontomerus mcintoshi (*Taylor and others, 2011); currently the youngest and most eastern described dinosaur in the Paradox Basin. (B) Rabbit Valley, Colorado, section (RV)measured at 39°11'56.04"N, 109°1'29.16"W about 0.5 km northwest of the Trail Through Time. (C) Index map. (D) Cedar Mountain exposure and approximate line of Rabbit Valley section. Symbols for sections in figure 10.

2183 occurs on the surface of a Poison Strip channel sandstone and forms a bench more than 1 km across that vanishes under a road to the west of the site. However, if one stands on the sandstone bench and looks to the west, the Poison Strip sandstone bed holding up the escarpment there can be traced east and to the north back across the road to a point where it pinches out upslope of site DMNH 2183. Thus, this site is mapped as being in the Poison Strip Member (figure 18) on the geological map of the area (Doelling and Kuehne, 2013a).

The Poison Strip Member has little evidence regarding its age beyond biostratigraphy (see flora and fauna section below) and chemostratigraphy. At the Ruby Ranch Road section (figure 11), a U-Pb laser ablation age of detrital zircons yields a maximum age of 146 ± 0.49 to 0.47 Ma (75% confidence), which is Upper Jurassic. The two youngest zircons yielded a nearly identical age of 131 Ma and a U-Pb age from diageneticly enriched uranium in an algal limestone lense a few meters lower (near the base of the Poison Strip) yielded a maximum age of 119.4 ± 2.6 Ma (Ludvigson and others, 2010a). Chemostratigraphic studies of stable carbon isotopes from pedigenic carbonate nodules suggest the base of the Ruby Ranch Member is approximately 118 Ma (Ludvigson and others, 2010a, 2015). Overall, an early to middle Aptian age assignment seems most likely for these strata (see also section on geochemistry).

Flora and Fauna of the Poison Strip Member

Trace fossils are so abundant and diverse in the Poison Strip Member that they may be considered a defining character of the member. Petrified logs and cycads are common in these beds (Dayvault and Hatch, 2005). Unfortunately, most wood specimens do not preserve adequately defined cell structure for specific identification (W.D. Tidwell, Brigham Young University, personal communication, 1997).

Dinosaurs are less commonly preserved and, unfortunately, these strata have not received the paleontological attention that they deserve. The first dinosaur described from the Cedar Mountain Formation was a large polacanthid ankylosaur from the Poison Strip Member on BLM lands on the western side of Arches National Park. It was originally referred to as cf. *Hoplitosaurus* (Bodily, 1969) and subsequently, mistakenly assigned to *Sauropelta* (Carpenter and others, 1999). The specimen is characterized by massively constructed and very dense armor (figure 25E to G). The UGS has found another site preserving this same type of armor in the Poison Strip Member well to the east, south of Cisco, Utah, but excavation of the site has not been undertaken.

Carpenter's team (Carpenter, 2006; Kinneer and others, 2016) has completed the description of *Gastonia lorriemcwhinneyae* from the Poison Strip Member (see above), represented by an extraordinary amount of material, including many partial skulls (Kinneer and others, 2016). This material includes numerous examples (figure 25H) of a distinct armor type described as splates (Blows, 2001), not known to be so well-developed in any other polacathid ankylosaurs except those in Europe and *Hoplitosaurus marshi* from the Lakota Formation of South Dakota. *Hoplitosaurus* preserved a splate so similar to the English, Barremian-age *Polacanthus foxi* that Pereda-Suberbiola (1994) renamed it *Polacanthus marshi* and proposed that *Polacanthus* represented a transatlantic Early Cretaceous genus. Although we do not agree with this synonoymy, perhaps *Gastonia lorriemcwhinneyae* is more closely related to *Hoplitosaurus* than to *Gastonia burgei* and provides a biostratigraphic link to the Lakota Formation.

Iguanodontids are relatively common in the Poison Strip Member. DiCroce and Carpenter (2001) described a partial skeleton of a small iguanodont with a distinctive ilium and no skull as *Planicoxa venenica*. A few years later, Gilpen and others (2006) described a larger, even more incomplete iguanodont, *Cedroestes crichtoni*, from nearly the same stratigraphic level about 1 km to the northwest. The genus was based largely on a prominent "antitrochanter" dorsal to the ischial peduncle. This same feature is present, although not so well developed, in the juvenile holotype of *Planicoxa*, and examination of the illia in both specimens indicates than any differences between the specimens can be explained by ontogeny and distortion (figure 25I). Thus, *Cedroestes* would be a junior synonym of *Planicoxa* (Kirkland and Madsen, 2007). A different view has been put forth by McDonald and others (2010) who proposed that *Planacoxa* was too distorted to represent a valid taxon and

Figure 25. Flora and fauna from Poison Strip Member. (A) "Conifer" log in the Poison Strip Member on top of the Poison Strip escarpment with the late Brigham Young University paleobotanist William D. Tidwell for scale. (B) "Conifer" log in the vertical cliff of Poison Strip Member on western margin of Yellow Cat flats with Tom Mellenthin for scale. (C) Bennetalian *Cycadeoidea* weathered out of the top of the Poison Strip Member in the Moab area. (D) *Venenosaurus* bones in Tony's bonebed (DMNS 2182). Photo courtesy of Ken Carpenter, Prehistoric Museum (Utah State University Eastern). (E) Massive dorsal osteoderms from Bodily's "Hoplitosaurus" site, BYU 1072. (F) Tail vertebrae from Bodily's "Hoplitosaurus" site. (G) Caudal plates from Bodily's "Hoplitosaurus" site. (G) Caudal plates from Bodily's "Hoplitosaurus" site. (H) Splates from Gastonia *lorriemcwhinneyae*. from Lorrie's site (DMNH 2183) (figure 18). (I) Comparison of ilia from a) *Cedrorectis* and b) *Planocoxa*.

that of the two, *Cedrorectes* was the valid taxon. The reassignment of *Camptosaurus depessus* from the Lakota Formation in western South Dakota to *Planicoxa depressus* (Carpenter and Wilson, 2008; Carpenter and Ishida, 2010) provides another possible biostratigraphic link between the Poison Strip Member and the Lakota Formation, although this assignment has also been questioned (McDonald, 2011) in that *P. depessus* is also too distorted to be taxonomically valid.

The titanosauromorph sauropod *Venenosaurus dicrocei* was recovered in Tony's bonebed (figure 25D) with the type of *Planacoxa* (Tidwell and others, 2001). This sauropod has been found to be part of the same clade as the Spanish brachiosaurid *Tastavinsaurus* and *Cedarosaurus* from the upper Yellow Cat Member (Royo-Torres and others, 2012, 2014), suggesting a further transatlantic connection.

Dinosaurs from Poison Strip Member

Theropoda

cf. *Utahraptor* sp. (Joe Sertich, Denver Museum Nature and Science, personal communication, 2016)

Sauropoda

Venenosaurus dicrocei Tidwell and others (2001)

Thyreophora

Gastonia lorriemcwhinneyae Kinneer and others (2016)

Ornithopoda

Planicoxa venenica DiCroce and Carpenter (2001)
?Cedroestes crichtoni Gilpen and others (2006)
large steracosternid iguanodontid n. gen. n. sp. (A. Scheetz, Brigham Young University, personal communication, 2014)

Ruby Ranch Member

The Ruby Ranch Member is present everywhere the Cedar Mountain Formation is recognized and thickens to the west and northwest, probably indicating the earliest development of a foreland basin caused by Sevier thrust belt in central Utah (Kirkland and others, 1997, 1998b; Currie, 1998; Kirkland, 2005a, 2005b; Kirkland and Madsen, 2007; Ludvigson and others, 2010a, 2015) (figures 3, 5, and 6). The type section is just north of the Ruby Ranch Road (figures 11, 15A, and 26), above the massive "calcrete" reported by Aubrey (1998; Kirkland and others, 1997). The Ruby Ranch Member is lithologically similar to the Yellow Cat Member east of the Salt Valley anticline, except that carbonate nodules are much more common and cover the ground to such an extent making it difficult to find fossil bone fragments. The carbonate nodules developed in paleosols and ephemeral ponds formed under semiarid conditions. Ribbon sandstones representing low-sinuosity rivers are prevalent in this member (Kirkland and others, 1997, 1999; Kirkland and Madsen, 2007). They are very well expressed southwest of Green River, Utah, between the Green River and SR 24 to the west. These ribbon sandstone units form classic geomorphic examples of inverse topography, weathering in relief to cap branching and sinuous ridges that can be traced for kilometers (figure 26E) and are now being employed as an analogue for interpreting similar features on Mars (Harris, 1980; Lorenz and others, 2006; Williams and others, 2007, 2011).

Across most of the northern Paradox Basin, the Ruby Ranch Member is of rather uniform thickness ranging from 15 to 30 m. A dramatic exception is immediately west of the Salt Valley anticline, where a thick lacustrine sequence (Montgomery, 2014) overlies a major northeast-trending coarse-grained, trough cross-bedded sandstone interpreted to represent a braided, low-sinuosity river channel overlying an otherwise typical sequence of Ruby Ranch Member for this region (figure 11). This large ribbon sandstone has been nicknamed the "Klondike River" and it was originally mapped as the basal unit of the "Dakota Formation" (Doelling, 1985). The thick lacustrine section has been nicknamed "Lake Carpenter" as Carpenter (Prehitoric Museum, Utah State University Eastern, verbal communication, 2008) reported on the presence of a thick lacustrine sequence in the "Dakota Formation" on the east side of Arches National Park. Upon examination of the section, we determined it was overlain by a quartzite pebble conglomerate typical of the basal Naturita Formation (= Dakota Formation). The recent geological map for the Klondike Bluffs 7.5-minute quadrangle incorporates this change (Doelling and Kuehne, 2013a). This distinctive sequence will be examined in detail on the afternoon of day 1.

Across the the northern part of the Paradox Basin, these strata are a rather monotonous sequence of purplish-gray mudstone with abundant carbonate nodules. Studies have revealed an impressive amount of diagenetic complexity to these carbonates reflecting their formation in a variety of floodplain environments (Ludvigson and others, 2010a, 2015). Where the Naturita Formation (= Dakota Formation) directly overlies the Ruby Ranch Member east of the San Rafael Swell, several meters at the top of the member may be bleached to a pale green color, such that it may appear superficially to represent the Mussentuchit Member. The abundance of carbonate nodules in this interval provides evidence that this is not the case.

The Ruby Ranch Member thickens across the San Rafael Swell, as well as from south to north along its western side (Kirshbaum and Schenk, 2011). The thickest section measured by Kirkland was on the the north end of the San Rafael Swell to the east of where the Price River crosses the Cedar Mountain outcrop belt (figure 27). The Ruby Ranch Member at the Price River section rests upon approximately 18 m of Buckhorn Conglomerate Member and ranges from approximately 100 to 160 m thick, depending on how much of an overlying Mussentuchit Member is recognized below the Naturita Formation (= Dakota Formation). At approximately 94 m above the Buckhorn, there is a major complex of multitiered calcrete 6 to 8 m thick. That had been previously interpreted as Aubrey's (1998) marker calcrete in a number of publications (Kirkland and others, 1997; Burton and others, 2006). This calcrete caps a distinctive red bed interval that could represent a North American aridification event that may have peaked about 114 to 113 Ma (Al-Suwaidi, 2007; Ludvigson and others, 2015; also see the geochemistry section below). Stratigraphically above this interval, the mudstone becomes significantly more smectitic and was initially thought to represent the Mussentuchit Member of the Cedar Mountain Formation (Carpenter and others, 2001, 2008; Kirkland and Madsen, 2007; Ludvigson and others, 2010a). However, this interval preserves abundant small carbonate nodules that characterize the top of the Ruby Ranch Member in its thicker section along the western side of the San Rafael Swell. We think it represents a transition zone below the sequence boundary separating the Mussentuchit Member from the Ruby Ranch Member as discussed more fully below. It is worth noting that this has not been the first misinterpretation of these strata. The PR1 sandstone bed in or near the top of the Ruby Ranch Member yielded a partial cf. *Tenontosaurus* from the Price River I Quarry (Utah Em271v). That bed was mistakenly identified as the Poison Strip Member (Kirkland and others, 1997), largely due to the red mudstone interval underlying the calcrete interval in this area identified as marking the top of the Morrison Formation (figure 27).

Burton and others (2006) published four maximum U-Pb ages from detrital zircons in the upper part of the Price River section (figure 27) by the Price River II Quarry (Utah Em372), Carbon County, Utah. They logged these dated samples relative to their placement above the Morrison Formation, which were picked at the top of the Price River calcrete. These maximum detrital zircon ages are 114 Ma at 1.6 m, 116 Ma at 14 m, 113 Ma at 15 m, and 109 Ma at 40 m. The maximum age of the lowest sample may fit the chemostratigraphy (see geochemistry section below) of the interval just below the calcrete. The overlying two zircon samples would represent the "younger" upper Ruby Ranch transitionary facies. The maximum age of the highest sample may be correlative with the transitionary facies or even the Mussentuchit Member; however, the dates seem to be too old for these strata given that these are maximum ages and is inconsistent with reported ages elsewhere. Overall, based on zircon ages and chemostratigraphic studies, the Ruby Ranch Member ranges in age from approximately middle Aptian to middle Albian (about 118 to 105 Ma) for the western Paradox Basin and northern San Rafael Swell. Other radiometric ages indicate the presence of upper Albian strata as well (Chure and others, 2010; Ludvigson and others, 2010a, 2015; Sprinkel and others, 2012).

Note that some workers had assumed the base of the Cedar Mountain Formation should always be marked by a calcrete (see Aubrey, 1998; Burton and others, 2006; Roca and Nadon, 2007). It was also assumed by Kirkland and others (1997, 1999) and (Kirkland and Madsen, 2007) that the first prominent conglomerate encountered going down section through the Ruby Ranch Member around the San Rafael Swell must be the Buckhorn Conglomerate. However, a prominent discontinuous conglomerate is present at many places in the middle of the Ruby Ranch Member unrelated to the Buckhorn Conglomerate. This was the case in the Mussentuchit Wash area as well (Doelling and others, 2009; H. Doelling, Utah Geological Survey [retired] verbal communication 2010). Because of this revelation, the Ruby Ranch Member was found to be as much as twice as thick as previously assumed, although this had no effect on our definition of the type section of the Mussentuchit Member. An additional case is Kirkland and others (1997, 1999, figure 20) analysis of the section at the Carol site (type locality for *Eolambia*) east of Castle Dale, Utah, where a laterally extensive conglomeratic channel sandstone in the medial Ruby Ranch Member was mistaken for the Buckhorn Conglomerate Member.

It has recently become apparent that utilizing the simple presence of smectitic mudstones overlying ilitic mudstones is not sufficient to identify the contact between the Ruby Ranch and Mussentuchit Members of the Cedar Mountain Formation because the two members are separated by a sequence boundary (Kirkland and others, 1999; Kirkland and Madsen, 2007; Sprinkel and others, 2012). The Mussentuchit Member is often lignitic with plant debris and does not preserve carbonate nodules. We have noted that there seems to be less than a meter of smectitic, carbonate nodule-bearing strata below the base of the Mussentuchit Member in its type area around Mussentuchit Wash on the southwestern margin of the San Rafael Swell. This interval thickens to the north as the Ruby Ranch correspondingly thickens.

Where radiometrically dated, these strata are Albian in age and may reflect an interval of wetter climatic conditions as the Skull Creek-Thermopolis Seaway expanded toward northeastern Utah and into central Colorado. This transgression occured during the late Albian based on three high-precision U-Pb ages of 103.8, 103.9, and 104.6 Ma ± 0.04 Ma, respectively, from volcanic ash beds in the Plainview Formation at Fossil Ridge along

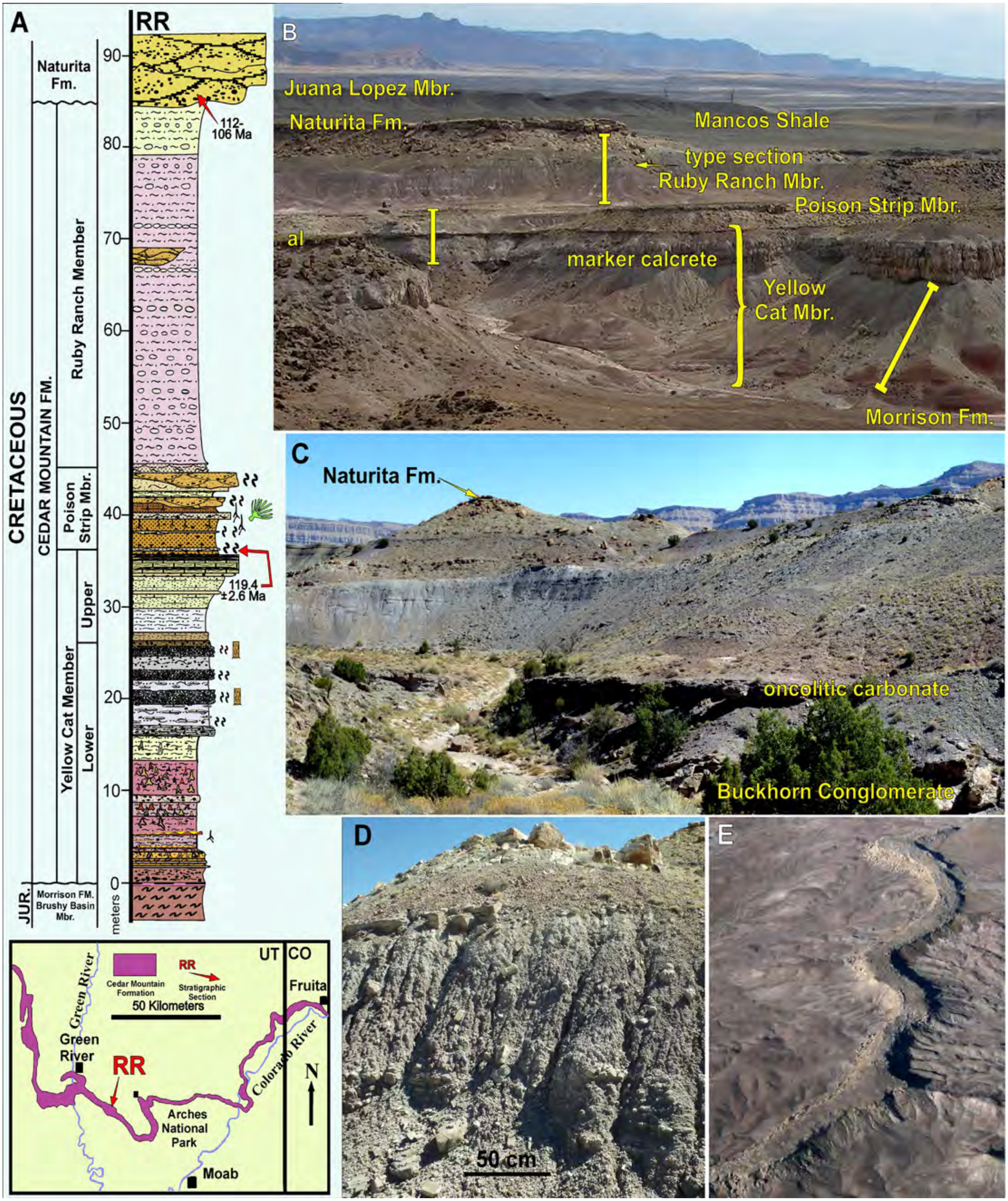

Figure 26. Caption on following page.

Figure 26 (figure on previous page). Ruby Ranch Member. (A) Ruby Ranch Road section (RR) includes type Ruby Ranch Member measured from 38°51'15.12"N, 109°59'16.24"W, 38°51'18.49"N, 109°59'8.85"W via three segments in B. Radiometric dates from Ludvigson and others (2010a). (B) Overview of Ruby Ranch section from ridge to southwest; al = cherty algal limestone near top of the Yellow Cat Member. (C) Easily accessible Ruby Ranch section exposed on west end of Green River Cutoff Road on northeastern side of San Rafael Swell about half way between Green River, Utah, and the Price River sites. Oncolitic carbonate described by Shapiro and others (2009); (39°12'4.43"N, 110°22'36.31"W). (D) Typical exposure of Ruby Ranch Member with abundant pedogenetic carbonates in situ and covering slope at top. Lower portion of section in C. (E) Exhumed Ruby Ranch sinuous paleo-channel (ribbon sandstone) southwest of Green River, Utah. Photo courtesy of Rebecca M.E. Williams of the Planetary Science Institute.

the Front Range escarpment west of Denver. Sam Bartlett (Friends of Dinosaur Ridge), Kirk Johnson (Smithsonian Institution [formerly the Denver Museum of Nature and Science]), and Sam Bowring (Massachusetts Institute of Technology [MIT]) collected the ash beds. The age analysis was done at MIT by Robert Buchwaldt and Sam Bowring as part of the Earthtime Initiative. Unfortunately, these dates have only been published in a short article in the Friends of Dinosaur Ridge Newsletter (annonymous, 2009). These "transitional facies" also cap the Cedar Mountain Formation to the southeast of Capitol Reef National Park and in northeastern Utah where they were also referred to as Mussentuchit Member (Kirkland and Madsen, 2007; Chure and others, 2010; Ludvigson and others, 2015). Unfortunately, these transitional facies were mapped as Mussentuchit Member on the Fruita 7.5-minute quadrangle (McLelland and others, 2007).

The abundant carbonate nodules in the Ruby Ranch Member have been the subject of a number of diagenetic studies and are providing a source of primary pedogenic carbonate that is being utilized for stable carbon and oxygen isotope studies. These are, in turn, being applied to Early Cretaceous paleoclimatologic and paleohydrographic studies, and the chronology is discussed in geochemistry studies. What is most pertinent here is the developing utility of stable isotope geochemistry in forming a basis for chronostratigraphic correlations within the Aptian-Albian time interval (Smith and others, 2001; Sorenson and others, 2002; Ludvigson and others, 2002, 2003a, 2003b, 2004, 2006; Kirkland and others, 2003; Ludvigson and others, 2010a, 2015). The correlation of stable carbon isotope curves with those of marine reference sections (figure 28) suggests the Ruby Ranch ranges in age from approximately middle Aptian to middle Albian (about 118 to 105 Ma) for the western Paradox Basin and northern San Rafael Swell; however, the radiometric ages from the Ruby Ranch Member in northeastern Utah indicate the presence of upper Albian strata as well (Chure and others, 2010; Sprinkel and others 2012; Ludvigson and others, 2015).

Ruby Ranch Fauna(s)

Given the extent of Ruby Ranch exposures across east-central Utah, it would seem logical that these strata would have yielded the bulk of fossils from the Cedar Mountain Formation; however, this is not the case. The vast abundance of fragmented carbonate nodules and sandstone covering the slopes makes prospecting for bone fragments and microvertebrates difficult. Additionally, even where fossils are found to be plentiful, carbonate encrustation may make excavation and preparation difficult as with the Long Walk Quarry (UMNH 0002) (DeCourten, 1991; Kirkland and others, 1997). Regardless, numerous localities are being found throughout the Ruby Ranch outcrop belt with new excavations, and preparations are ongoing.

The following discussion is divided into a section of the lower (Aptian) Ruby Ranch fauna and a section on the upper (Albian) Ruby Ranch fauna, although potentially more faunal levels are present or a continuity between the currently recognized Aptian-Albian faunas may be distinguished in the future.

Dinosaurs from the Ruby Ranch Member are distinct from those identified in the underlying members of the Cedar Mountain Formation. There are no polacanthid ankylosaurs, steracosternid iguanodontids, and sauropods with thick spatulate teeth; instead nodosaurid ankylosaurs, basal iguanodontian tenontosaurs (opportunists?), and slender toothed titanosauriform sau-

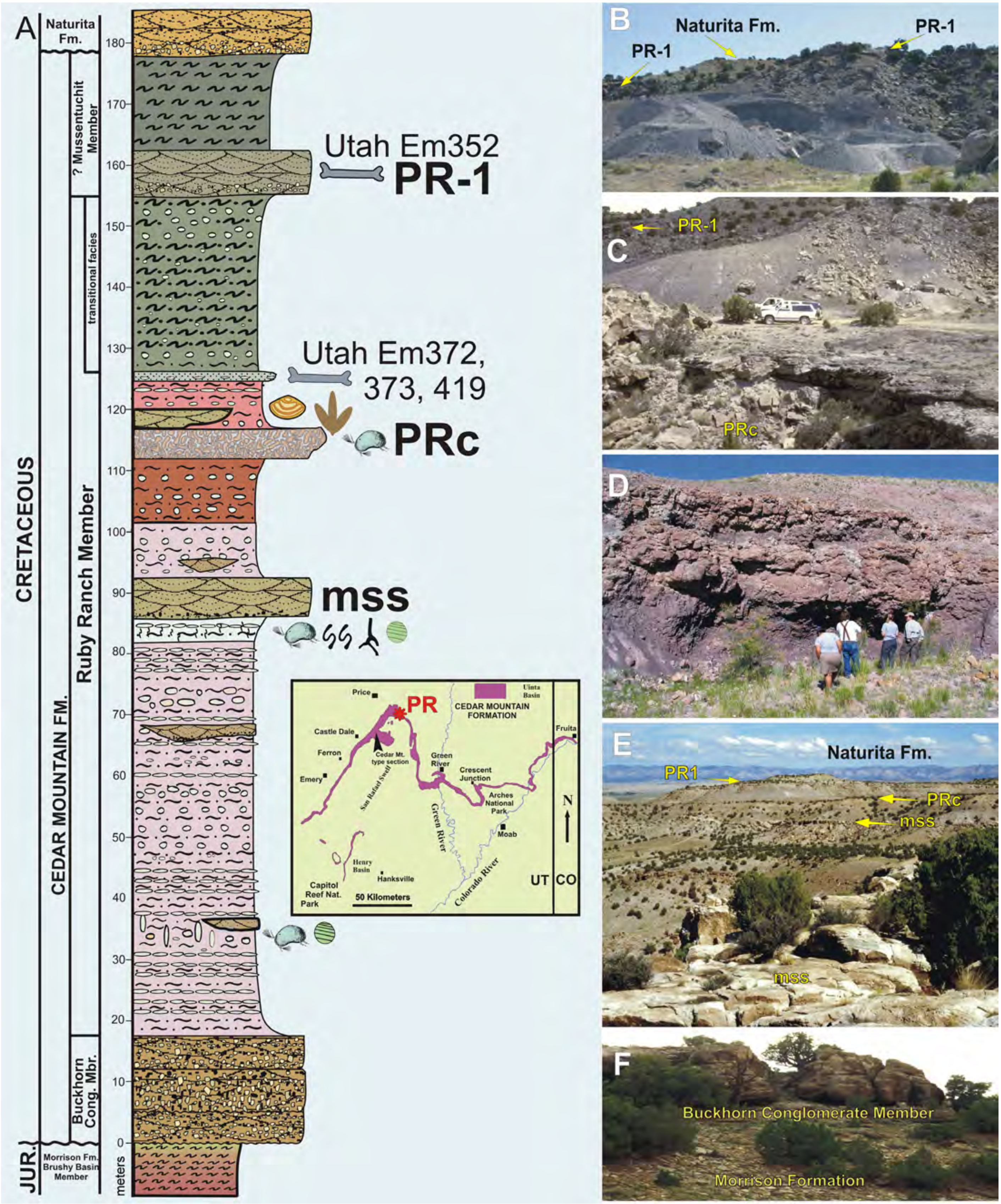

Figure 27. Caption on following page.

Figure 27 (figure on previous page). Cedar Mountain Formation on the north end of the San Rafael Swell in the Price River area. (A) Price River section (PR) as updated from Carpenter and others (2001) and Ludvigson and others (2010a, 2015); section measure in several steps between 39°25'25.45"N, 110°37'14.11"W and 39°26'21.44"N, 110°37'7.54"W"; Abbreviations: mss = middle Ruby Ranch sandstone that is a useful marker bed in area, PR1 = laterally extensive sandstone bench hosting the PR-1 cf. Tennontosaurus locality (Utah Em 352) high or perhaps at the top of the Ruby Ranch member. PRc = Price River calcrete marker bed high in the Ruby Ranch Member (Ali-Suwadi, 2007). (B) PR-2 Quarry (Utah Em372). (C) Overview of PR-2 Quarry to show track-bearing sandstone lense overlying Price River marker calcrete below locality. (D) Price River marker calcrete beds. (E) View to north toward CEU vertebrate localities along approximate line of measured section. (F) Buckhorn Conglomerate at base of section.

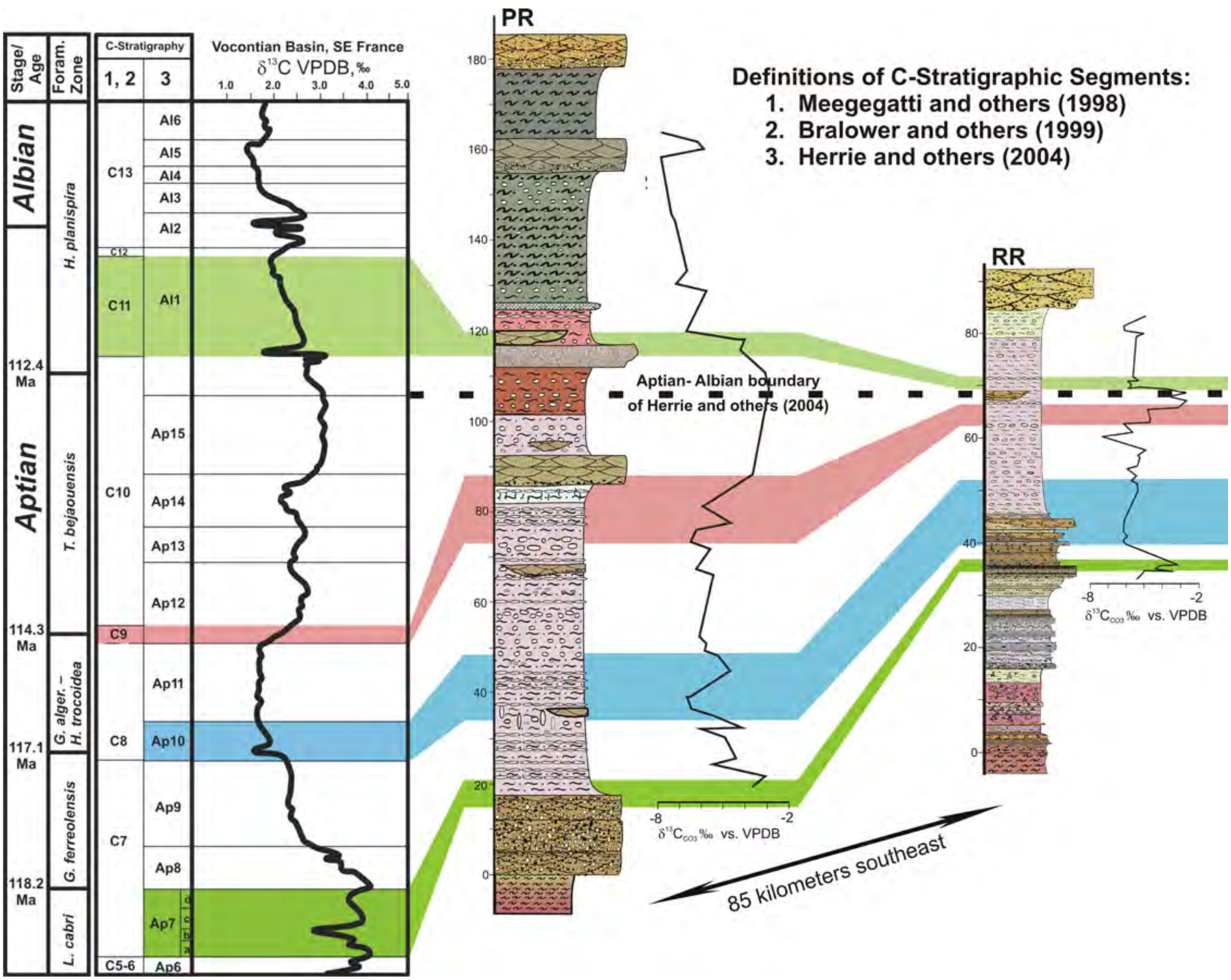

Figure 28. Temporal correlation of Price River and Ruby Ranch sections based on the correlation of high-resolution Aptian-Albian chronostratigraphy and C-isotope stratigraphy from the Vocontian Basin of southeast France (Herrle and others, 2004) with the C-isotope chemostratigraphy of the Cedar Mountain Formation at the Price River (PR, figure 27) and Ruby Ranch Road (RR, figure 26) sections, with the radiometric dates that constrain the chronostratigraphy of the Cedar Mountain Formation at Ruby Ranch Road and Price River. The curve of Herrle and others (2004) is a ten-point moving average. Absolute ages in the left panel are from Leckie and others (2002). Modified from Ludvigson and others (2010a).

ropods replace them (Kirkland and others, 1997, 1998b, 1999; Kirkland and Madsen, 2007). Instead of this faunal change occurring at the end of the Barremian, as previously thought, it apparently occurred sometime during the Aptian and may reflect biological processes occurring across the Northern Hemisphere during the Aptian (Kirkland and others, 2013, 2015).

The University of Utah's Long Walk Quarry near the base of the Ruby Ranch Member on the west side of the San Rafael Swell was the first Ruby Ranch locality to be extensively excavated, but given the difficulty in excavating the carbonate hosted bones, excavation ended in the early 1990s even though the site was donated to the Natural History Museum of Utah (DeCourten, 1991; Kirkland and others, 1997). Numerous specimens were collected and bone preservation is excellent with an abundance of sauropod elements and a large allosaurid noted among the material (figure 29). The Denver Museum of Nature and Science has taken the lead on the difficult preparation and research on this important collection. Mori (2009) averaged three different, somewhat discordant, U-Pb ages from three detrital zircon sites and calculated an overall maximum age of 115 Ma for the lower 35 m of the Cedar Mountain section at the Long Walk Quarry.

Kirkland was alerted to an illegal dinosaur excavation on the east side of the Colorado River at Hotel Mesa (figure 24A) in the mid-1990s. Preliminary investigation revealed that the site was low in the Ruby Ranch Member and that there was a significant amount of sauropod material with a fair amount of small bone (theropod claws and crocodilian teeth). The site was turned over to the Oklahoma Museum of Natural History, who are investigating microvertebrate fossils in the Cedar Mountain Formation. The site was visited over a three-day weekend to collect the exposed bones and the matrix for screenwashing, and to backfill the site. Given that the sandstone matrix would not break down,

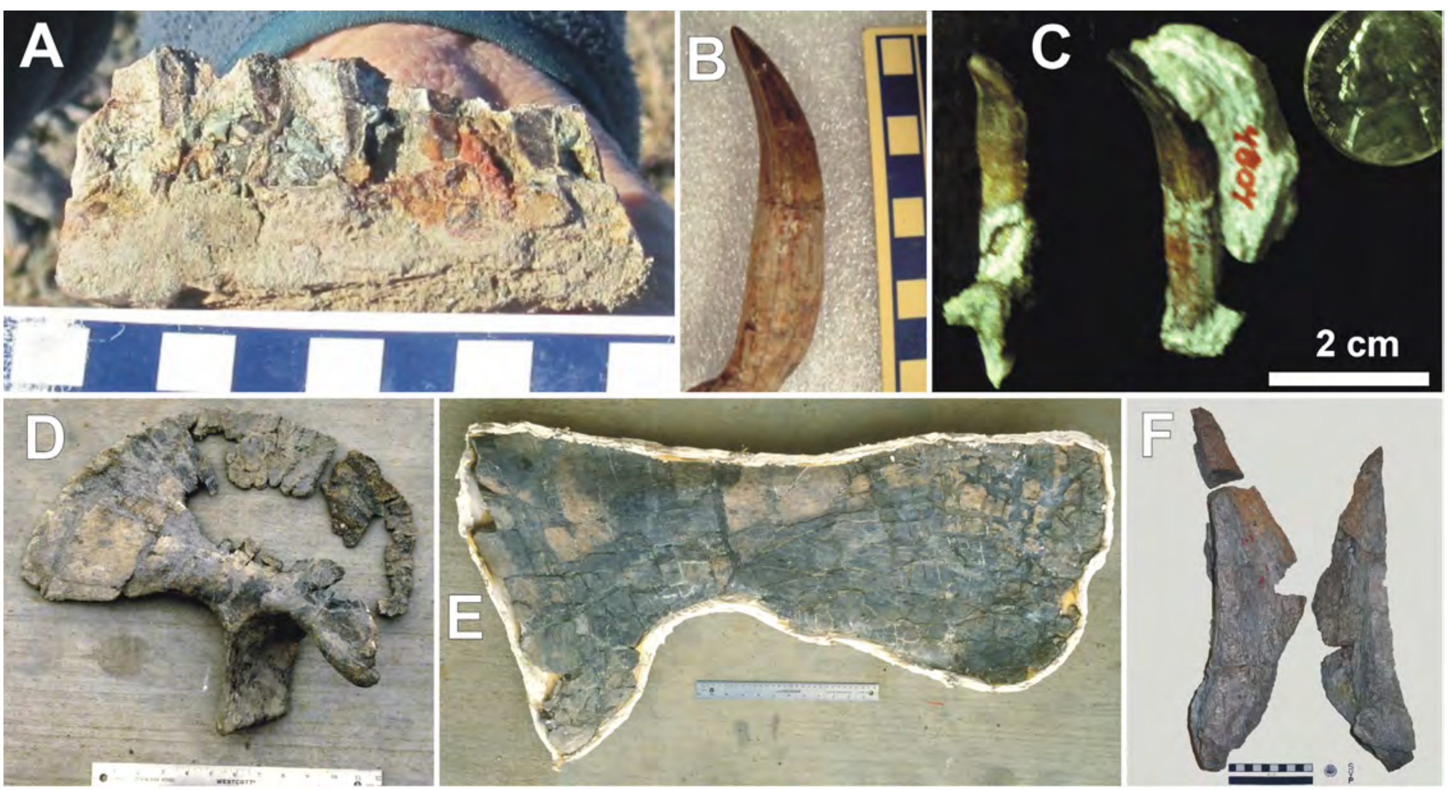

Figure 29. Aptian dinosaurs from lower Ruby Ranch Member. (A) Iguanodont jaw fragment from east of Arches National Park. (B) Allosauroid tooth from Long Walk Quarry (UMNH 0002). (C) Slender titanosauriform sauropod teeth from Long Walk Quarry. (D) Holotype juvenile *Brontomirus* ilium (OMNH 66430) from Hotel Mesa site (OMNH v857). (E) Adult sauropod scapula assigned to *Brontomirus*. (F) Cervical spines from cf. *Sauropelta*.

the site was not reopened; however, the bones that were collected were from a mix of juvenile and adult sauropods that includes unique diagnostic characters, which became the basis for the sauropod *Brontomirus mcintoshi* (Taylor and others, 2011) (figure 29). The site also preserved hybodontid sharks, lungfish tooth plates, unidentified bits of boney fishes, a variety of aguatic crocodilian teeth, and small theropod material. It is hoped that this interesting site will be reopened and researched further someday.

The Denver Museum of Nature and Science has found a number of sites in the Ruby Ranch Member in the northern Paradox Basin that yielded parts of basal iguanodontians best referred to cf. *Tenontosaurus* until further research is carried out. One site, south of Green River, Utah (DMNH 2840), yielded an incomplete large nodosaurid (Warren and Carpenter, 2004) that was within 10 m of the underlying Poison Strip Member and appears to be similar to Sauropelta (Ostrom, 1970; Carpenter and Kirkland, 1998) from the Cloverly Formation (figure 29). Finally, Carpenter (Prehistoric Museum, verbal communication, 2001) randomly picked up a carbonate nodule north of the UGS's Doelling's Bowl site and recognized that it encased a complete eilinodontid sphenodontian skull, further emphasizing the potential for important discoveries in these Aptian strata.

Fauna from the Lower Ruby Ranch Member

Chondrichthyes
indet. hybodontid (Taylor and others, 2011)
?*Polyacrodus* sp. (Taylor and others, 2011)

Osteichthyes
indet. (Taylor and others, 2011)
indet. gar (Taylor and others, 2011)

Dipnoi
Ceratodus sp. (Taylor and others, 2011)

Chelonia
Unidentified

Rhynchocephalia
Eilenodontid, cf. *Toxolophosaurus* sp.

Crocodylia
Gen. et sp. indet. (Taylor and others, 2011)
Bernissartia sp. (Taylor and others, 2011)
Indet. goniopholid (Taylor and others, 2011)
Indet. atopoaurid (Taylor and others, 2011)

Dinosauria

Theropoda
indet. small theropod (Taylor and others, 2011)
large allosauroid

Sauropoda
Brontomerus mcintoshi Taylor and others (2011)

Thyreophora
cf. *Sauropelta* sp. (Warren and Carpenter, 2004)

Ornithopoda
cf. *Tenontosaurus* sp.

The fauna from the Albian strata at the top of the Ruby Ranch is best documented at the Price River Quarries (figures 27 and 30) which have been excavated since the 1990s (Kirkland and others, 1997, 1999; Carpenter and others, 2001, 2008). The only dinosaurs described to date are ankylosaurs, including a gigantic nodosaurine nodosaurid *Peloroplites cedrimontanus* (figure 30F) that is perhaps related to *Sauropelta* (Carpenter and others, 2008). A more surprising discovery is the long-skulled basal ankylosaur *Cedarpelta bilbyhallorum* (Carpenter and others, 2001, 2008). The first specimens of this taxon were identified by two large, juvenile disarticulated skulls with associated postcranial skeletal elements from the KEM site across the valley from the larger PR-2 Quarry. It most obviously groups with shamasaurine grade ankylosaurids because it has short distal limb elements, straight Ischia, skull texture, and because it closes off the lower temporal opening in lateral view (figure 30D and E). In phylogenetic analyses, *Cedarpelta* variably forms a clade with nodosaurids (Vickyarous and others, 2004) or ankylosaurids (Thompson and others, 2011; Arbour and Currie, 2015) reflecting its potential significance in phylogenerics and paleobiogeography. Much larger diagnostic post-cranial elements of *Cedarpelta* from the PR-2 Quarry indicates that Cedarpelta reach the same large size as *Peloroplites*

Figure 30. Dinosaur fossils from the Ruby Ranch Member. (A) Proximal caudal vertebrae and chevrons from cf. *Tennontosaurus* PR-1 (Utah Em352v). (B) Teeth from cf. *Tennontosaurus* PR-1 (Utah Em352v). C) Teeth from cf. *Tennontosaurus* from upper Ruby Ranch transitional facies just east of Capitol Reef National Park (Utah Wn). (D) Type partial juvenile skull of *Cedarpelta* in dorsal view from the KEM site (Utah Em419v) in the upper Ruby Ranch Member at same horizon but across the valley from main Price River Quarries (figure 27). (E) Same partial holotype skull of *Cedarpelta* in lateral view. (F) *Peloroplites* mounted skeleton in the Utah State University Eastern's Prehistoric Museum in Price, Utah. (G) Prehistoric Museum's exhibit of Cedar Mountain ankylosaur skulls; a) *Peloroplites*, b) *Cedarpelta*, and c) *Gastonia*. (H) Holotype skull of Abydosaurus from Upper Ruby Ranch transitional facies at Dinosaur National Monument (DNM 16). (I) Articulated of mired brachiosaurid sauropods from PR-2 (Utah Em272); a) forefoot, b) hind foot. (J) Brachiosaurid sauropod femurs from PR-2 (Utah Em272). (K) Additional brachiosaurid sauropod femurs from PR-2 (Utah Em272) including from back to front: dorsal vertebrae, cervical vertebrae, and metatarsals.

(Kirkland and Madsen, 2007; Carpenter and others, 2008). With multiple individuals of both taxa preserved at these correlative sites, it raises the question as to how these two gigantic ankylosaurs were nitch partitioning the same habitat?

Sauropods (figure 30I to K) are the dominant taxa at PR-2 and are represented by at least two taxa (R. Barrick, former Director of Prehistoric Museum, personal communication, 2000; K. Carpenter, Prehistoric Museum, personal communication, 2016; and M. Taylor, University College London, personal communication, 2016). The site has also produced some ornithopod material and an indeterminant pterosaur phalanx. A limited amount of large allosauroid theropod material has been collected in these sites as well. A large tooth from PR-3 (Utah Em273) has extremely fine serrations for a tooth that size and seems to be closest to the older genus *Acrocanthosaurus* (Currie and Carpenter, 2000).

In northeastern Utah, a sauropod bonebed in the Cedar Mountain Formation near the Carnegie Quarry at Dinosaur National Monument (DNM 16) has been dated to a maximum of 104 Ma (Chure and others, 2010). This site has yielded four sauropod skulls of *Abydosaurus mcintoshi* (Chure and others, 2010), and part of a dromaeosaurid skeleton (Chure and others, 2007). To the north across DNM, the UGS collected a scrappy ornithopod skeleton (Utah Un153v) that is best referred to cf. *Tenontosaurus*. Another partial skeleton referable to cf. *Tenontosaurus* (figure 30A and B) was collected from the PR-1 site (Utah Em352v) up section from the Price River sites discussed above.

Additional ornithopod partial skeletons tentatively assigned to cf. *Tenontosaurus* have been collected by UGS and Oklahoma Museum of Natural History (OMNH) crews from Ruby Ranch transitional facies in the area east of Capitol Reef National Park. Ludvigson and others (2015) published a U-Pb zircon age of 103.7 ± 2.6 Ma obtained from a volcanic ash (preserved within dinosaur tracks) underlying a particularly interesting lacustrine facies near Muddy Creek that preserves snail opercula, fragments of bony fish, and turtles. The site has also yielded a partial titanosauriform sauropod femur and parts of an allosauroid theropod skeleton that had mostly eroded away (Judd and others, 2013). It is important to note that all of the isolated sauropod teeth found in the Ruby Ranch are slender, spatulate-teeth and may represent several species, often referred to as *Astrodon* or *Pleurocoelus* (Kirkland and others, 1998b; Chure 2000; Coulson and others, 2004; Bird, 2005; Chure and others, 2006, 2010).

Fauna from the Upper Ruby Ranch Member

Osteichthyes
Indet. bones and teeth

Chelonia
Unidentified

Crocodilia
Aquatic goniopholid crocodilians

Pterosauria
Pterosaur indet. (Reese Barrick, Prehistoric Museum, personal communication, 2000)

Dinosauria

Theropoda
cf. *Deinonychus* (Chure and others, 2007)
Large allosauroid cf. *Acrocanthosaurus* based on minute tooth serrations
Large allosauroid with short neural spines (Judd and others, 2013)

Sauropoda
Abydosaurus mcintoshi Chure and others (2010)
At least one maybe two additional taxa (Carpenter and others, personal communication, 2016)

Thyreophora
Cedarpelta bilbyhallorum Carpenter and others (2001)
Peloroplites cedrimontanus Carpenter and others (2008)

Ornithopoda
cf. *Tenontosaurus* sp.

Similar dinosaur faunas are known across much of North America, suggesting these rocks formed 115 to 101 Ma when flowering plants first radiated and came to dominate the world's floras (Kirkland and others, 1998b). The Ruby Ranch dinosaur assemblage includes several taxa known only from North America at this time (slender toothed brachiosaurs, *Tenontosaurus*, and large nodosaurid ankylosaurs). This suggests isolation of North America from the rest of the world as the result of rising sea levels flooding Europe prior to the development of the Alaskan land bridge connecting North America and Asia and as sea levels flood the Dawson Straights in western Canada in the late Albian (Plafker and Berg, 1994; Cifelli and Muzion, 1997; Kirkland and others, 2015; Brikiatis, 2016). The apparent low diversity of dinosaurs across all of North America during this time interval lends further support to the concept of North America as an island continent during the late Early Cretaceous following a middle Aptian extinction event that resulted in the loss of spatulate-toothed sauropods, polacanthid ankylosaurs, and steracosternid iguanodontids (Kirkland and others, 1997, 1998b, 1999, 2013, 2015; Kirkland and Madsen, 2007).

Short Canyon Member

Separating the Ruby Ranch Member from the overlying Mussentuchit Member north of I-70 on the western side San Rafael Swell is a discontinuous series of pebble to cobble conglomerates. These conglomerates were referred to as the "Moore Road Conglomerate" by Kirkland and Madsen (2007), but has recently been named the Short Canyon member as an informal member of the Cedar Mountain Formation (Doelling and Kuehne, 2013b). They designated a type section north of Short Canyon at about 38°58'50.68"N, 111°2'13.70"W. Doelling and Kuehne (2013b) found that the Short Canyon member consisted of up to three conglomerate beds separated by slope-forming sandstone and locally gray to black carbonaceous (and possibly coaly) shale and was best developed near Short Canyon on the northern end of the Short Canyon 7.5-minute quadrangle. Thickness ranges from 12 to 32 m, thickening at the expense of both the Ruby Ranch and Mussentuchit Members. This bed is as distinctive as the underlying Buckhorn Conglomerate with which it is often confused (Kirkland and others 1997; Kirkland and Madsen, 2007). The Buckhorn Conglomerate is also discontinuous in this area and, where present, lacks the distinctive quartzite clasts. The presence of these quartzite-bearing conglomerate beds have been used as a marker for the base of the Naturita Formation (= Dakota Formation) (Lawton and others, 1997, 2007, 2010) and they are a characteristic of the coarse-grained units of the third detrital zircon chronofacies (figure 6) of Hunt and others (2011). In fact, the presence of white, "sugary-looking" quartzite pebbles and cobbles are characteristic of the conglomerates (figure 31). The clasts are derived from the initial unroofing of Ordovician Eureka Quartzite in the Sevier thrust belt and separates the basal Upper Cretaceous from the underlying uppermost lower Cretaceaus strata of the Ruby Ranch Member (Lawton and others, 1997, 2007, 2010; Hunt and others, 2011). A quartzite-rich conglomerate of this same type overlies the Lower Cretaceous (Albian) San Pitch Formation in the Sevier thrust belt foredeep in central Utah marking the base of the Upper Cretaceous (Sprinkel and others, 1999).

At present no fossils of any kind have been recognized from the Short Canyon member other than Paleozoic invertebrates preserved within chert cobbles.

Mussentuchit Member

The Mussentuchit Member forms the top of the Cedar Mountain Formation and is only present along the west side of the San Rafael Swell (figures 4, 5, and 6). In its type area (figure 32) on the southwest side of the San Rafael Swell in the Mussentuchit Wash area, it is separated from the underlying Ruby Ranch Member by a black chert-pebble lag (Kirkland and others, 1999; Kirkland and Madsen, 2007). In the area of the Moore Cutoff Road in the central portion of the western San Rafael Swell, it is separated by a cobble conglomerate as much as 5 m thick and characterized by abundant quartzite clasts, and informally designated the Short Canyon member of the Cedar Mountain Formation (Doelling and Kuehne, 2013b).

The upper contact of the Mussentuchit Member, and the Ruby Ranch Member to the east, is overlain by the Naturita Formation (= Dakota Formation). Where the Naturita has been removed by Late Cretaceous erosion, the base of the Tununk Member of the Mancos Shale includes a darkly stained chert and quartzite pebble lag mixed with shallow, open-marine oysters (*Pycnodonte newberryi* subundata) characteristic of the basal Turo-

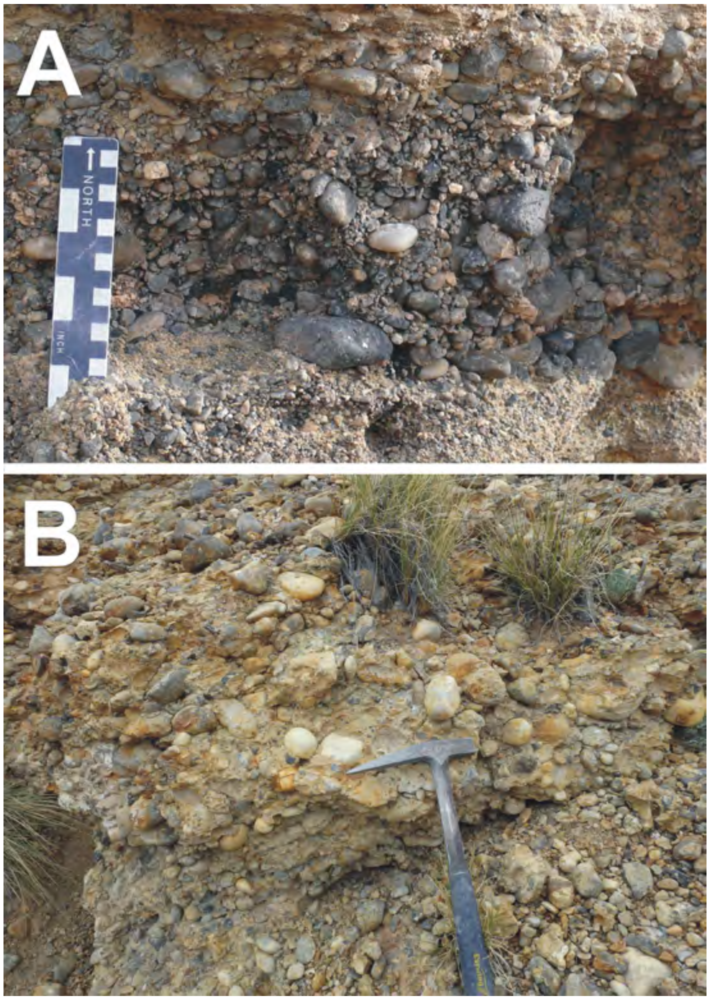

Figure 31. Quartzite-rich conglomerate beds forming the base of the upper Cedar Mountain chronofacies 3 of Hunt and others (2011); the Muddy-Mowry sequence of Ludvigson and others (2010b). (A) The basal Naturita conglomerate on the Poison Strip Bench east of Doelling's Bowl. Note the "snowy" white Eureka Quartzite pebble near center of picture. (B) The Short Canyon member on the south side of the Moore Cutoff Road with an abundance of Eureka Quartzite pebbles.

nian (Kirkland, 1996; Leckie and others, 1997; Kirkland and Madsen, 2007). These marine conglomeratic units also cap the Naturita Formation (= Dakota Formation) in this area, indicating that as sea level rose in the latest Cenomanian, uplift along the general trend of the San Rafael Swell exceeded sea level rise with subsequent coastal erosion through to the basal Naturita conglomerate, which continued to be reworked across the area by storm waves even after the sea had submerged the area (Eaton and others, 1990; Kirkland and Madsen, 2007).

The Mussentuchit Member is characteristically distinguished by the abundance of smectitic clays (altered volcanic ash) in its mudstone beds, a near absence of carbonate nodules, and the local presence of lignite (low-grade coal) beds (Kirkland and others, 1997, 1999). Locally, the smectite is so pure that these swelling clays are mined for this industrial material. A radiometric age of 98.37 ± 0.07 Ma was obtained by the OMNH from volcanic ash within the Mussentuchit Member (Cifelli and others, 1997, 1999). Additional ages by Garrison and others (2007) ranging from 96.7 ± 0.5 to 98.2 ±0.6 Ma indicate that the Mussentuchit Member was deposited over an interval of 1.5 Ma during the early Cenomanian and supports a correlation with the siliceous marine Mowry Shale to the north, which 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; Ogg and Hinnov, 2012; Sprinkel and others, 2012) near the base of the Upper Cretaceous.

Where radiometrically dated, isolated outcrops of smectitic strata mapped by UGS geologists as Cedar Mountain Formation in southwestern Utah (figure 1) are all of latest Albian to earliest Cenomanian age (Biek and others, 2009, 2010, 2015; Hylland, 2010). Therefore, these strata correlate to the Mussentuchit Member, which they most closely resemble lithologically.

In addition to being a basal mudstone unit restricted to the foreland basin, the Mussentuchit Member represents the terrestrial strata equivalent to the basal Cenomanian Muddy-Mowry Marine Cycle (Ludvigson and others, 2010b) and is equivalent to the Wayans Formation in the foredeep of eastern Idaho (Krumenacker, 2010; Krumenacker and others, 2016). This member is also equivalent to fossiliferous strata occurring in piggyback basins within the Sevier thrust belt. The Willow Tank Formation at Valley of Fire State Park in southern Nevada preserves a dinosaur fauna that may include Eolambia (Bonde and others, 2008, 2012).

Recently acquired high-precision U-Pb zircon ages obtained from the middle carbonaceous interval of the Naturita Formation (= Dakota Formation) at the pa-

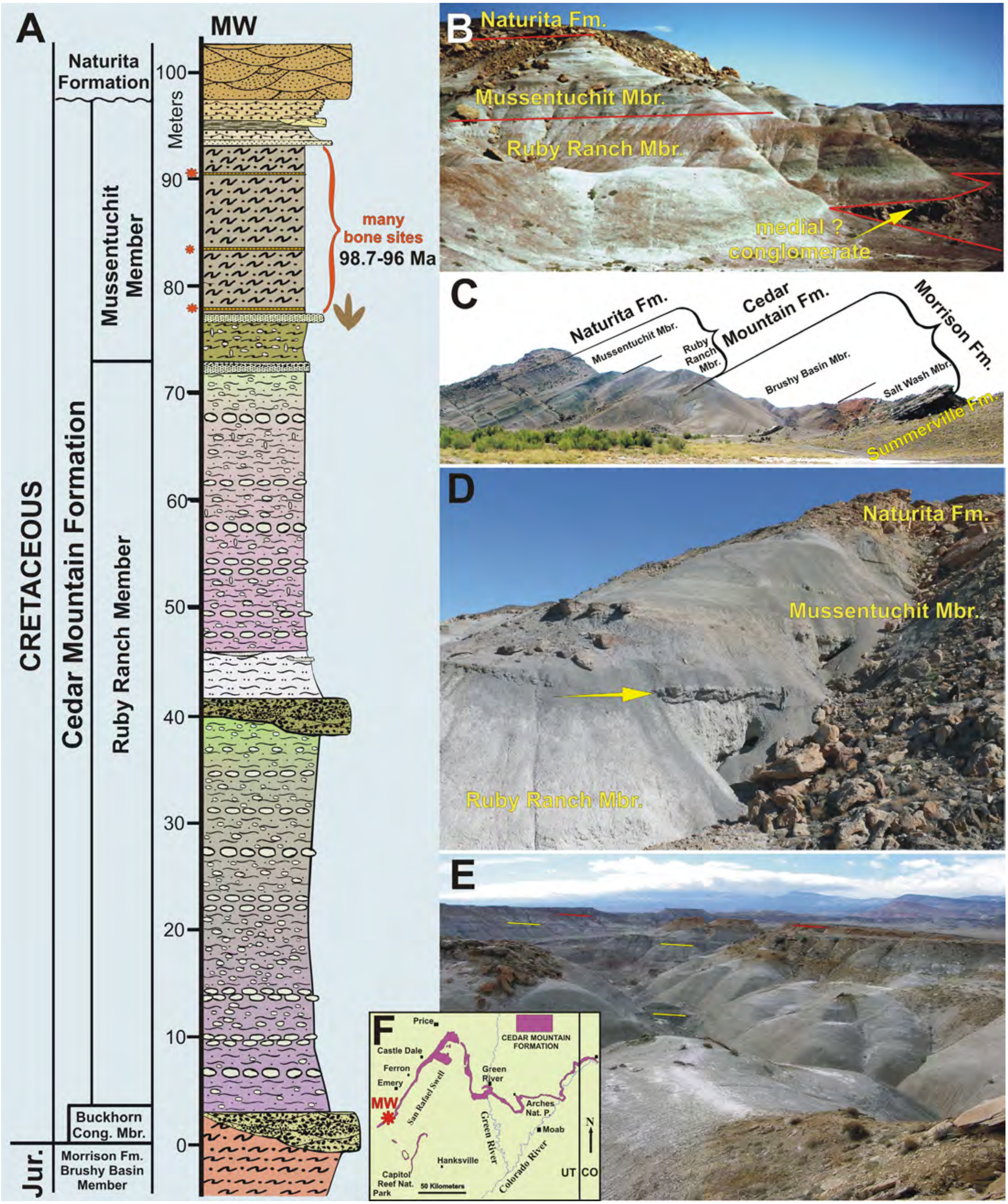

Figure 32. Caption on following page.

Figure 32 (figure on previous page). Mussentuchit Member of the Cedar Mountain Formation in the Mussentuchit Wash area. (A) Revised type section (MW) reflecting the thicker Ruby Ranch Member measured from 38°39'46.47"N, 111°15'31.31"W to 38°39'47.66"N, 111°15'39.66"W. (B) Type section of the Mussentuchit Member on the south side of Mussentuchit Wash viewed from the south. (C) Well exposed section of the Cedar Mountain Formation along the Last Chance monocline viewed from the west (38°39'32.73"N, 111°17'52.72"W). (D) Well-exposed section of the Mussentuchit Member in Mussentuchit Wash. (E) Looking south across Mussentuchit Wash with yellow dashes indicating the Ruby Ranch-Mussentuchit contact and the red dashes indicating the position of the Naturita Formation which pinches out locally in this area. (F) Index map showing the location of the Mussentuchit Wash area.

leobotanical sites near Westwater in eastern Utah range from 97.95 +0.037 -0.12 Ma to 97.601 +0.049 -0.13 Ma and overlap with those from the Mussentuchit. Whereas, ages obtained from the middle carbonaceous interval of the Naturita Formation (= Dakota Formation) from the eastern Kaiparowits Basin in southern Utah are younger than the Mussentuchit ages (Barclay and others, 2015). This once again validates Young's (1960) theories regarding the west to east transition from more inland to more coastal facies along time lines (marker sandstones) or as currently viewed within sequence stratigraphic architecture.

It is difficult for some geologists to reason why the Mussentuchit Member in its type area was separated from the underlying Ruby Ranch Member. Were it not for the pebble lag at the base of the Mussentuchit, indicating the position of a sequence boundary, many of our colleagues would not have accepted it as being worthy of separation. North of I-70 along the Moore Cutoff Road, the Short Canyon member makes the break obvious (Doelling and Kuehne, 2013b). This unit pinches out to the north, reappears, and pinches out again. It is not until the outcrop reaches the latitude of Castle Dale and the Cleveland Lloyd Quarry that the conglomerate becomes continuous and part of the Naturita Formation proper (= Dakota Formation). There is still a proper smectitic mudstone interval that is characteristic of the Mussentuchit Member up section from the basal Naturita conglomerate in this area (Kirshbaum and Schenk, 2011; Sorenson, 2011). Clearly, the Musentuchit interfingers into the Naturita (= Dakota) to the north. This pattern has led geologists working on the Naturita Formation (= Dakota Formation) to look at these strata from the top down, while the geologists working on the Cedar Mountain Formation look at these strata from the bottom up. The solution to this is to consider the Mussentuchit as a member of the Cedar Mountain Formation in the south and to be a member of the Naturita Formation (= Dakota Formation) in the north, in much the same way that the Smoky Hill is a member of the Niobrara Chalk on the Great Plains, but is considered to be a member of the Mancos Shale in western Colorado (Hattin, 1982; Leckie and others, 1997).

Flora and Fauna of the Mussentuchit Member

The Mussentuchit Member has yielded significant paleobotanical materials. These materials include a diversity of unique fossil wood taxa including what had been interpreted as some of the oldest known angiosperm wood (Thayne and others, 1983, 1985; Thayne and Tidwell, 1984; Tidwell and Thayne, 1985; Tidwell, 1996). The only palynomorph assemblages described from the Cedar Mountain Formation are from these rocks and were considered to indicate an Albian age (Tschudy and others, 1984; Garrison and others, 2007) prior to the lower placement of the Albian-Cenomanian boundary based on ammonite correlations with the type Cenomanian in Europe (Cobban and Kennedy, 1989; Nichols and Sweet, 1993; Ogg and Hinnov, 2012). However, one recent paper (Arens and Harris, 2015) on an angiosperm-dominated flora from the northeastern side of the San Rafael Swell almost certainly pertains to the overlying Naturita Formation (= Dakota Formation) and not the Cedar Mountain Formation (Mike Leschin, BLM geologist, personal communication, 2015).

The OMNH have been using wet screen-washing techniques (Cifelli, 1996; Cifelli and others, 1997, 1999) to recover tiny fossil mammal remains from microvertebrate sites in the Mussentuchit Member (figure 33). Most of these sites are in the type area of the Mussentuchit Member on the southwest side of the San Rafael Swell. Other researchers have conducted less ambitious screen washing programs to the north in the Mussentuchit east of Ferron and Castle Dale (Nelson and Crooks, 1987; Eaton, 1987; Fiorillo, 1999). By sorting the bone residues generated in this way, more than 90 species have been recognized (Cifelli and others, 1997, 1999;) including a diversity of fish (Kirkland and others, 1997, 2013b; Fiorillo, 1999; Garrison and others, 2007), frogs (Cifelli and others, 1997; Gardner and DeMar, 2013), albanerpetonids (Gardner, 1999), salamanders (Gardner and DeMar, 2013), turtles (Cifelli and others, 1997; Fiorillo, 1999; Herzog and others, 2015), lizards (Cifelli and Nydam, 1995; Nydam, 1999, 2000, 2002, 2013), some of the oldest North American snakes (Gardner and Cifelli, 1999), crocodilians (Cifelli and others, 1997; Fiorillo, 1999; Garrison and others, 2007), bird teeth (Cifelli and others, 1997), and mammals (Eaton and Nelson, 1991; Cifelli and Muizon, 1997; Cifelli and Madsen, 1998, 1999; Eaton and Cifelli, 2001; Cifelli and others, 2016), including the world's oldest and most primitive marsupials (Cifelli, 1993, 2004; Cifelli and Muizon, 1997). This is one of the most diverse terrestrial faunas in the Mesozoic of North America (Eaton and Kirkland, 2003) with 22 species of mammals alone (Cifelli and others, 2016). Additionally, no other fauna of this age has ever been found anywhere else in the world. A wealth of dinosaur teeth have also been recovered with Ornithischia represented by ankylosaurid and nodosaurid ankylosaurs, several ornithopod taxa (a new small species, *Tenontosaurus*, and *Eolambia*), dome-headed pachycephalosaurs, and primitive horned dinosaurs (Cifelli and others, 1997, 1999; Kirkland and others, 1997; Chinnery and others, 1998; Kirkland and others, 1998b). Tiny, slender brachiosaurid sauropod teeth (figure 33G) represent the last known sauropods in North America until the titanosaurid *Alamosaurus* appeared more than 30 million years later in the North Horn Formation as an immigrant back into North America (Maxwell and Cifelli, 2000; Kirkland and Madsen, 2007). Meat-eating dinosaur teeth are diverse and abundant, including primitive coelurosaurs, troodontids, dromaeosaurine and velociraptorine dromaeosaurids, and North America's earliest known tyrannosau-

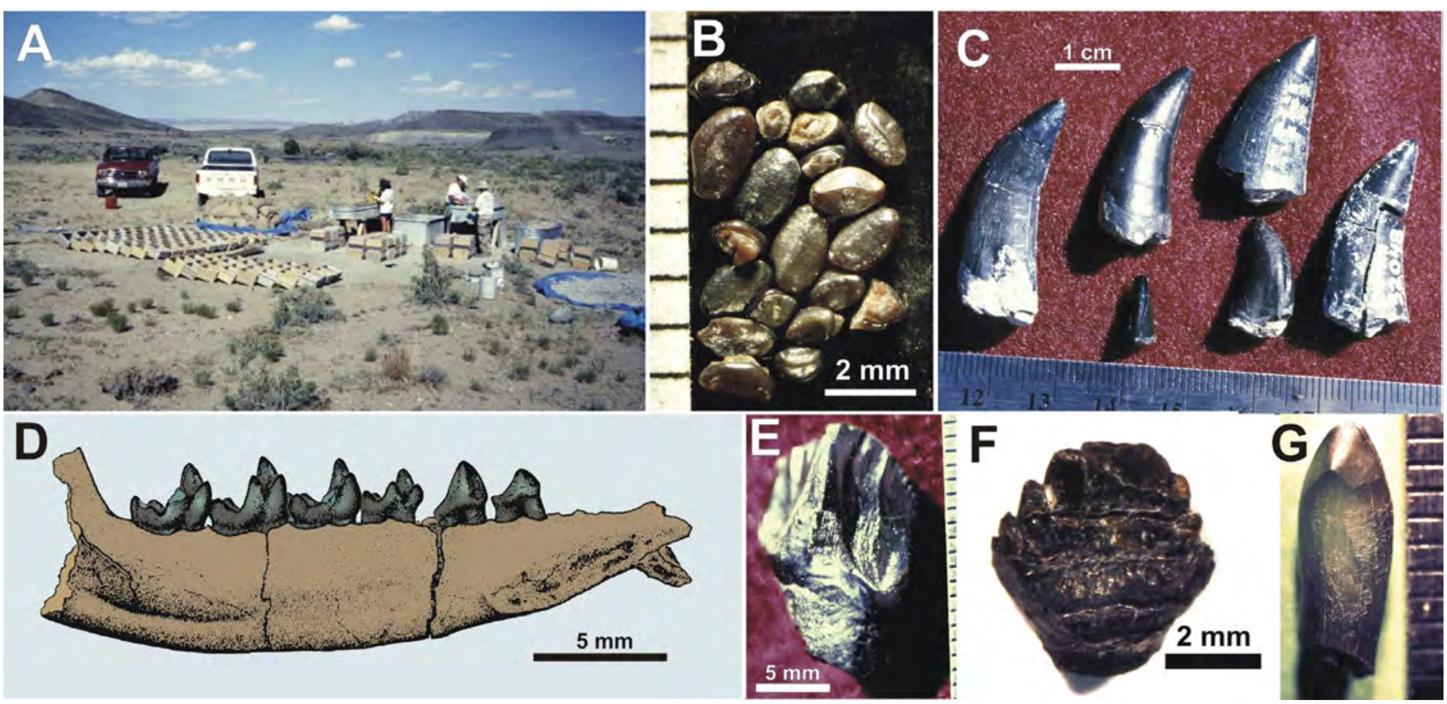

Figure 33. Oklahoma Museum of Natural History's microvertebrate project. (A) OMNH's screen-washing station. (B) Teeth of the freshwater pavement toothed guitarfish *Cristomylus nelson*. (C) Tyrannosaurioid teeth, smallest tooth is a diagnostic premaxillary tooth. (D) Jaw of early marsupial *Kokopellia juddi* courtesy of Rich Cifelli (OMNH). (E) Neoceratopsian tooth. (F) Nodosaurid tooth, perhaps *Animantarx*. (G) Small slender-toothed brachiosaurid sauropod tooth. Tick marks are in mm.

rids (figure 33C). Suarez and others (2012) obtained abundant stable isotope data from these microvertebrate sites (see geochemistry section below).

Only two dinosaur species from the Mussentuchit Member are so far represented by relatively complete skeletons (holotypes now housed in the collections of the Utah State University Eastern's Prehistoric Museum in Price, Utah) (figure 34). They are named for a husband/wife team of amateur paleontologists from Castle Dale, Utah. The advanced iguanodont ornithopod *Eolambia caroljonesa* (Kirkland, 1998b; Head, 2001; McDonald and others, 2012a) was named for Carol Jones,

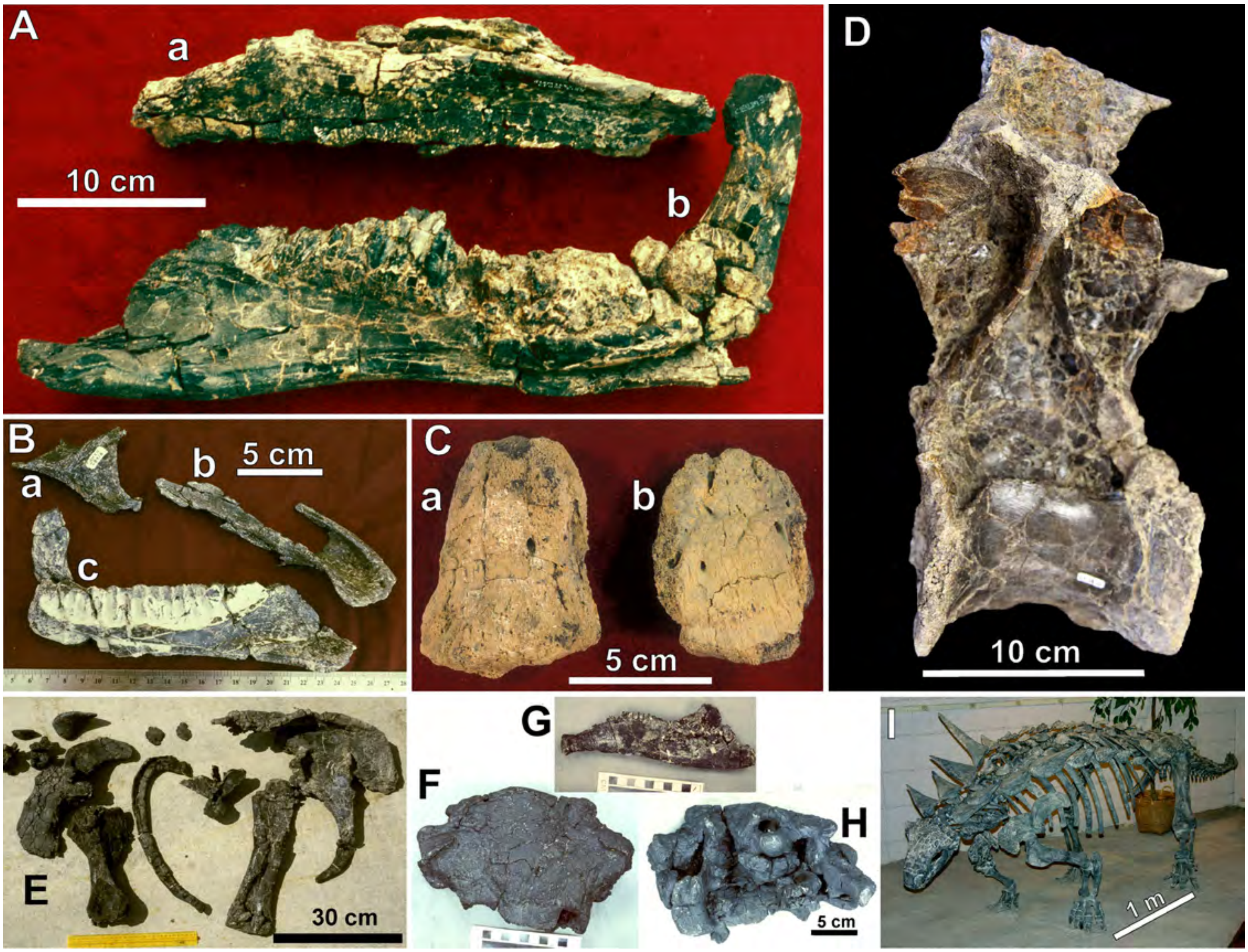

Figure 34. Dinosaurs from Mussentuchit Member of the Cedar Mountain Formation. (A) Jaws of holotype *Eolambia caroljonesa* from Carol site, northwestern San Rafael Swell in CEU collection, a) left maxilla, b) right dentary. (B) Juvenile *Eolambia* from Mussentuchit area, southwestern San Rafael Swell in OMNH collection, a) left squamosal, b) right premaxilla, c) left dentary. (C) Adult *Eolambia* manual unguals from Cifelli I site (= *Eolambia* 1 site), Mussentuchit area in CEU collection, a) "thumb-spike," b) typical manual ungual. (D) Holotype dorsal vertebra of the large neoventorid allosauroid *Siats meekerorum* in collection of the Chicago Field Museum of Natural History. Photo courtesy of Lindsay Zanno (North Carolina Museum of Natural History). (E–I) Holotype of *Animantarx ramaljonesi* from Carol site, northwestern San Rafael Swell in CEU collection. (E) Postcranial skeleton (F) Dorsal view of partial skull. (G) Lower jaw. (H) Ventral view of partial skull. (I) Reconstructed skeleton on exhibit at Utah State University Eastern's Prehistoric Museum constructed by Gastondesign.

who discovered the Carol site east of Castle Dale. The late University of Utah radiological technician Ramal Jones discovered the skeleton of the primitive nodosaurid ankylosaur, *Animantarx ramaljonesi* (Carpenter and others, 1999), as part of a highly refined radiological survey made of the Carol site (Jones and Burge, 1998). This is the only dinosaur ever discovered by technology alone. Fragments of a large neovenatorid allosauroid, *Siats meekerorum* (figure 34D), have recently been described by Zanno and Makovicky (2013).

Dinosaur eggshell is fairly common in the Mussentuchit Member and includes some of the first fossil eggshell material recognized in North America (Jensen, 1970; Bray, 1998). *Botetuoolithus carlyensis* was reassigned to the oogenus *Macroelongolithus* (Zelenitsky and others, 2000), which has subsequently been shown to represent the eggshell of the huge (10 m) Asian caenegnathid oviraptoroid *Gigantoraptor* (Paul, 2010, p. 153). Recently, Makovicky and others (2014) have recovered skeletal remains verifing the presence of a giant caenegnathid oviraptoroid nearly as large as *Gigantoraptor* in the Mussentuchit Member as indicated by the fossil eggshell.

The Mussentuchit fauna is particularly interesting in that it is the oldest dinosaur fauna with representatives of each family characteristic of the remainder of the Late Cretaceous in North America (Cifelli and others, 1997), in addition to preserving a few last examples of Early Cretaceous dinosaurs (basal titanosaurimorph sauropods and cf. *Tenontosaurus*). The direct ancestors of the tyrannosaurids, the derived hadrosauroid iguanodont *Eolambia*, and the marsupials have Asian affinities. Therefore, their presence in the basal Cenomanian of Utah suggests that these rocks document the first immigration of animals across the Alaskan land bridge. This event may have led to an immigration-induced extinction of many of North America's "homegrown" (endemic) dinosaur groups (Cifelli and others, 1997; Kirkland, and others, 1997, 1998b, 1999, 2015; Kirkland, 2005a, b; Kirkland and Madsen, 2007). The Alaskan land bridge has remained an important migration corridor for life on land in the Northern Hemisphere periodically to the present day. As the Mussentuchit Member appears to preserve a mixture of Early and Late Cretaceous dinosaurs, it has been said that Utah's dinosaurs are dating the origin of Alaska, having caught the immigration-induced extinction in the act. The thick Cedar Mountain Formation sections exposed along the western margin of the San Rafael Swell preserve dinosaurs at several stratigraphic levels and have the potential to document this immigration-induced faunal turnover in considerable detail.

Vertebrate Fauna from the Mussentuchit Member

Chondrichthyes
Hybodontidae?
Hybodus? sp. (Fiorillo, 1999)

Polyacrodidae
Lonchidion n. sp.? (Kirkland and others, 2013)

Orectolobidae
Cretorectolobus sp. (Fiorillo, 1999)

Rhinobatidae
Rhinobatis? sp. (Cifelli and others, 1997, 1999)
Cristomylus nelsoni Kirkland and others (2013)

Scelerorhynchiidae
Texatrygon n. sp. (Cifelli and others, 1999, in sense of Kirkland and others [2013])

Osteichthyes
Neopterygii
gen. and sp. indet.

Semionotidae
n. gen. n. sp. (double spined dorsal ridge scales)

Lepisosteiformes
?Lepisosteidae
gen. and sp. indet. (Garrison and others, 2007)
?Pycnodontidae
gen. and sp. indet. (Garrison and others, 2007)

Amiiformes
gen. and sp. indet. (Garrison and others, 2007)
Dipnoi

Neoceratodontidae
Ceratodus sp. cf. C. *frasieri* (Kirkland, 1987)

Lissamphibia
Albanerpetontidae

Albanerpeton sp. cf. *A. nexuosum* (Gardner and DeMar, 2013)
gen. and sp. indet. (Gardner and DeMar, 2013)

Urodela
Scapherpetontidae 2 n. gen. and spp. (Cifelli and others, 1997; Gardner and DeMar, 2013)

Anura
Family incertae sedis
gen. et sp. indet. (multiple taxa)

Sauropsida
Chelonia
Baenidae
gen. et sp. indet. (Cifelli and others, 1997)

Solemydidae
cf. Naomichelyssp.

Glyptopsidae
Glyptops sp. (Cifelli and others, 1997)

Trionychidae
gen. and sp. indet. (Fiorillo, 1999)

Squamata
Teiidae
Bicuspidon numerosus Nydam and Cifelli (2002)
Dicothodon moorensis Nydam (1999)
Harmodontosaurus emeryensis Nydam (2002)
Dicothodon sp. (Nydam, 1999)

?Paramacellodidae
cf. *Pseudosaurillus* sp. (Nydam, 2002)

Scincoidea
Dimekodontosaurus madseni Nydam (2002)
Bothriagenys mysterion Nydam (2002)
gen. and sp. indet. (Nydam, 2002)

Anguidae
(2) indet. spp.

Monstersauria
Primaderma nessovi Nydam (2000)

Serpentes
Aniliidae
Coniophis sp. (Gardner and Cifelli, 1999)
gen. et sp. indet.

Crocodilia
Bernissartidae
Bernissartia (2) sp. (Garrison and others, 2007)

Goniopholidae
cf. *Dakotasuchus* sp. (Cifelli and others, 1997)
Polydectes sp.

Atoposauridae
gen. and sp. indet. (Garrison and others, 2007)

Teleosauridae
Machimosaurus sp. (Cifelli and others, 1997)
gen. and sp. indet. (Cifelli and others, 1997)

Pholidosauridae
gen. and sp. indet. (Garrison and others, 2007)

Dinosauria
Theropoda
Neoventordae
Siats meekerorum Zanno and Makovicky (2013)

Tyrannosauroidea
gen. and sp. indet. (Zanno and Makovicky, 2013)

Caenagnathoidea
giant n. sp. (Makovicky and others, 2014)

Dromaeosauridae
gen. and sp. indet. dromaeosaurine
gen. and sp. indet. velociraptorine

Troodontidae
? gen. and sp. indet. (Cifelli and others, 1997)

Family indet.
Richardoestesia sp. cf. *R. isosceles* (Garrison and others, 2007)

Family indet.
cf. *Paranychodon* sp. (Garrison and others, 2007)

Avialae
Hesperornithiformes
gen and sp. indet. (Cifelli and others, 1997)

Order indet.
Gen. and sp. indet. (Cifelli and others, 1997)

Sauropoda
Titanosaurimorpha
cf. *Astrodon* sp. (Maxwell and Cifelli, 2000)

Ornithopoda
Basal Ornithopoda
Gen. and sp. new (Makovicky and Zanno, in press)

Orodrominae
gen. and sp. new (Makovicky and others, 2014)

Iguanodontia (basal)
cf. *Tenontosaurus* sp. (Kirkland and others, 1997, 1999; Kirkland and Madsen, 2007)

Hadrosauridiformes
Eolambia caroljonesa Kirkland (1998b)

Ankylosauria
Nodosauridae
Animantarx ramaljonesi Carpenter and others (1999)

Pachycephalosauria
Family indet.
gen. and sp. indet. (Cifelli and others, 1997)

Ceratopsia
Neoceratopsia
gen. and sp. indet. (Chinnery and others, 1998; Carpenter and Cifelli, 2016)

Mammalia
gen. and sp. indet.

Eutriconodonta
Triconodontidae
Astroconodon delicatus Cifelli and Madsen (1998)
Corviconodon utahensis Cifelli and Madsen (1998)
Jugulator amplissimus Cifelli and Madsen (1998)

Multituberculata
?Plagiaulacidae
gen. et sp. indet.

Neoplagiaulacidae
?*Mesodma* sp. (Eaton and Cifelli, 2001)

Family incertae sedis
Janumys erebos Eaton and Cifelli (2001)
cf. *Paracimexomys perplexus* Eaton and Cifelli (2001)
Dakotamys robisoni (Eaton and Nelson, 1991)
Bryceomys intermedius Eaton and Cifelli (2001)
Cedaromys bestia (Eaton and Nelson, 1991)
Cedaromys parvus Eaton and Cifelli (2001)
Ameribaatar zofiae Eaton and Cifelli (2001)

Trechnotheria
Spalacotheriidae
Spalacolestes cretulablatta Cifelli and Madsen (1999)
Spalacolestes inconcinnus Cifelli and Madsen (1999)
Spalacotheridium noblei Cifelli and Madsen (1999)

?Spalacotheriidae
gen. et sp. indet.

Tribosphenida
Family incertae sedis
Dakotadens pertritus Cifelli and others (2016)
Culicolestes kielanae Cifelli and others (2016)

Metatheria
?Stagodontidae
Pariadens mckennai Cifelli (2004)

Family incertae sedis
Adelodelphys muizoni Cifelli (2004)
Kokopellia juddi Cifelli (1993)
Sinbadelphys schmidti Cifelli (2004)

GEOCHEMICAL STUDIES OF THE CEDAR MOUNTAIN FORMATION IN EAST-CENTRAL UTAH

Geochemical data pertaining to the Cedar Mountain Formation are mostly centered in east-central Utah and can be grouped into two types of data. One group includes data relating to chemostratigraphy for which the goal is correlation between sections within the Cedar Mountain Formation and to better dated marine sequences. The principle behind C-isotope chemostratigraphy is related to the fact that the carbon cycle during the Cretaceous experienced a number of perturbations (likely a result of phases of volcanic eruptions and oceanic crust production as well as abundant carbon burial) that led to changes to the $\delta^{13}C$ of ocean-atmosphere system (Scholle and Arthur, 1980). These changes are reflected in all of the interacting reservoirs of the carbon cycle including sedimentary organic carbon and carbonate carbon. A good overview of C-isotope chemostratigraphy, especially as it pertains to use in continental strata, can be viewed in Ludvigson and others (2010a, 2015) and references therein.

The second group is primarily stable isotope data of various materials including carbonate beds and nodules (lacustrine, palustrine, and pedogenic), and vertebrate tooth enamel, ganoine scales, scutes, and bone. These data pertain to elucidating paleoenvironmental and paleoclimatic conditions of the Cedar Mountain Formation. Table 1 provides a summary of the data detailed in the sections below.

Lower Yellow Cat Member

Chemostratigraphy

Carbon isotope profiles of bulk sedimentary organic carbon have been constructed from a number of localities in eastern Utah (Suarez and others, in press) for both the lower and upper Yellow Cat Member. These localities include Doelling's Bowl, a section near Andrew's site (YC), the locality termed "Lake Madsen" (figure 18), and a site off the Yellow Cat Road. The results of these carbon isotope profiles, however, were ambiguous, and correlation was initially based off the appearance of the regional calcrete. From overall trends in the carbon isotope record, the lower Yellow Cat Member is tentatively correlated to the Barremian. The C-isotope record of the Barremian is relatively constant indicating no major C-cycle perterbations; however, at the beginning and end of the Barremian, the Faroni and Taxy events respectively occur. Globally, these two events are thought to correspond to warm humid episodes. Overall, however, the Barremian globally is thought to have been cool and arid.

Paleoclimate

Geochemical paleoclimate proxies for the lower Yellow Cat Member are somewhat limited owing to the fact that the recognition of the "lower" Yellow Cat Member is relatively recent. In addition, typical climate archives used for interpretations such as soil carbonates are not present in the lower Yellow Cat Member. Suarez and others (2014) used the oxygen isotopic composition of phosphate from a variety of taxa to suggest that the oxygen isotopic composition of meteoric water was relatively enriched during the deposition of the lower Yellow Cat Member (-4.2‰ vs. Vienna Standard Mean Ocean Water [VSMOW] based on semi-aquatic taxa, specifically crocodilia). Herbivorous dinosaurs such as sauropods consumed rather isotopically enriched water (-3.4‰), likely due to physiological effects, and iquanodontids consumed isotopically light waters (-9.3‰), likely due to consumption of isotopically depleted river water drained from the Mogollan highlands. Some turtle material from UMNH 1208 (figure 16F) have been recovered and await analyses for $\delta^{18}O$ of phosphate.

Recent data from Hatzell (2015) pairs the $\delta^{13}C$ of tooth enamel with $\delta^{13}C$ of bulk sedimentary organic matter to calculate mean annual temperature from equations derived from Kohn (2010) and Diefendorf and others (2010). Hatzell (2015) suggests the mean annual precipitation (MAP) for the Cedar Mountain Formation was 850 mm/yr. If correct, such rainfall amounts could have supported forests. Demko and others (2004) have described the paleosol at the top of the Morrison Formation, but as mentioned above, we suggest the strata making up these paleosols are Creteceous. The presence of redoximorphic characteristics, iron accumulations, and lack of carbonates suggest wetland or at least seasonally saturated conditions. While this seems slightly wetter than the estimates of Hatzell (2015), it is still consistent with the carbon isotope-derived MAP estimate. Depending on the age of pedogenesis, the wetland soils may be consistent with globally warm and humid episodes associated with either the Taxy or Faroni events (Föllmi, 2012).

Table 1. Summary of data types and key interpretations for each of the members of the Cedar Mountain Formation. See text for details and references. Abbreviations used: DB = Doelling's Bowl; PR2 = Price River 2 locality; RRR = Ruby Ranch Road; YCR = Yellow Cat Road; NAS = Near Andrew's site (UMNH 1207); LM = Lake Madsen; LC =Lake Carpenter; CIE = carbon isotope excursion; VSMOW = Vienna Standard Mean Ocean Water; ppmV = parts per million by volume; MW = meteoric water.

Member	Chemostratigraphy	Temperature	Hydrology	*p*CO_2
Lower Yellow Cat	DATA: bulk organic C from DB, NAS, LM, YCR INTERPRETATION: Inconclusive, though tentatively correlated to Barremian to lower Aptian	DATA: no geochemical data currently exists	DATA: $\delta^{18}O_{PO4}$; $\delta^{13}C$ of bioapatite; and $\delta^{13}C$ bulk sedimentary organic carbon. INTERPRETATION:$\delta^{18}O_{mw}$ range from -2.9‰ (allosauroid) to -9.3‰ (iguanodontid) vs VSMOW; $\delta^{13}C$ derived MAP = 850 mm/year	DATA: no geochemical data currently exists
Upper Yellow Cat	DATA: bulk organic C from DB, NAS, LM, YCR; carbonate C from YCR INTERPRETATION: Inconclusive, though tentatively correlated to Barremian to lower Aptian	DATA: $\delta^{18}O_{CO3}$undifferentiated by member; Δ_{47} (clumped isotope) data from carbonate nodule from NAS INTERPRETATION: temperature of carbonate formation averages 27.5°C for undifferentiated nodules; Δ_{47} derived temperature = 34°C	DATA: $\delta^{18}O_{PO4}$; $\delta^{13}C$ of bioapatite; $\delta^{13}C$ of bulk sedimentary organic carbon; Δ_{47} derived data from NAS INTERPETATION:$\delta^{18}O_{mw}$ range from -8.1‰ (turtle scute) to -5.4‰ (*Utahraptor*) vs VSMOW;$\delta^{18}O_{mw}$ = -4‰ vs VSMOW from Δ_{47} derived temperature; $\delta^{13}C$ data used to estimate MAP of 455 mm/yr.	DATA: $\delta^{13}C_{CO3}$ INTERPRETATON: 1900 to 3500 ppmV
Poison Strip Member	DATA: carbonate C from RRR INTERPRETATION: Aptian	DATA: $\delta^{18}O_{CO3}$ data from RRR INTERPRETATION: No temperature have been estimated from these data	DATA: $\delta^{18}O$ of carbonate data from RRR; $\delta^{18}O$ derived data from lacustrine oncoids from Woodside anticline INTERPRETATION: $\delta^{18}O_{mw}$ = -7 to -9‰ vs VSMOW from lacustrine oncoids	DATA: $\delta^{13}C_{CO3}$ INTERPRETATION: 1179 ppmV
Ruby Ranch	DATA: carbonate C from RRR, PR2; bulk organic C and carbonate C from LC INTERPRETATION: upper Aptian to lower Albian. More specifically, carbon isotope segments include the C10 CIE	DATA: $\delta^{18}O_{CO3}$ from RRR, PR2, LC INTERPRETATION: No temperatures have been estimated from these data	DATA: $\delta^{18}O_{CO3}$; $\delta^{18}O_{PO4}$; $\delta^{13}C$ of bioapatite; $\delta^{13}C$ of bulk sedimentary organic carbon INTERPRETATION: Meteoric Calcite Lines and independent latitudinal temperature gradients used to estimate $\delta^{18}O_{mw}$ = -6‰ vs. VSMOW; Positive Linear Covariant Trends suggest significant precipitation deficits especially in C10 CIE interval at PR2. $\delta^{18}O_{mw}$ range from -15.5‰ (ornithischians) to -2‰ vs VSMOW (allosauroid). $\delta^{13}C$ data used to estimate MAP = 643 mm/year	DATA: $\delta^{13}C_{CO3}$ INTERPRETATION: range from 746 to 1335 ppmV, with peak at the C10 CIE.
Mussentuchit	DATA: no C-isotope stratigraphy currently available	DATA: No geochemical data currently available, though leaf physiognomy data exists INTERPRETATION: 16°C to 26°C.	DATA: $\delta^{18}O_{PO4}$; $\delta^{13}C$ of bioapatite and bulk sedimentary organic C. Leaf physiognomy data INTERPRETATION: $\delta^{18}O_{mw}$ averages about -6‰ but is as light as -9.3‰ vs VSMOW. MAP estimated from $\delta^{13}C$ proxies = 1278 mm/year; MAP based on leaf physiognomic proxies = 810 mm/year	DATA: no geochemical data currently available

Upper Yellow Cat Member

Chemostratigraphy

The carbon isotope profiles described above also extend into the upper Yellow Cat Member (Suarez and others, in press). The tentative correlation of the upper Yellow Cat Member is Barremian to lower Aptian. The prominent negative isotope excursion (C3 isotope segment of Menegatti and others, 1998) in the lower Aptian has yet to be confirmed in the existing chemostratigraphic profiles; however, the excursion has been tentatively identified in the Yellow Cat Road section in the uppermost Yellow Cat and lower Poison Strip Member. This dramatic carbon isotope excursion globally is thought to represent a significant disturbance to the carbon cycle, an increase in atmospheric CO_2 due to volcanism, and a warm humid phase (Föllmi, 2012).

Paleoclimate

One of the distinguishing characteristics of the upper Yellow Cat Member is the abundant carbonate nodules interpreted as pedogenic carbonates. One carbonate nodule from the NAS section has been analyzed in duplicate for Δ47, a measure of the abundance of ^{13}C-^{18}O bonds in the carbonate. The abundance of these bonds (multiply substituted isotopologues or "clumped isotopes") is a relatively new and exciting opportunity to determine temperature using stable isotopes without having to assume the oxygen isotopic composition of precipitating fluid (Ghosh and others, 2006; Schauble and others, 2006; Eiler, 2011; Eagle and others, 2013). Preliminary clumped isotope analysis of this carbonate nodule from the NAS provides a temperature of 34°C (Suarez and Passey, 2014). Clumped isotope temperatures are known to generally be warm season biased (Passey and others, 2010) so mean annual air temperatures would likely have been lower. Skipp (1997) also utilized stable isotopes of carbonate nodules to estimate temperature (using assumptions about $\delta^{18}O$ of water). While Skipp (1997) does not use the member nomenclature used here, the stratigraphic descriptions suggest that most of the nodules come from the upper Yellow Cat Member. Temperature estimates of Skipp (1997) average 27.5°C, much cooler than the clumped isotope derived estimate. This may not be a very large discrepancy considering the various assumptions necessary for the estimates of Skipp (1997) and the warm season bias of the clumped isotope paleothermometer. Recently, Suarez and Passey (2014) investigated the possibility of utilizing bone carbonate clumped isotopes as a substitute for soil carbonates. However, it would appear that bone carbonate is much more susceptible to burial diagenetic conditions and the clumped isotope temperature derived from a sauropod bone fragment from the Dalton Wells Quarry resulted in a temperature of about 51°C.

An additional advantage to the clumped isotope paleothermometer is the fact that the Δ47 derived temperature and the $\delta^{18}O$ of carbonate (determined during the analysis of Δ47) can be used to determine the $\delta^{18}O$ of the precipitating fluid (meteoric water). Based on the preliminary analysis of carbonate nodules, this is -4‰ vs. VSMOW, which is more enriched than estimates based on lacustrine oncoids from the Woodside anticline by Shapiro and others (2009), that range from as low as -9‰ to -7‰ vs. VSMOW. Phosphate $\delta^{18}O$ of Suarez and others (2014) has somewhat similar values. These estimates range from 8.1‰ vs. VSMOW for turtle (likely aquatic to semi-aquiatic) to -5.4‰ vs. VSMOW for *Utahraptor*. The more enriched value for the soil carbonate estimate via clumped isotope analysis is likely due to soil carbonate growth typically occurring during warm seasons when evaporation is greater. Soil carbonate formation generally occurs when there is a precipitation deficit, and a reduction in precipitation from the lower Yellow Cat Member is consistent with a lower MAP estimate from Hatzell (2015) of 455 mm/year. The increasing aridity is thought to be a result of a rain shadow effect due to the uplift of the Sevier highlands.

Finally, Skipp (1997) used carbonate nodule $\delta^{13}C$ and the diffusion model of Cerling (1991) to estimate pCO_2 values. These values range from 1900 to 3500 ppmV.

Poison Strip Member

Chemostratigraphy

Locations where C-isotope profiles span the Poison

Strip Member include Ruby Ranch Road (Ludvigson and others, 2010a, 2015) and the Yellow Cat Road sections (Suarez and others, in press). Ludvigson and others (2010a) correlate the $\delta^{13}C$ trend across the Poison Strip Member to the Aptian, particularly to the positive and negative isotope excursions (C5 to C7).

Paleoclimate

Overall, few paleoclimate proxies have been widely sampled from the Poison Strip Member. The lowermost sample Ludvigson and others (2015) used for determining pCO_2 from carbonate nodules occurs in the Poison Strip Member. This sample provides a value of 1179 ppmV. While this value is lower than the pCO_2 values that were estimated by Skipp (1997), it is likely that the two estimates cannot be compared due to various sources of error and various assumptions about variables involved in the calculation of pCO_2. Sources of error include the concentration of soil CO_2 used, the $\delta^{13}C$ value of atmosphere, and the $\delta^{13}C$ value of soil CO_2. For example, the estimate of soil CO_2 used by Skipp (1997) comes from an estimate of organic matter from the Morrison Formation.

Ruby Ranch Member

Chemostratigraphy

A number of C-isotope profiles have been constructed for the Ruby Ranch Member. These profiles are from carbonate nodules collected at the Price River section and Ruby Ranch Road type section (Ludvigson and others, 2010a) and organic matter from lacustrine strata (Lake Carpenter) near Klondike Bluffs Road (Montgomery, 2014). These profiles (figure 28) suggest that the Ruby Ranch Member spans the Aptian-Albian boundary and encompass carbon isotope segments C8 through ^{13}C of Herrle and others (2004).

Paleoclimate

Ludvigson and others (2010a) extensively sampled carbonate nodules through the Ruby Ranch Member to estimate pCO_2 concentrations. The most significant finding by this study is that pCO_2 values peak during the ^{10}C carbon isotope excursion. In addition, Ludvigson and others (2015) use trends in $\delta^{18}O$ vs. $\delta^{13}C$ space to determine that evaporation peaked during the carbon isotope segment. Overall, Ludvigson and others (2015) suggest that meteoric water values determined from average $\delta^{18}O$ were approximately -6‰ vs. VSMOW. Suarez and others (2014) used carbonate nodules to estimate $\delta^{18}O$ of meteoric water as -5.6‰ vs. VSMOW, which is consistent with water values determined from crocodile bioapatite (-5.3‰ vs. VSMOW). Meanwhile, the isotopic composition of most dinosaurs are much lower (as low as -15.5‰ for ornithischian dinosaurs). We interpret this as representing the incorporation of isotopically depleted water from the Sevier highlands into the catchment basin. This water may have been additionally depleted by snowmelt since the Sevier highlands would locally have been reaching high elevation. Hatzell (2014) calculated a slight increase in MAP at 643 mm/year, and considering the large error, the MAP likely is not changed significantly from the upper Yellow Cat Member.

Mussentuchit Member

Chemostratigraphy

No chemostratigraphic profiles are published for the Mussentuchit Member. This is partially because $^{40}Ar/^{39}Ar$ ages determined by Cifelli and others (1997) and Garrison and others (2007) reflect a Cenomanian age. Therefore greater efforts were shifted toward the less well-constrained portion of the Cedar Mountain Formation. There is certainly a need to obtain high-resolution chemostratigraphic profiles for the Mussentuchit Member.

Paleoclimate

One of the characteristics of the Mussentuchit Member is the lack of carbonate nodules. A significant amount of data, however, has been derived from bioapatites as the Mussentuchit contains numerous fossil sites, especially microvertebrate sites. This large dataset of phosphate samples suggest that the area became significantly more humid during the deposition of the Mussentuchit Member (Suarez and others, 2012, 2014). Dinosaur-ingested water as well as precipitation water isotope proxies suggest a rather stable isotopic composition around -6‰ with values as light as -9.3‰, which likely represented water drained from highlands. A likely controlling factor of this return to humidity was the advancement of the Western Interior Seaway. Tooth enamel carbonate isotopes support this interpretation with a large increase in MAP calculated at 1278 mm/yr. No temperature estimates from geochemical data have been determined from the Mussentuchit Member. Recently, however, leaf fossils purportedly from the Mussentuchit Member (see Flora and Fauna from the Mussentuchit Member section) have been used to determine both temperature and precipitation via leaf physiognomic methods (Arens and Harris, 2015). Depending on the method used, temperature ranged from a low of 16°C to a high of 26°C. MAP is estimated at 810 mm/yr and mean growing season precipitation is estimated at 1380 to 1870 mm/yr.

A BRIEF OVERVIEW OF THE CEDAR MOUNTAIN FORMATION IN NORTHEASTERN UTAH

Lithostratigraphy and Correlation

Significant exposures of the Cedar Mountain Formation are also present in northeastern Utah (figure 1) along the northern margin of the Uinta Basin (extending into Colorado). These outcrops are geographically isolated from the east-central Utah exposures by the central Uinta Basin; however, the Cedar Mountain Formation is present in the subsurface of the basin (McPherson and others, 2006; Sprinkel, 2006, 2007; Currie and others, 2008). Though this field trip will not visit these northern exposures, a brief look at the geology and paleontology of this corner of Utah is included here for general information purposes.

The presence of Lower Cretaceous terrestrial rocks has long been recognized in northeastern Utah. While exposures are fairly limited due to folding and faulting in the area, exposures are generally along hogbacks in the vicinity of DNM (figure 35), SR 40 (extending east into Colorado), and US 191 and SR 44 (north of Vernal, Utah, and near the Wyoming border).

Stokes (1952), Young (1960), Hansen (1965), and others conducted some of the more detailed early work in the area. The Early Cretaceous age (Aptian-Albian) was confirmed based on charophyte and ostracod evidence found near Flaming Gorge and correlations with other strata. Though disputes and resolution of nomenclature, exact ages, and relationships of sandstone bodies continues, these and other workers recognized several of the basic features that characterize the Cedar Mountain, Cloverly, and Burro Canyon Formations. These include (generally from the bottom up): (1) limonite staining in the uppermost few meters of the Brushy Basin Member of the Morrison, (2) the presence of a basal conglomeratic sandstone, (3) calcareous sandstone lenses common in the lower part of the section, (4) an upper mudstone unit that becomes more carbonaceous upward and is commonly drabber in color and more fissile than in the Morrison, (5) abundant calcareous nodules in mudstone units, and (6) locally abundant, highly polished pebbles ("gastroliths"). Though many of these features are discontinuous or not present at all locations, together they form a relatively easy way to recognize the formation. In addition, these features typically appear in roughly the same stratigraphic succession as they do along I-70 and the San Rafael Swell, although the ages and paleoenvironments may be somewhat different (figure 35).

Little additional research was done since the 1960s until interest in the Cedar Mountain Formation was revitalized in the early 1990s. At this time the "Morrison Ecosystem Project" (see Turner and others, 2004; Turner and Peterson, 2004) focused some attention on the long-standing boundary issues, addressing the criteria used to distinguish the contact between the Morrison and Cedar Mountain Formations and attempting to place some age constraints on the rocks (e.g., Currie, 1998; McPherson and others, 2006; Currie and others, 2008, 2012). Their lower boundary was defined at the base of the lowest calcrete if the Buckhorn Conglomerate Member was not present. Our own research used the first occurrence of significant gravel within the mudstones as an identifier of interfluvial facies lateral to the channels represented by the Buckhorn Conglomerate Member, which were identified in northwestern Colorado as pediment gravels by Dolson and Muller (1994). In this way, the limonite-stained intervals (figure 35) were shifted from the top of the Morrison Formation to

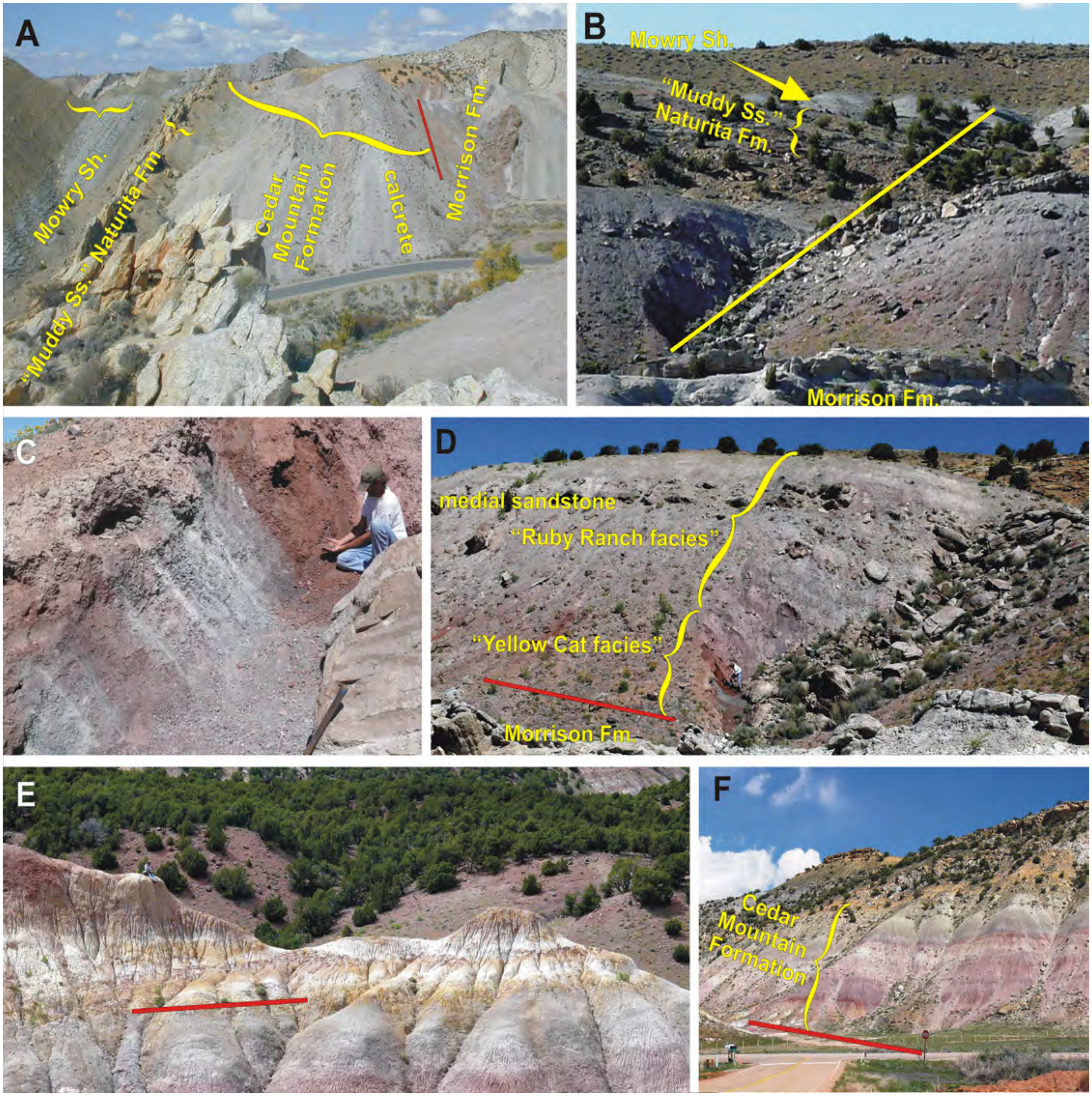

Figure 35. Cedar Mountain Formation in northeastern Utah. (A) The middle Mesozoic section looking west from the Carnegie Quarry at Dinosaur National Monument to the DNM 16 section; line of section along ridge crest. (B) Reef Pipeline section with line of section indicated in yellow measured from 40°29'53.72"N, 109°22'3.74"W to 40°29'58.71"N, 109°22'1.46"W. (C) Gary Hunt examining a pebbly red mudstone in the Yellow Cat facies near base of the Cedar Mountain Formation at the Reef Pipeline section. (D) The Yellow Cat and Ruby Ranch facies of the Cedar Mountain Formation at the Reef Pipeline section. (E) Basal contact of Cedar Mountain Formation at Six Mile Draw north of DNM (40°33'51.74"N, 109°12'53.30"W). (F) Cedar Mountain section east of SR 191 by north end of Steinaker Reservoir north of Vernal, Utah (40°31'59.22"N, 109°31'11.07"W). Red lines mark base of Cedar Mountain Formation.

the base of the Cedar Mountain Formation (Ludvigson and others, 2003a, 2003b; Sprinkel and others, 2012).

Constraining the age of the Cedar Mountain Formation in northeastern Utah has so far proved difficult and has been the subject of much recent work (Sprinkel and others, 2012). Until recently in this area, the relative lack of diagnostic vertebrate fossils, invertebrates and microfossils (either flora or fauna), and the apparent scarcity of rocks within the Cedar Mountain Formation datable by radiometric means has meant that most work focused on bracketing the age by dating the Morrison (early Tithonian) (Trujillo and Kowallis, 2015) and Dakota Formations (Albian-Cenomanian) (Sprinkel and others, 2012). Elsewhere in Utah, paleontological and geological evidence suggests an age range of Albian-Barremian is represented in the Cedar Mountain Formation (as discussed elsewhere herein); however, lacking published well-log data, direct correlations with the nearest dated outcrops to the south (some 165 km) has been problematic. Currie (1998) has identified the Buckhorn Conglomerate at the base of the Cedar Mountain Formation in the Colorado portion of DNM to the east. The Buckhorn Conglomerate has also been mapped near the western side of Steinaker Reservoir (Haddox, 2005; Haddox and others, 2010) to the east.

Recent research on terrestrial carbon isotope stratigraphy from pedogenic carbonate nodules at DNM (Smith and others, 2001; Sorenson and others, 2002; Ludvigson and others, 2002, 2003a, 2003b, 2015; Kirkland and others, 2003) has established the correlation between the outcrops of the fine-grained upper Cedar Mountain Formation at DNM with the Ruby Ranch Member of the Cedar Mountain Formation near Price, Utah, indicating the lower part of the section is at least as old as Aptian. Studies of palynomorphs and microfaunas near the top of the section supports an Albian age for the top of the Cedar Mountain Formation and at least the lower part of the Dakota Formation, as well as a marine influence (Currie and others, 2006; Sprinkel and others, 2012). However, the correlation between the Mussentuchit Member of the San Rafael Swell area and the Mowry Shale at DNM indicates that the entire Dakota Formation at DNM can be correlated with part of the Cedar Mountain Formation (upper Ruby Ranch Member up through the Short Canyon member) in central Utah, supporting the prior correlations of Young (1960) and Molenaar and Cobban (1991). Directly datable materials from the Cedar Mountain Formation at DNM are still lacking.

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 restrained from extending this terminology across the Uinta Basin to the Vernal area. However, for the purpose of this discussion, the Cedar Mountain Formation will be discussed as being divided into three superimposed facies (figure 36): (1) a basal "Yellow Cat" facies, (2) a middle "Ruby Ranch" facies, and (3) an upper "transitional" facies.

Basal "Yellow Cat" Facies

The basal "Yellow Cat" facies can be considered as the interfluvial facies of the Buckhorn Conglomerate fluvial system in this area. As such, if the Buckhorn Conglomerate in this region represents the "down river" equivalents to the Buckhorn in the San Rafael Swell area, these strata would be essentially equivalent to the lower Yellow Cat in the Paradox Basin and the "Yellow Cat" facies of the Buckhorn Conglomerate in the San Rafael Swell region. Indeed these sediments share almost all the characteritics of the lower Yellow Cat south of the Uinta Basin, including chert and limestone gravels mixed into the basal mudstone and sandstones, ferruginous paleosols, and even locally thin chert laminae. Likewise, these basal strata are composed largely of recycled material from the underlying Morrison Formation. An attempt to date a basal light-gray, siliceous siltstone bed (porcelainite) at the base of the the section at the Reef Pipeline section (figure 36) yielded a detrital zircon U-Pb maximum age of Late Jurassic, 153.05 ± 3.69 Ma (Sprinkel and others, 2012). We now tentatively interpret this bed as a loessite derived from the underlying Morrison Formation.

Middle "Ruby Ranch" Facies

The middle "Ruby Ranch" facies in northeastern Utah, as with the Ruby Ranch to the south, is characterized by illitic mudstones with abundant pedogenetic carbonate nodules. In many areas, a prominent cherty

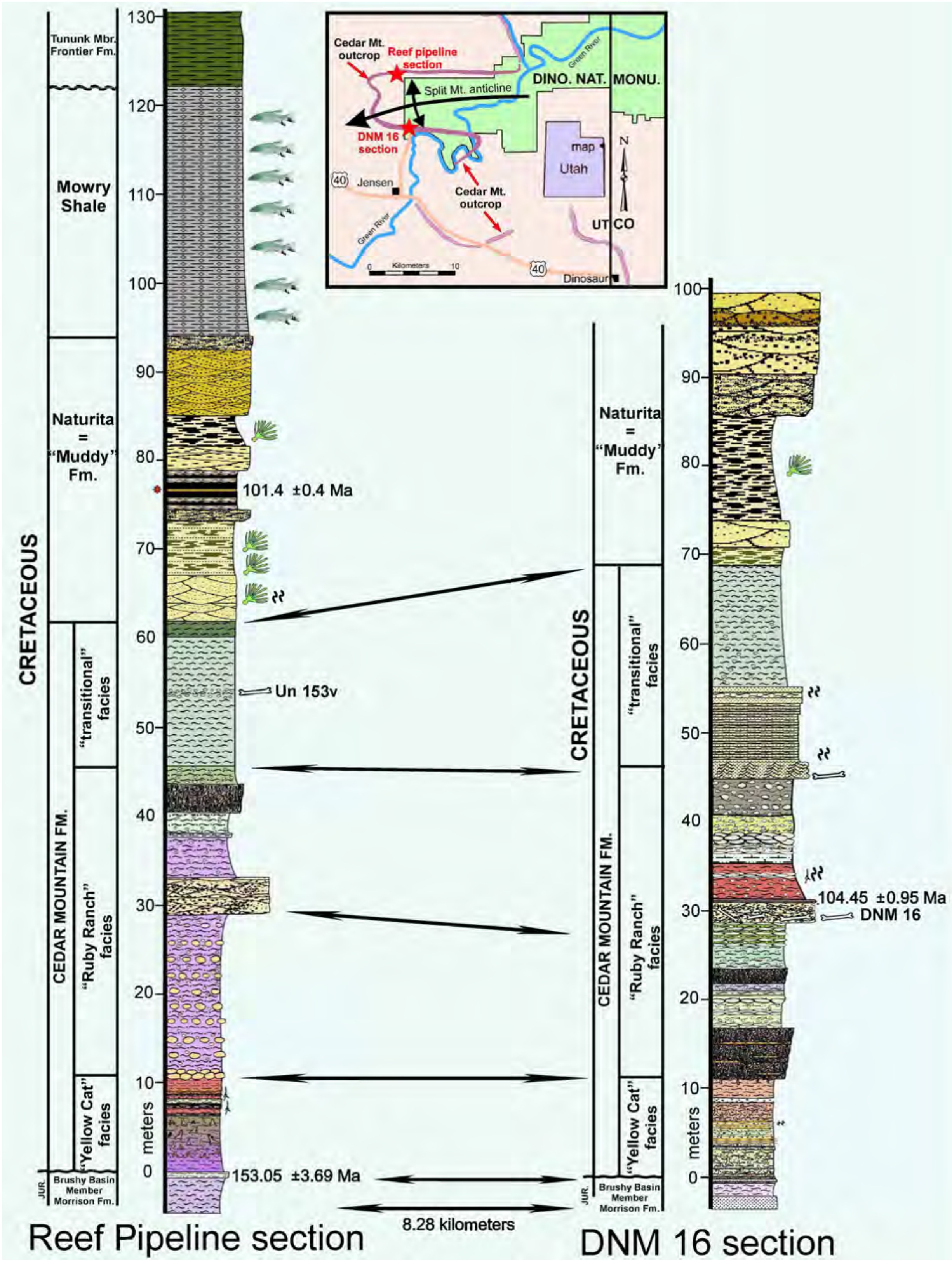

Figure 36. Correlation of the Reef Pipeline section with the DNM 16 section at west end of Dinosaur National Monument across the Split Mountain anticline with radiometric dates and important dinosaur sites indicated. Key to stratigraphic symbols as in figure 10. Modified from Sprinkel and others (2012).

calcrete marks the base that makes a prominent break in the slope such as at the DNM 16 section (figures 35A and 36). Elsewhere, the contact is noted at the sudden appearance of abundant carbonate nodules such as at the Reef Pipeline section (figures 35B, 35C, and 36). A prominent sandstone occurs near the middle of this unit, which has been referred to the Poison Strip Member. A late Albian age is indicated for the sandstone by a maximum U-Pb age of 104.46 ± 0.95 Ma from detrital zircons collected from this sandstone at DNM16 (Chure and others, 2010). This precludes a correlation with the Poison Strip to the south because the Poison Strip Member is well constrained as Aptian in age (Ludvigson and others, 2010a, 2015). The top of the "Ruby Ranch" facies is gradational with the overlying "transitional" facies.

Upper "Transitional" Facies

The upper "transitional" facies is characterized by a reduction of carbonate nodule abundance and an increasing amount of swelling clay in the mudstone beds such that the upper part of the facies, below the base of the overlying Naturita Formation (= Dakota Formation), are drab and very smectitic. Although these strata are similar to the Mussentuchit Member on the west side of the San Rafael Swell, they are never lignitic. The late Albian age for the "transitional" facies at the top of Cedar Mountain Formation is constrained by middle to late Albian palynomorphs obtained from the base of the overlying basal Naturita Formation (= Dakota Formation) (Sprinkel and others, 2012). Of particular importance in dating the top of the Cedar Mountain is that dinoflagellates are present in the floral assemblage at the base of the Naturita Formation (= Dakota Formation) at the Strike Valley section (40°33'57.06"N, 109°29'47.97"W) of Sprinkel and others (2012), indicating the incursion of at least brackish water into the area during peak sea level rise of the Albian Skull Creek Seaway. Marine strata of this age (Thermopolis Shale), overlie the Cloverly Formation in the Bighorn Basin (Ostrom, 1970). The Kiowa-Skull Creek cycle is dated by $^{40}Ar/^{39}Ar$ analysis of sanidine grains from bentonites in the Thermopolis Shale in Wyoming at about 104.4 to 100.9 Ma (Obradovich and others, 1996; Scott and others, 2009). The top of the Cedar Mountain Formation is further constrained by a U-Pb zircon age of 101.4 ± 0.4 Ma from a volcanic ash near the center of the Naturita Formation (= Dakota Formation) (Sprinkel and others, 2012) The age of these strata also supports their correlation with the "transitional" facies at the top of the Ruby Ranch Member in the western San Rafael Swell.

The middle Cretaceous within the Western Interior basin includes the Kiowa-Skull Creek marine depositional cycle (Aptian-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 the landward time-equivalent of the Kiowa-Skull Creek cycle (figure 37). The basal dinoflagellate-bearing mudstone and shale unit of the Naturita Formation (= Dakota Formation) represents peak sea level during the Kiowa-Skull Creek cycle and the initial marine incursion into northeastern Utah. The overlying non-marine part of the Dakota Formation and marine Mowry Shale represents the newly recognized Muddy-Mowry cycle (figure 37). Marine environments did not transgress into central Utah until the late Cenomanian (Elder and Kirkland, 1993,1994; Cobban and others, 1994). Since the Muddy Formation is the proper term for the sandstone dominated coastal sequence between upper Albian marine strata (Skull Creek and other units) and basal Cenomanian marine strata (Mowry Shale) (Weimer, 1984; Ludvigson and others, 2010b), perhaps the Naturita Formation (= Dakota Formation) on the northern side of the Uinta Basin would most properly be referred to as the Muddy Formation.

Cedar Mountain Vertebrate Remains in Northeastern Utah

The many fossil discoveries in the Cedar Mountain Formation in central Utah inspired staff at DNM to focus more attention on fossil inventories and excavations in the Cedar Mountain in DNM and vicinity; work has yielded some spectacular results. Diagnostic vertebrate fossils from the Cedar Mountain Formation of northeastern Utah have proven to be uncommon;

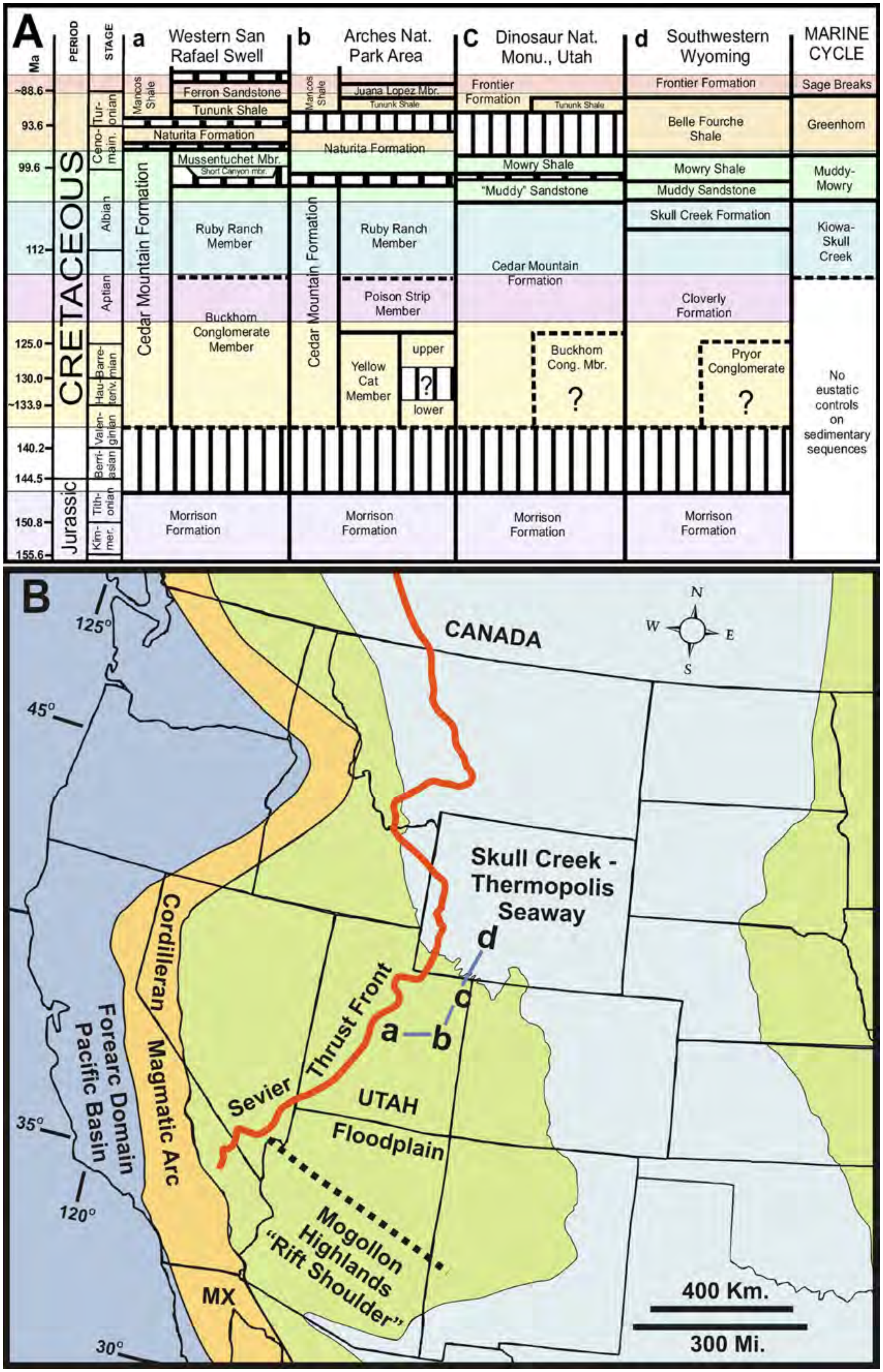

Figure 37. Caption on following page.

Figure 37 (figure on previous page). (A) Correlation chart of Cretaceous formations from the San Rafael Swell in central Utah to southwest Wyoming and associated marine depositional cycles. Modified after Sprinkel and others (2012). (B) 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).

even scrap bone is uncommon. A notable exception is a quarry at DNM located just across the road, west of the Carnegie Quarry. This quarry, DNM16 was first identified by researchers working in the area on a model for the dinosaur sites present in the Morrison Formation (Dodson and others, 1980). This quarry in the middle of the Cedar Mountain Formation has produced several complete and incomplete titanosauriomorph sauropod skulls (figures 30H and 36) as well as postcranial material described as *Abydosaurus mcintoshi* (Chure, 2000; Chure and others, 2010). In addition, this site (DNM 16) produced a partial skeleton of a dromaosaurid (cf. *Deinonychus* sp.) (Chure and others, 2007, 2010) and provided the maximum U-Pb age from detrital zircons of 104.46 ± 0.95 Ma.

A site just outside DNM boundaries has recently produced iguanodontid remains assigned to cf. *Tenontosaurus* (figure 30C) and a single mammalian tooth. These and other sites may eventually provide enough diagnostic material that comparisons and correlations can be made with Cedar Mountain Formation faunas known elsewhere. We hope that these fossils, together with the renewed geological interest in the area, will soon produce a more detailed picture of the tectonics, depositional setting, and environment of the Cedar Mountain Formation in northeastern Utah.

CONCLUSION

Geologically, research on the Cedar Mountain Formation has confirmed that Young (1960) was largely correct regarding the use of marker beds to correlate Lower Cretaceous strata across Utah. Research has also confirmed that within these rock packages, the mudstone intervals with carbonate nodules (drier) in the west gave way to more organic-rich (wetter) strata toward the east. Deposition and preservation of the Yellow Cat Member in the northern Paradox Basin is the result of Early Cretaceous salt tectonics as proposed by Doelling (1988). Additionally, ferruginous paleosols at the Jurassic-Cretaceous contact indicate a period of wet climatic conditions in the middle Mesozoic (Demko and others, 2004). The occurrence of the marker calcrete at the top of the lower Yellow Cat Member and stable isotope geochemistry refects a strong drying of the climate caused by the onset and long-term effect of a rain shadow that formed east of the Sevier orogenic belt (Ludvigson and others, 2010a, 2015; Suarez and others, 2014). However, the development of the foreland basin is delayed by several million years as indicated by the first thickening of stratigraphic packages to the west beginning with the Aptian-Albian Ruby Ranch Member. Farther to the west, this thickening is well documented in the synorogenic deposits of the San Pitch Formation in the central Utah thrust belt (Sprinkel and others, 1999; Hunt, 2016). These synorogenic conglomerate beds intertongue and grade into the dominantly fine-grained beds to the east (Sprinkel and others, 1999). Thickening of the section continues up through the Mussentuchit Member, which is only developed in the distal foreland basin (figure 38).

Utah's Cedar Mountain dinosaurs are contributing critical information about an important period in the history of terrestrial life in the Northern Hemisphere. Globally, this was a time of changing climatic conditions and exceptionally high atmospheric carbon dioxide levels causing "super-greenhousing" (a world with no polar ice caps and a sluggish, poorly oxygenated ocean), major restructuring of biogeographic migration corridors, and a complete restructuring of plant communities, i.e., the origin and rapid rise to dominance of flowering plants. Researchers from a host of different institutions continue to discover and integrate new data from the Cedar Mountain Formation into an increasingly robust history of Utah during the Early Cretaceous. This research over the past 25 years, first on microvertebrate assemblages, then on skeletal materials,

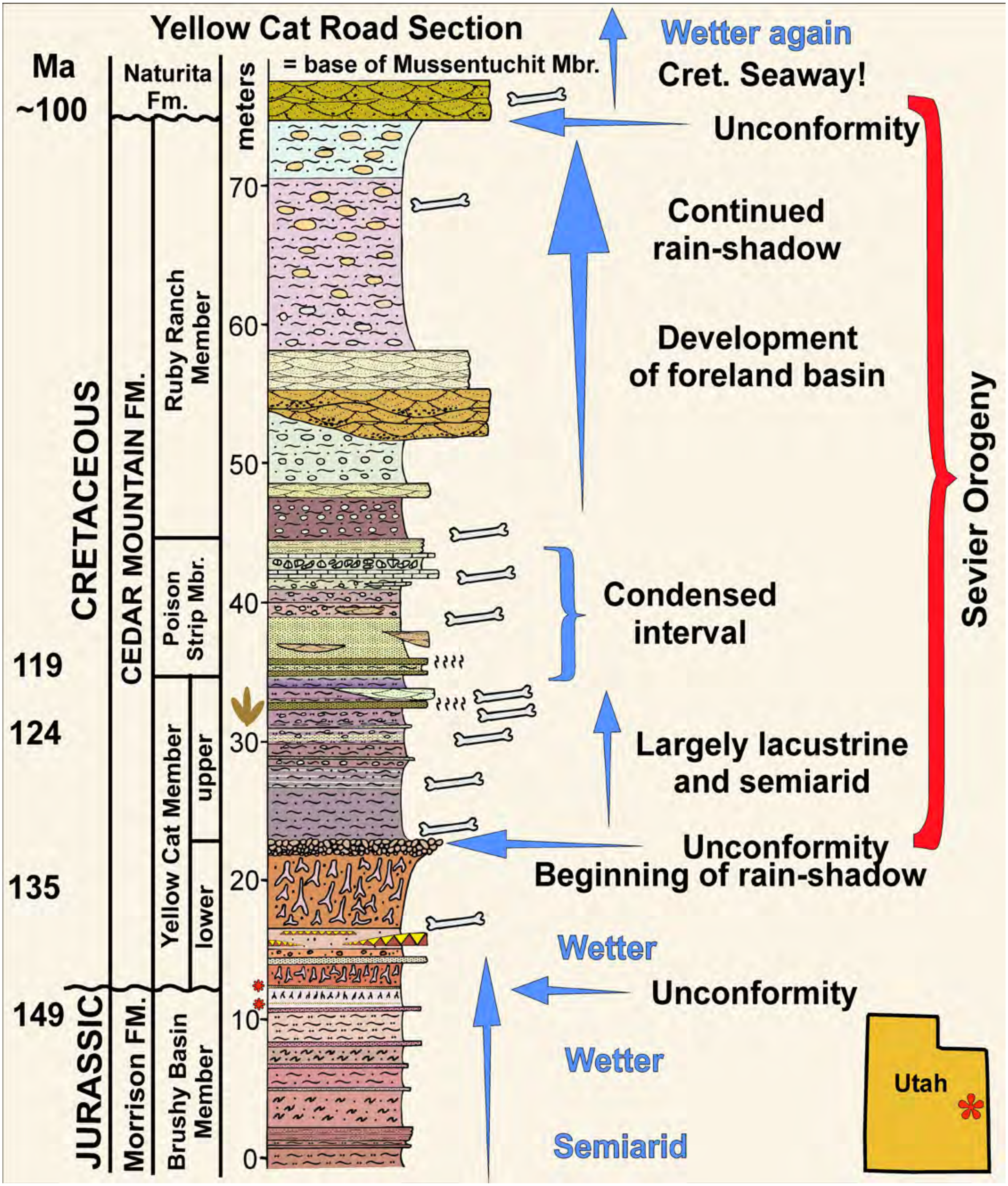

Figure 38. Simplified history of the middle Mesozoic of central Utah plotted against the Yellow Cat Road section.

has established that a robust, well-dated record of lower Cretaceous terrestrial faunas is preserved in central Utah (see Kirkland and others, 1997, 1999, 2012; Cifelli and others, 1997, 1999; Eaton and Kirkland, 2003; Kirkland and Madsen, 2007; Kirkland and Farlow, 2012). Coupled with new research in the Jurassic and Upper Cretaceous sequences in southern Utah, these new dinosaur discoveries only serve to show that Utah has the most complete middle Mesozoic dinosaur record in the world (figure 39), and that there is still a great deal to learn from this extraordinary record.

These discoveries have been made in lockstep with a series of extraordinary discoveries in China (Zhou and others, 2003; Pan and others, 2015; Zhou, 2015). The European Lower Cretaceous faunas of southern Britain have been well documented for more than 150 years (Martill and Naish, 2001a; Batton, 2011; Lomax and Tamura, 2014). New faunas being recovered from Hungary (e.g., Osi and others, 2012) and Spain (e.g., Pereda-Suberbiola and others, 2012; Alcala and others, 2012; McDonald and others, 2012b; Kirkland and others, 2013a) are filling out the middle Cretaceous story for Europe. While the temporal resolution of these strata in Utah is good, precise correlation of these strata between continents is still far from resolved. Correlation of Lower Cretaceous strata in Utah is even difficult with strata in the northern USA.

The earliest Cretaceous strata in the Cedar Mountain Formation of east-central Utah (Yellow Cat through Poison Strip Members) preserve a series of terrestrial faunas dominated by polacanthid ankylosaurians, styracosternan iguanodontians, and basal macronarian and brachiosaurid sauropods from the Barremian to middle Aptian (125 to 115 Ma). The oldest of these faunas could possibly extend back to more than 135 Ma (Kirkland and others, 2012; Hendrix and others, 2015). These faunas in Utah broadly correlate to the European Wealden fauna and Asian Hekou and Jehol faunas, indicating European paleogeographic connections and not Asian at this time (Kirkland and others, 1998b, 2015; Brikiatis, 2016). The most characteristic taxa in these Asian faunas are species of *Psittacosaurus* not known in Europe or North America. A marked faunal change (extinction?) within the Aptian may be tied to the isolation of North America with the opening of the Atlantic Basin and the flooding of much of Europe (Kirkland and others, 2013a, 2015) and/or global changes during Oceanic Anoxic Event OAE 1a or OEA 1b. An interval of marked short-term intense volcanic activity and global cooling spanning the end of the Aptian has also been identified at this time (Leckie and others, 2002; Herrle and others, 2015).

The middle Cedar Mountain faunas of the late Aptian through Albian preserved in the Ruby Ranch Member overlap the better known Aptian-Albian faunas of the Cloverly Formation (Ostrom, 1970; Oreska and others, 2013). They are characterized by nodosaurid ankylosaurians, basal iguanodontians (tenontosaurids), and exclusively slender-toothed, basal somphospondylan titanosauroids, suggesting isolation from Eurasia. A number of taxa are known from the Cloverly fauna that are considered Asian taxa and are thought to indicate immigration events from Asia in late Aptian to earliest Albian. These immigrants include caenegnathid oviraptors, tyrannosaurids (Zanno and Makovicky, 2011), neoceratopsians (Farke and others, 2014), and the triconodontid mammaliform *Gobiconidon* (Jenkins and Schaff, 1988). As current research reveals new data, these taxa may have entered from Europe, but key European fossils may not yet been discovered. The mammal *Gobiconodon* is pan-Laurasian and was present in the Barremian of both China (Yuan and others, 2009) and Europe (Cuenca–Bescósand and Canudo, 2003). In Asia, basal neoceratopsians along with possible polacanthids and basal ankylosaurid ankylosaurians, more derived hadrosauroid iguanodontians, and titanosaurid sauropods typify the Mazongshan fauna; *Psittacosaurus* is notably absent (Tang and others, 2001). In Europe, struthiosaurine nodosaurids replace polacanthids whereas styracosternid iguanodonts continue to dominate along with titanosaurids (Ariño fauna) (Alcala and others, 2012; Kirkland and others, 2013a).

A significant faunal change occurs in the Mussentuchit Member at the top of the Cedar Mountain Formation at the base of the Cenomanian of Utah at about 100 to 98 Ma. Hadrosauroids replace tenontosaurids among iguanodontians during a shift from Early to Late Cretaceous style faunas associated with an Asian immigration event (Cifelli and others, 1997; Kirkland and others, 1997, 1999) and/or the OAE 1D. The over-

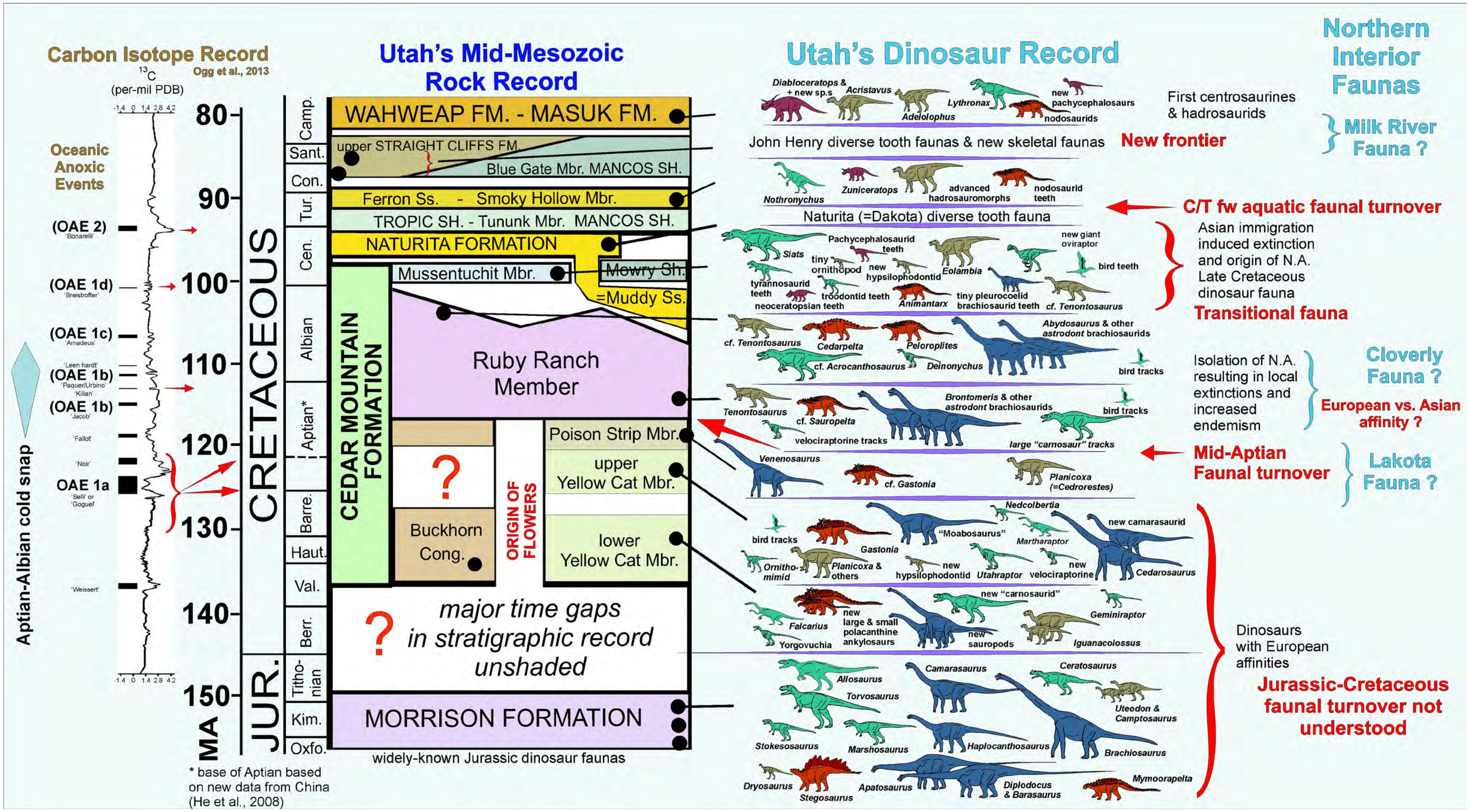

Figure 39. Distribution of dinosaur faunas during the middle Mesozoic in Utah plotted against stable carbon isotope curve (Ogg and Hinnov, 2012), linear time, and the generalized stratigraphic sequence of southern Utah, with hypothetical correlations of Cretaceous dinosaur faunas in the northern Western Interior. Distribution of dinosaur faunas highly modified from Kirkland and Farlow (2012), and Aptian-Albian cold snap after Leckie and others (2002).

lap of sauropod and tennontosaurid teeth together with the presence of a large allosauroid theropod (Zanno and others, 2014) suggest that this Mussentuchit fauna may actually preserve the transition between faunas of Lower Cretaceous aspect with those of Upper Cretaceous aspect in the Mussentuchit Member of the Cedar Mountain Formation over an interval of 1.5 to 2 Myr. In Utah, extensive microvertebrate faunas in the middle to late Cenomanian (95 to 93 Ma) Naturita Formation (= Dakota Formation of others; Young, 1960, 1965; Carpenter, 2014) preserve a Jurassic-grade aquatic fauna dominated by lungfish, semionotids, and "glyptopsid" turtles (Eaton and others, 1997; Eaton and Kirkland, 2003). No major changes in terrestrial faunas are noted at the beginning of the Turonian, but the aquatic fauna changes to one dominated by gars and amioids are significant, coinciding with the Cenomanian-Turonian extinctions in the marine realm (OAE 2) (Elder, 1989, 1991; Ogg and Hinnov, 2012).

From middle Turonian through late Santonian, the Straight Cliffs Formation of Utah documents the continued dominance of nodosaurid ankylosaurians and hadrosauroid iguanodonts and the introduction of more derived neoceratopsians (Eaton and others, 1997: Eaton and Kirkland, 2003). A similar pattern is documented by the Bissekty, Bayn Shire, and Iren Dabasu faunas in Asia with titanosaurs, ankylosaurids, hadrosauroids, and protoceratopsians (Averianov and Sues, 2012). The more restricted Santonian record (Iharkút fauna) of central Europe is characterized by neoceratopsians, basal rhabdodontid iguanodonts, and struthiosaurine nodosaurids, suggesting a more endemic fauna (Osi and others, 2012).

Approximately 10 discrete terrestrial faunas are documented in Utah in the Lower Cretaceous through the Santonian. Similarities in the dinosaur faunas suggest that four to five more broadly based dinosaur assemblages can be recognized roughly correlated to similarly broadly based assemblages in Asia and Europe. Such correlations are, at most, only generally correlative, and any definitive causation of these patterns at a global and even in most cases a local scale are highly speculative. However, it would seem that for the first time, there is real potential to look at these patterns at a large scale, begin intelligent discussions, and develop protocols to improve the basis for these discussions. The future for such research appears bright.

THE FIELD TRIP

Day 1 (AM) – Cedar Mountain Formation in the Region North of Arches National Park

From Salt Lake City we will travel south on I-15 to Spanish Fork, and proceed on US 6 across Soldier Summit through Price to Green River between the San Rafael Swell to the west and the Book Cliffs. After refueling in Green River, we will drive east on I-70 continuing along the south side of the Book Cliffs, one of the longest continuous exposures of the regressing Late Cretaceous coastline anywhere in North America (Van Wagoner and others, 1991). We will make a short stop at the rest area immediately prior to Crescent Junction for a brief overview of the Salt Valley anticline to the south to discuss the importance of the Paradox Basin and salt tectonics on Mesozoic depositional patterns in this area (figures 1 and 40). Note that all road distances are given in miles to match odometers. All aerial distances will continue to be given in metric.

Crescent Junction Rest Area

This stop provides an excellent view of the geology south of the Book Cliffs and north of Arches National Park. The rest area is built on a carbonate-cemented gravel pediment of Pleistocene age formed on the marine Upper Cretaceous Mancos Shale. Keep this exposure in mind when we examine the basal Cedar Mountain Formation over the next couple of days. In this area, a nearly complete section of the Mesozoic is exposed.

The Book Cliffs form the escarpment north of I-70. This magnificent exposure of Upper Cretaceous rocks extends east-west from Green River, Utah, to Grand Junction, Colorado. West of here at Green River, the escarpment extends north past Price, before bending west and then south around the north end of the San Rafael Swell, where it is called the Coal Cliffs/Wasatch Plateau on the west side of the Swell. The marine Mancos Shale is overlain by the marginal-marine and coastal-floodplain-deposited strata of the Mesaverde Group. This 165-km cross section of the eastward-regressing

Campanian facies track of the Late Cretaceous Western Interior Seaway has become a research and educational model for petroleum geologists for stable continental shelf environments (see Van Wagoner and others, 1991).

The mountains on the skyline to the south were formed by the unroofing of 29-million-year-old laccoliths (Doelling, 2001) following the uplift of the Colorado Plateau—the Henry Mountains to the southwest and the La Sal Mountains to the southeast. To the west, the San Rafael Reef is visible, and far off to the east, the Uncompahagre Plateau, which approximates the position of the Uncompahagre Mountains of the Pennsylvanian-aged Ancestral Rocky Mountains, is visible along the Colorado border.

On the east side of US 191, the Salt Valley anticline can be seen trending directly north-northwest toward the rest area. This is a collapsed salt anticline and forms most of Arches National Park. Along the axis of this structure, intact sections of the Cedar Mountain Formation are preserved overlying strata as old as late Paleozoic (Doelling, 1985, 1988; Lockley and others, 2004; Stikes, 2006; Doelling and Kuehne, 2013a). The Cedar Mountain sections we will examine today are on the northeast and southeast flanks of this structure. Exposures of the fossiliferous middle Mesozoic section on land managed by the BLM and the State of Utah in the area around Arches National Park are a world-class paleontological resource (figure 40).

The rest area is built upon alluvium deposited on a broad pediment surface cut into the Mancos Shale. The alluvium is cemented with pedogenic carbonate that forms a resistant caprock that protects the Mancos from erosion. The pediment has subsequently been dissected forming alluvial-capped mesas. A hypothesis to be presented on this trip will be that the basal Yellow Cat sediments represent a distal pediment developed on the unconformity above the Morrison Formation under wetter climatic conditions. Perhaps the basal Yellow Cat Member strata are better compared to Holocene sediments deposited on the surface of the Great Plains of central North America rather than pediment deposits laid down near their source area (e.g., Book Cliffs).

From here, we will proceed east to the Cisco exit on I-70 and take the frontage road on the south side of the highway to the Yellow Cat Loop Road. **Beware** of a series of drainage dips over this stretch of road. The Yellow Cat Loop Road cuts through the Cedar Mountain escarpment, running along the escarpment to the Yellow Cat uranium mining district before to turning back north to I-70. This region includes many important fossil sites (figure 4) that have been developed since Rob Gaston of Fruita, Colorado, first showed Kirkland the Gaston Quarry site (figure 20) in 1990, which yielded the type specimens of *Utahraptor* (Kirkland and others, 1993) and *Gastonia* (Kirkland, 1998a). The UGS, Prehistoric Museum (Utah State University Eastern), BYU Paleontology Museum, and DMNS have and are actively excavating paleontological sites in this area. As with all public lands, no collection of fossil vertebrates or their traces can be made without valid permits from the appropriate land management agency (in the case of this area, the BLM or the State of Utah).

East End of the Poison Strip

The lower Yellow Cat Member is not well exposed along the road, but farther to the east and west where Poison Strip escarpment rises, it is well developed as described below with distinct ferruginous nodules. Aubrey's (1998) marker calcrete is thin here, but it makes a low and distinctive break in the slope (figures 17I). The east end of the Poison Strip has an easily accessed section of the Cedar Mountain Formation. A stratigraphic section east of the road contains many sedimentary facies of interest including some features not documented elsewhere (figure 41).

The upper Yellow Cat Member has yielded many interesting fossils in this area, including common fish, turtles, and eileenodontid sphenodont remains, as well as eggshell fragments. Most dinosaur fossils in this area have been recovered in the upper Yellow Cat Member and include the polacanthid ankylosaur *Gastonia*, a partial skeleton of an iguanodontid, and claws of a dromaeosaur. The type specimen of the brachiosaurid sauropod *Cedarosaurus* was excavated by the Denver Museum of Nature and Science about 2 km to the east (Tidwell and others, 1999). A number of other important dinosaur excavations are being actively worked by BYU and the UGS, including sites in the overlying

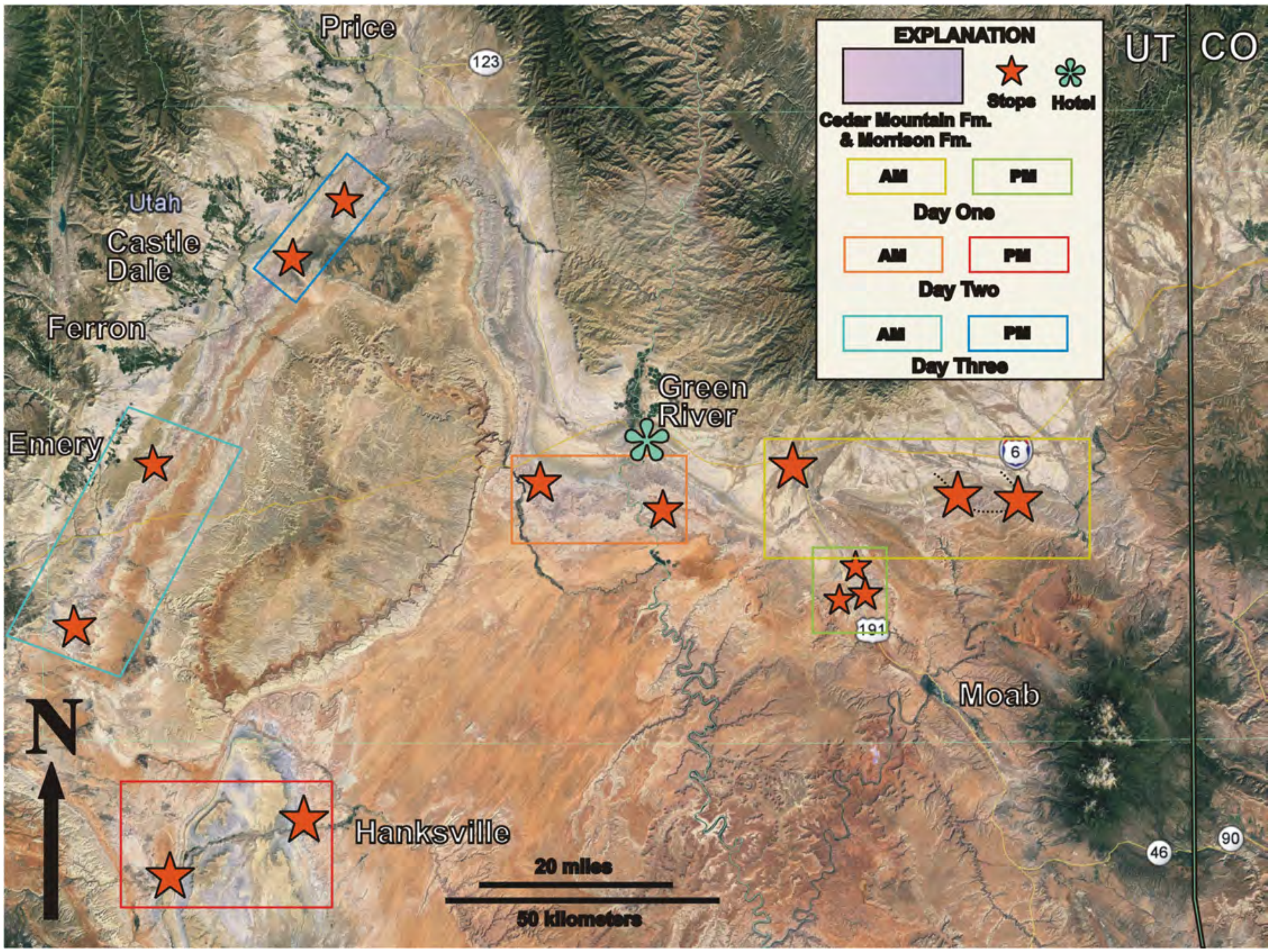

Figure 40. Google Earth view of the northern Paradox Basin and San Rafael Swell region to show field trip stops in the context of the spectacularly exposed Mesozoic stratigraphy in the region. Compare with figure 1.

Poison Strip Member. Those excavations have yielded well-preserved turtles (Brinkman and others, 2015), additional iguanodont skeletal material, a basal ornithomimid (Scheetz and others, 2010a), more *Utahraptor* material, and at least parts of the same massive polacanthid ankylosaur described from west of Arches National Park by Bodily (1969).

One of the two localities that yielded ostracods was low in the upper Yellow Cat section exposed in a gully about 300 m west of the road (Sames and others 2010; Sames, 2011). This is also one site where the matrix does not break down as well as it does at Lake Madsen (Scott Madsen, formerly UGS, personal communication, 2007). The charophytes reported by Kirkland and others (1997) came from a site on the east side of the road and were found with microvertebrates (fish and dinosaur teeth); howerver, the matrix would not break down at this site either.

The top of the Yellow Cat Member is interpreted to represent a lacustrine shoreline. An extensive sandstone lens representing the coastal bar facies forms a resistant ledge to the east of the road that has been mistaken for the Poison Strip Member, which is stratigraphically a few meters higher in the section (figure 41). The "beach facies" overlies thin, rippled sandstones with bivalve escape structures, and a variety of other invertebrate

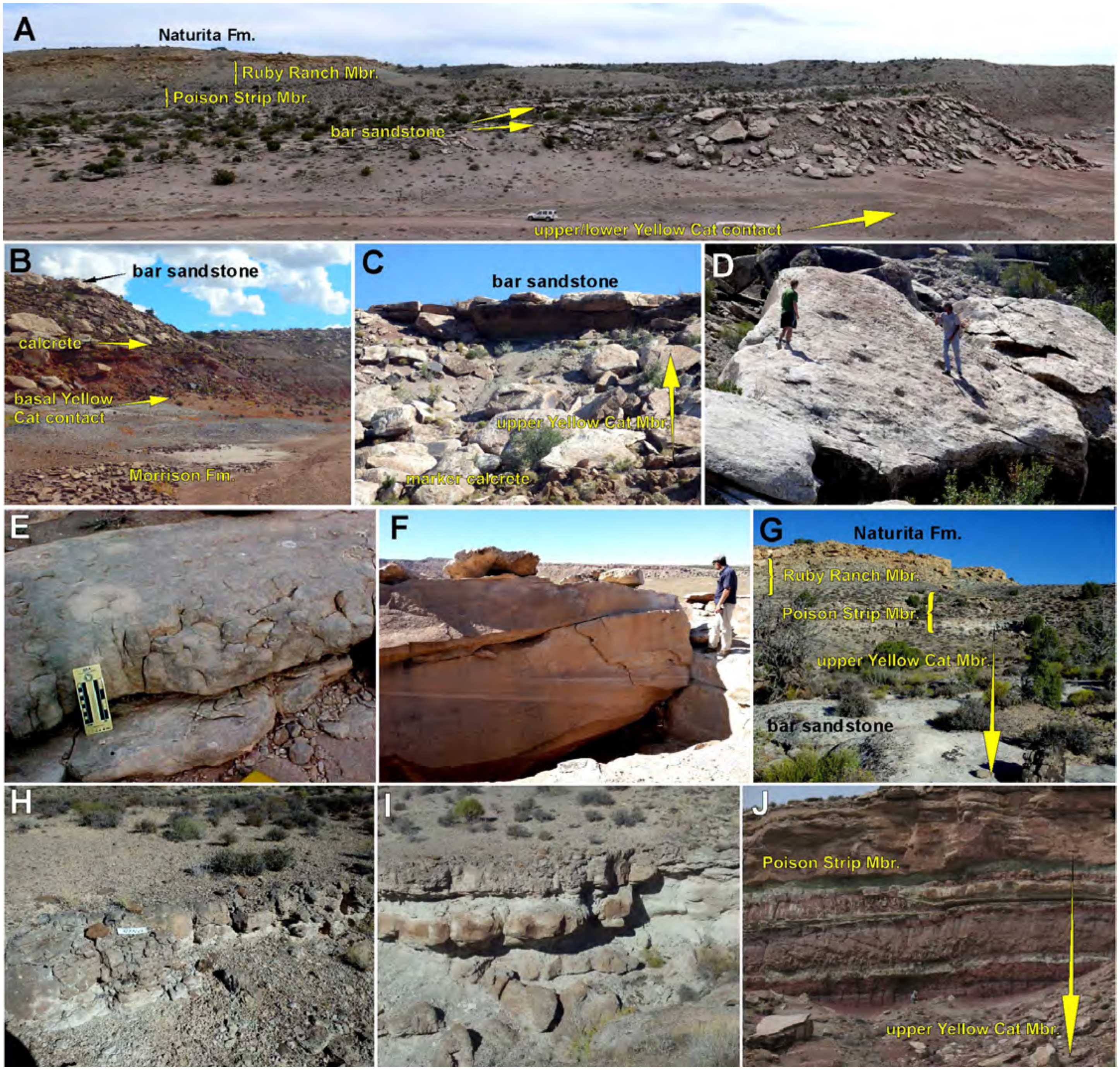

Figure 42. Cedar Mountain exposures at Poison Strip section (PS) on the east end of the Poison Strip (figure 41). (A) Cedar Mountain Formation on the east side of the Yellow Cat Loop Road. Line of section was just behind ridge in foreground. (B) Yellow Cat Member at base of Poison Strip Section. (C) Upper Yellow Cat Member below lenticular bar sandstone complex. (D) Possible sauropod track surface in lenticular bar sandstone complex. (E) Clam escape structures in base of lenticular bar sandstone complex above a series of thin ripple-bedded sandstone. (F) Aeolian cross-bedding in fine-grained sandstone exhibiting inverse graded laminae at top of lenticular bar sandstone complex. (G) Upper Cedar Mountain section from top lenticular bar sandstone complex to base of Naturita Formation. (H) Stromatolitic layer overlying sandstone in lower Poison Strip Member. (I) Capping Poison Strip sandstone with stromatolitic layer at the top of the Poison Strip Member. (J) Coastal vertisol complex on west side of the Yellow Cat Loop Road below fluvial Poison Strip Member approximately 1.5 km to the southwest.

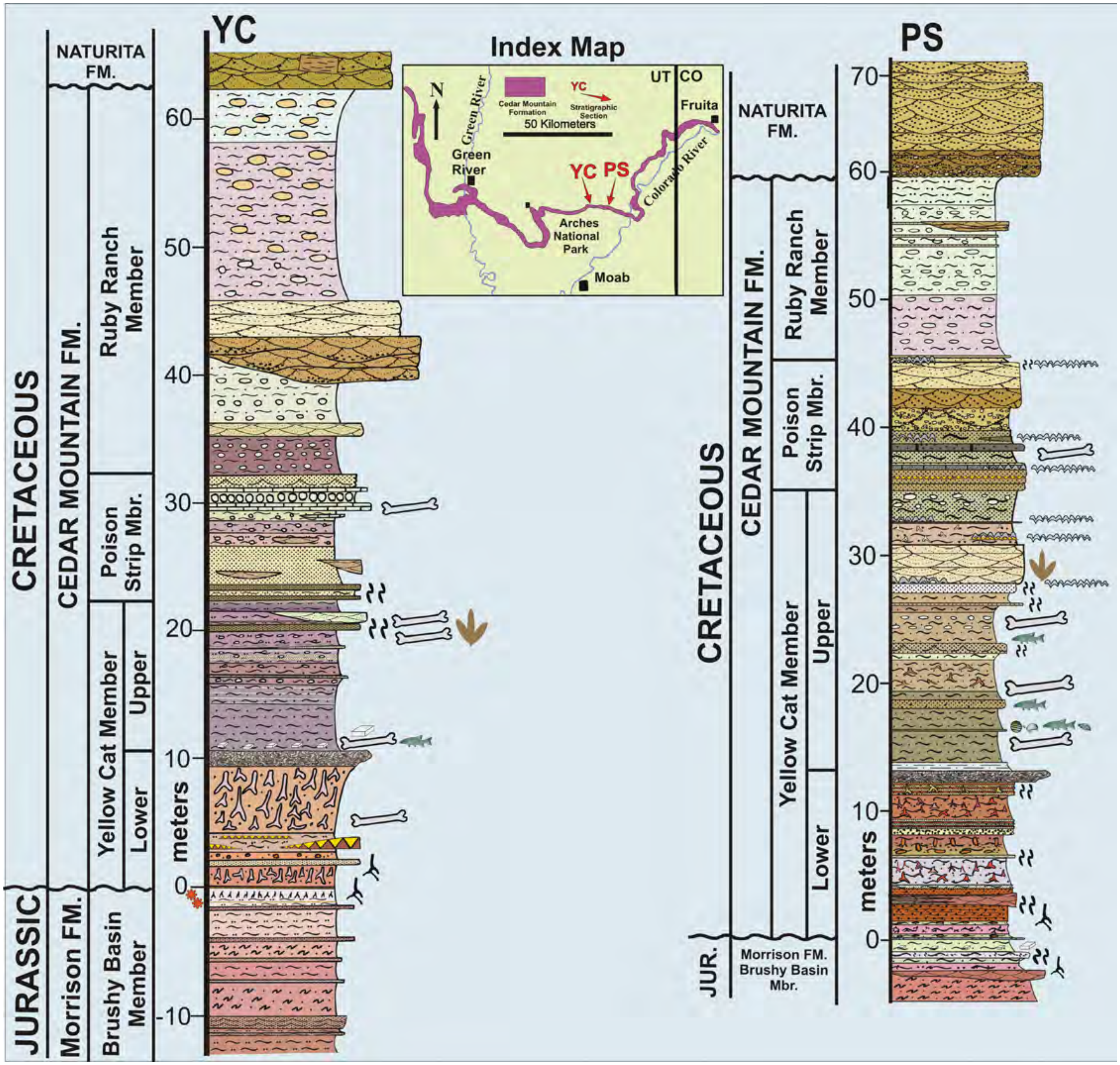

Figure 41. Comparison of the Yellow Cat Road section (YC) measured from 38°51'19.12"N, 109°32'37.38"W with the Poison Strip section (PS) measured from 38°52'25.39"N, 38°52'25.39"N to 38°52'37.36"N,109°26'18.50"W. For explanation see figure 10.

trace fossils. There are wind-drift cross-beds exhibiting inverse grading at the top indicating subaerial exposure of the bar (figure 42D and E).

Mudstone with weakly developed paleosols overlie this sandstone lens. Matt Joeckel (Nebraska Soil and Conservation Survey) has been working with the UGS in researching well-exposed vertisols exposed below the Poison Strip Member on the west side of the valley and farther to the east (figures 21D, 21E, 23F, and 42J).

Marginal lacustrine sandstone facies are recognized in a number of areas near the contact between the Yellow Cat Member and the fluvial Poison Strip Member. Even when closely associated with the cliff formed by the Poison Strip Member, their genetic relationship with the underlying fine-grained lacustrine facies of the upper Yellow Cat Member has resulted in the inclusion of these sandstone beds in the Yellow Cat Member (Stikes, 2006).

Unusual for this region is the abundance of stromatolite lenses and beds associated with sandstone beds at the top of the Yellow Cat and throughout the Poison Strip Member (figures 41, 42H, and 42I). As noted above, as the Cedar Mountain Formation is traced to the eastern margin of the Paradox Basin, first the Yellow Cat thins and pinches out followed by the Poison Strip Member (Young, 1960; Stikes, 2006, herein; figures 11 and 24). The overlying Ruby Ranch Member is exposed in this region but has not been the subject of any specific research.

The Poison Strip Escarpment

Proceeding south, the trip will cross the Morrison Formation by driving up through an escarpment held up by sandstone beds of the Salt Wash Member exposed on the east end of the Yellow Cat mining district. Bear right at the fork and head west along the Salt Wash bench with the Poison Strip escarpment on the right (north) side of the road for approximately about 6 km. The Brushy Basin Member of the Morrison through the Cedar Mountain Formation is exposed. The fluvial sandstone architecture of the Poison Strip Member is excellently expressed (Stikes, 2006). Where the Naturita Formation (= Dakota Formation) is preserved on the Cedar Mountain Formation in this area, it provides stark evidence that the Ruby Ranch Member is relatively thin compared to the Yellow Cat Member. This drive also provides an opportunity to practice placing the contact between the Morrison and the Cedar Mountain Formations; it is at the break in slope with the convex profile associated with the change from smectitic clays of the Morrison Formation to the non-smectitic clays in the Yellow Cat Member. This convex slope profile is in stark contrast to a flat to slightly concave slope profile that characterizes the overlying Yellow Cat Member, coupled with iron-stained (ferruginous) paleosols of the basal Yellow Cat and the overall drabber variegated color of the Yellow Cat Member (figure 23C).

Toward the west end of the escarpment, we will pass the Ringtail mine workings below the type section of the Poison Strip Member (figure 23A). As discussed in Kirkland and Madsen (2007), this was not a good choice for the type section as it is relatively inaccessible and there is no clear upper contact with the overlying Ruby Ranch Member.

Take the right fork at the west end of the Poison Strip escarpment turning north between the Poison Strip escarpment on the east and Gastonia Point to the west. After driving up through the escarpment capped by the poorly expressed Poison Strip Member, turn right and park on the oil-well pad, where we will have lunch and examine the Yellow Cat Member in its type area.

West End of the Poison Strip – The Yellow Cat Area

The type section of the Yellow Cat Member was initially defined by a stratigraphic section described on the west side of Gastonia Point (Kirkland and others, 1997) (figure 9). This research conducted in the early 1990s used the calcrete of Aubrey (1998) as the top of the Morrison Formation (figure 12). During the summer of 2005, while excavating the nearby Andrew's site, Kirkland recognized that both the calcrete and a chert or silcrete layer several meters lower down in the section could be correlated to another fossil-producing area known as Doelling's Bowl to the west (figure 16F to H). The chert layer is 5 to 30 cm thick, displays fine wavy bedding, and is associated with silicified root traces.

The chert layers at Doelling's Bowl had been identified as being near the base of the Cedar Mountain Formation as Early Cretaceous fossils are preserved just above this interval. Initially, when first discovered in 1990, Kirkland had assumed that the chert beds correlated to the basal calcrete. The correct correlation of the chert and calcrete bed resulted in recognizing Cedar Mountain Formation beds below the calcrete and redefining the Jurassic/Cretaceous boundary downward in this area (Dick and others, 2006). The presence of a poorly sorted, chert-pebble lag a short distance below

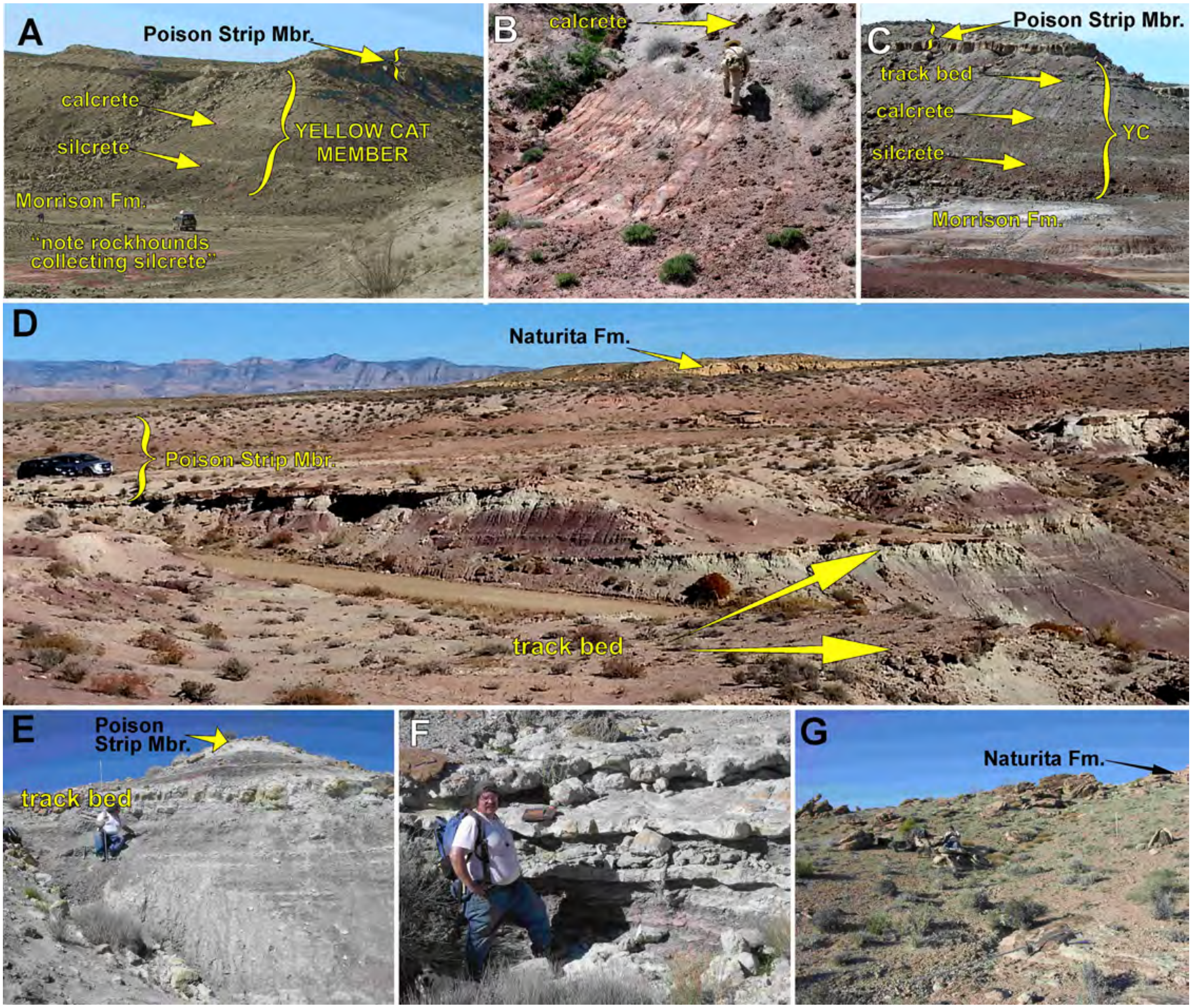

Figure 43. Cedar Mountain exposures at Yellow Cat Road section (YC) on the west end of the Poison Strip (figure 41). (A) Yellow Cat Member on the west side of the Yellow Cat Road from the northeast. Modified from Kirkland and Madsen (2007). (B) Lower Yellow Cat Member paleosols on the west side of the Yellow Cat road. (C) Same outcrop as in figure A from the east. YC = Yellow Cat Member. (D) Upper Yellow Cat and Poison Strip Members long the east side of the Yellow Cat Road. Note the difficulty in distinguishing the Poison Strip Member along the road. (E) Upper Yellow Cat as exposed just to the east of the Yellow Cat Road. (F) Series of limestone beds within the Poison Strip Member a bit farther east than shown in figure D. Laterally the limestone includes a carbonate bed that is basically a limestone conglomerate filled with broken dinosaur bone shards. (G) Poorly exposed Ruby Ranch Member at the top of the section.

the chert bed was utilized to redefine the base of the Cedar Mountain Formation in this area. This lower Yellow Cat Member represents a stack of ferruginous paleosols, separated by scours filled with chert pebbles (figure 43B). Only the upper one or two of these paleosols at the top of the lower Yellow Cat Member is characterized by pedogenic carbonate nodules (Kirkland and Madsen, 2007).

The upper Yellow Cat overlying Aubrey's (1998) calcrete is largely lacustrine with fossils concentrated in the lower and upper parts (lake margins?). Several *Nedcolbertia* have been recovered from the base of the sequence and it has been hypothesized that they became trapped in the mud at the the edge of a lacustrine system, accounting for the bias toward preserving the legs and tails of these small dinosaurs (Kirkland and others, 1998a). A laterally extensive dinosaur track site is preserved at the base of a bioturbated crevasse splay near the top of the Yellow Cat Member (Lockley and others, 1999) where the tracks are mostly preserved as natural casts (figures 22K, 42, and 43).

As with similar sites, fluvial sandstone beds are not well developed in the overlying Poison Strip Member. Where the road crosses the outcrop belt is an excellent place in which to observe how the fluvial sandstone of the Poison Strip hold up the cliffs and interfingers with the interfluvial facies from the southeast and southwest (figure 43).

Given the numerous dinosaur localities in the area and the excellent access afforded by the Yellow Cat Loop Road, a stratigraphic section was measured and described along the east side of the road to serve as a reference section for both the Yellow Cat and Poison Strip Members (figure 41). Excavations of many significant fossils have been made within 5 km of this point by the Prehistoric Museum in Price, DMNS, and the UGS. Several type species are included in this list, including the first dinosaur described from the Cedar Mountain Formation, the giant dromaeosurine *Utahraptor ostromaysorum* (Kirkland and others, 1993), *Gastonia burgei* (Kirkland, 1998a), *Nedcolbertia justinhoffmani* (Kirkland and others, 1998a), *Hippodraco scutidens* (McDonald and others, 2010), *Yurgovuchia doellingi* (Senter and others, 2012a) all from the Yellow Cat Member, and from the overlying Poison Strip Member, *Venenosaurus dicrocei* (Tidwell and others, 2001), *Planicoxa venenica* (DiCroce and Carpenter, 2001), and *Cedroestes crichtoni* (Gilpen and others, 2006). Several additional new species are under study by researchers at all three institutions. Eventually this small outcrop area will be the source of more than 10 genoholotype dinosaur specimens, making it one of the very most important paleontological research areas in the country.

In addition, this area yielded a rich assemblage of associated fossil vertebrates that includes lungfish tooth plates, a hybodont shark spine fragments and teeth, and spiral coprolites preserving abundant ganoid scales, turtle shell fragments, crocodilian teeth, and rare eileenodontid sphenodontian jaw fragments.

Day 1 (PM) – Cedar Mountain Formation on the West Side of Arches National Park Region

Following lunch, we will drive north to I-70 then west to Crescent Junction (with a brief stop at the Utah Welcome Center at the west-bound rest area). At Crescent Junction, we will drive south on US 191 toward Moab. As we travel south, the Ruby Ranch Member of the Cedar Mountain Formation is visible on the left side of road toward the west-dipping slope formed by the Salt Valley anticline in Arches National Park. After travelling about 13.2 miles, we will pass the Moab Airport on the right. We will turn left onto the Klondike Bluffs Road, a dirt road 1.5 miles south of the airport. Traveling southeast on this winding road, we will pass through the Cedar Mountain section for a few miles. Take a left as we drop into the Little Salt Valley and drive about 1.5 miles to the next stop where we will examine the Yellow Cat Member of the Cedar Mountain Formation before proceeding back up through the Klondike Road section (figure 44).

Klondike Bluffs Section – Yellow Cat through lower Ruby Ranch Members

A poorly indurated pebble conglomerate marks the base of the Yellow Cat Member at this section. Paleosols are only moderately well developed in the red mudstone beds of the lower Yellow Cat Member, but there are a number of unusually preserved casts of small *in situ* tree stumps (figure 44G). A bluish-gray, cherty limestone has been picked as the top of the lower Yellow Cat, but the contact may be higher in the section. A second ledge-forming septarized limestone bed occurs higher in the section with carbonate nodules occurring below the bed. Therefore, picking the contact between the lower and upper Yellow Cat is not as clear as in sections farther north. Dinosaur fossils are preserved in the upper Yellow Cat in this area with one site best described as a fragmentary dinosaur bone conglomerate with many small pieces of complexly pneumatic sauropod vertebra. Intact material consists of sauropod toe bones, spatulate sauropod teeth, and theropod teeth. This site has never been investigated properly.

The base of the Poison Strip Member is a sharp contact and placed at the base of a thick fluvial sandstone that is exposed along the entire western side of Arches National Park (figures 15K, 21B, 44A, and 44F). The top of the Poison Strip Member consists of an amalgam of sandstone channels and interfluvial units (figure 15K). At the Klondike Bluffs section, isolated ribbon sandstone beds in the lower Ruby Ranch Member may cut down into the top of the Poison Strip Member, making the pick of the upper contact difficult (figure 45A). However, tracing these sandstone beds laterally demonstrates that they interfinger with a continuous sequence of mudstone beds with abundant pedogenic carbonate nodules.

The lower Ruby Ranch Member is typical of exposures across the northern Paradox Basin. It is composed mostly of pale-purplish-red to pale-green mudstone slopes covered with carbonate nodules and includes isolated southwest- to northeast-trending ribbon sandstone beds. One dinosaur site is recorded south of the section that included an iguanodont jaw fragment in the float. The site is unusual as the bone is permineralized in red chert like many bone sites in the Morrison Formation. Carbonate nodules are pervasive in the site and may partially to completely encase many of the bones. As difficult as this site may be to excavate, it certainly deserves a more careful exploration in the future.

We will drive slowly back up the road to observe these characteristics of the Poison Strip and lower Ruby Ranch Members. After crossing the top of the lower Ruby Ranch Member, turn right on a small track heading directly west and park on the broad bench formed by the Klondike River facies of the Ruby Ranch Member.

Klondike Bluffs Section – Klondike River and Lake Carpenter Facies

In about 2010, Kirkland was contacted by Ken Carpenter regarding a thick lacustrine sequence in the Naturita Formation (= Dakota Formation) east of the Moab airport. On inspecting the site, we found that the lacustrine sequence was capped by the quartzite-rich pebble conglomerate of the basal Naturita (= Dakota). These strata had been mapped as part of the Naturita Formation (= Dakota Formation) since they were organic rich in their lower part and rested upon a thick, laterally extensive conglomeratic fluvial sandstone (e.g., Doelling, 1985). This conglomerate consists mostly of gravel-sized chert pebbles with some larger carbonate clasts derived from the underlying Ruby Ranch Member (figure 45B). Additionally, from the top of the main bluff capping our section, we observed that this fluvial sequence was simply a very large ribbon sandstone, 0.4 km across and extending north along the west side of Arches National Park, that we refer to as the Klondike River.

The base of the lacustrine sequence includes organic-rich strata initially described as coaly. These strata preserve the only identifiable plant material in the Ruby Ranch Member and include fragments of the horsetail *Equisetem* and ferns. These strata (figure 45C) are in a greenish weathering zone that preserves a siliceous dolostone at its base. We correlate that basal siliceous dolostone to the siliceous dolostone preserving the Mill Canyon Dinosaur Tracksite 4.7 km south-southwest of here (Lockley and others, 2014a, 2014b) (figure 45E). These dolostones were at first thought to represent altered volcanic ash; they are not. However, they were sampled for zircons and the second one up section (figure 45C) yielded a maximum age of 113 to 112 Ma (Montgomery, 2014). This age, however, may soon be irrelevant as samples collected from several volcanic ashes in the lower part of the sequence are pending and could potentially provide more accurate U-Pb ages. It is useful, at least locally, to note that the main body of the lacustrine sequence may be divided into three subequal intervals based on the overall color of the weathered strata. These are:

(1) Lower third of the sequence weathers drab green and is characterized by dark organic shales with plant debris, light-gray siliceous dolostone and sandstone. Tiny (1–2 mm) reddish-brown vesicular beads of calcite are a unique character-

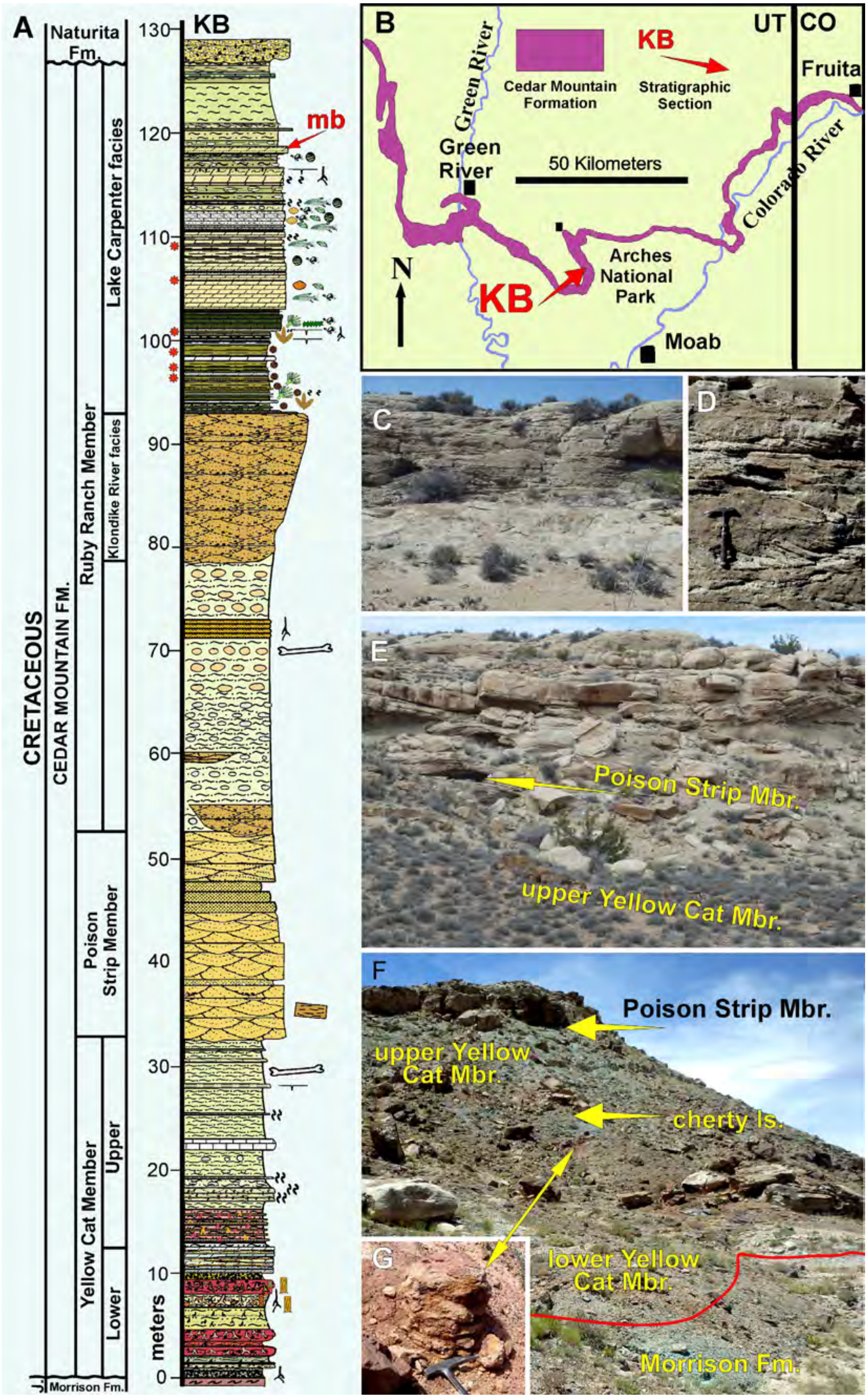

Figure 44. Caption on following page.

Figure 44 (figure on previous page). Klondike Bluffs Road Section (KB) and the lower Cedar Mountain Formation. (A) Klondike Bluff Road section (KB, figure 11) measured in four parts: 1) the lower section of the Yellow Cat Member was measured from 38°46'4.68"N, 109°42'34.45"W to 38°46'4.53"N, 109°42'38.81"W, 2) the middle section of the Poison Strip Member through the Klondike River facies of the Ruby Ranch Member from 38°46'16.89"N, 38°46'16.89"N to 38°46'6.62"N, 109°43'31.51"W, 3) the Lake Carpenter section was trenched by a track-hoe from 38°45'54.00"N, 109°43'36.83"W to 38°45'59.52"N, 109°43'39.68"W, and the last short interval from the dense brown dolomite marker bed to the basal Naturita conglomerate from 38°45'55.20"N, 109°43'51.68"W to 38°45'54.84"N, 109°43'52.73"W. Explanation of symbols in figure 10. (B) Index map for section. (C) Portion of Poison Strip Member. (D) Trough cross-bedding in course-grained sandstone to pebble conglomerate trending to the northeast. (E) Contact between the Yellow Cat and Poison Strip Members at the base of the middle section. (F) Yellow Cat Member of Cedar Mountain (lower section). Red line represents basal contact with Morrison Formation. (G) Sandstone filled stump in lower Yellow Cat Member with arrow indicating position in section in figure F.

istic of this interval.

(2) Middle interval weathers silvery gray and is characterized by fresh dark olive-black, well-laminated, calcareous shale, dolostone, and high-magnesium carbonate with fish debris. This interval appears to represent the deepest water and has the greatest lateral extent.

(3) Upper interval weathers yellowish and consists of pale-yellowish-gray limestone and dolostone preserving freshwater mollusks and fish debris capped by a resistant dark-brownish-stained dolostone marker bed.

We recognize the same three intervals to the south along the axis of the lake at the Mill Canyon Dinosaur Tracksite. The same lithostratigraphy of the limestone sequence at both sites supports our correlation between these areas.

The recognition of fish fossils raised hopes that complete fish might be located within these beds. Therefore, the Universty of Texas at San Antonio funded a trench to be excavated through these beds to collect fresh material for lithological and geochemical analysis, and perhaps uncover more complete vertebrate remains. Although no significant vertebrate remains were found, a significant amount of data resulted. The section excavated and described is approximately 30-m thick and starts at the top of a prominent conglomerate ("Klondike River facies"). Samples were collected every 25 cm to develop a C-isotope chemostratigraphic profile (figure 46) in an attempt to correlate this section with existing chemostratigraphic sections in the Ruby Ranch Member, and with global C-isotope chemostratigraphic profiles. The $\delta^{13}C_{org}$ profile correlated well with the existing profiles of Ludvigson and others (2010) suggesting the Lake Carpenter facies also span the Aptian-Albian boundary. This includes C-isotope segments C9-C11 of Bralower and others (1999). Lithologically, the lake sequence shows an overall shallowing environment. Many of the carbonate beds are dolomitic, and stable isotope analyses of the bulk carbonate reveals positive covariance in the $\delta^{18}O$ and $\delta^{13}C$ plots, both of which suggest a closed-basin lacustrine environment (figure 46). Interestingly, the $\delta^{18}O_{CO3}$ values have a distinct shift toward lighter values upsection which may indicate an increase in high altitude run off similar to the interpretation of $\delta^{18}O_{PO4}$ by Suarez and others (2014). The trench was reclaimed, but we hope to secure a full research core through this entire sequence, especially considering the amount of data already recovered from this simple trench.

No other sequence like this has been identified elsewhere in the Ruby Ranch Member. The Ruby Ranch Member underlying the Klondike River facies compares well in thickness with sections of the complete Ruby Ranch section to the east and to the west (figure 11). Additionally, this upper Ruby Ranch lacustrine sequence seems to extend nearly the entire length of the western side of the Salt Valley anticline from the north end of the structure south to near the end of this outcrop belt near Dalton Wells. Given this pattern we hypothesize that this lacustrine system was a result of Early Cretaceous salt tectonic activity with subsidence along the west side of the Salt Valley anticline resulting from

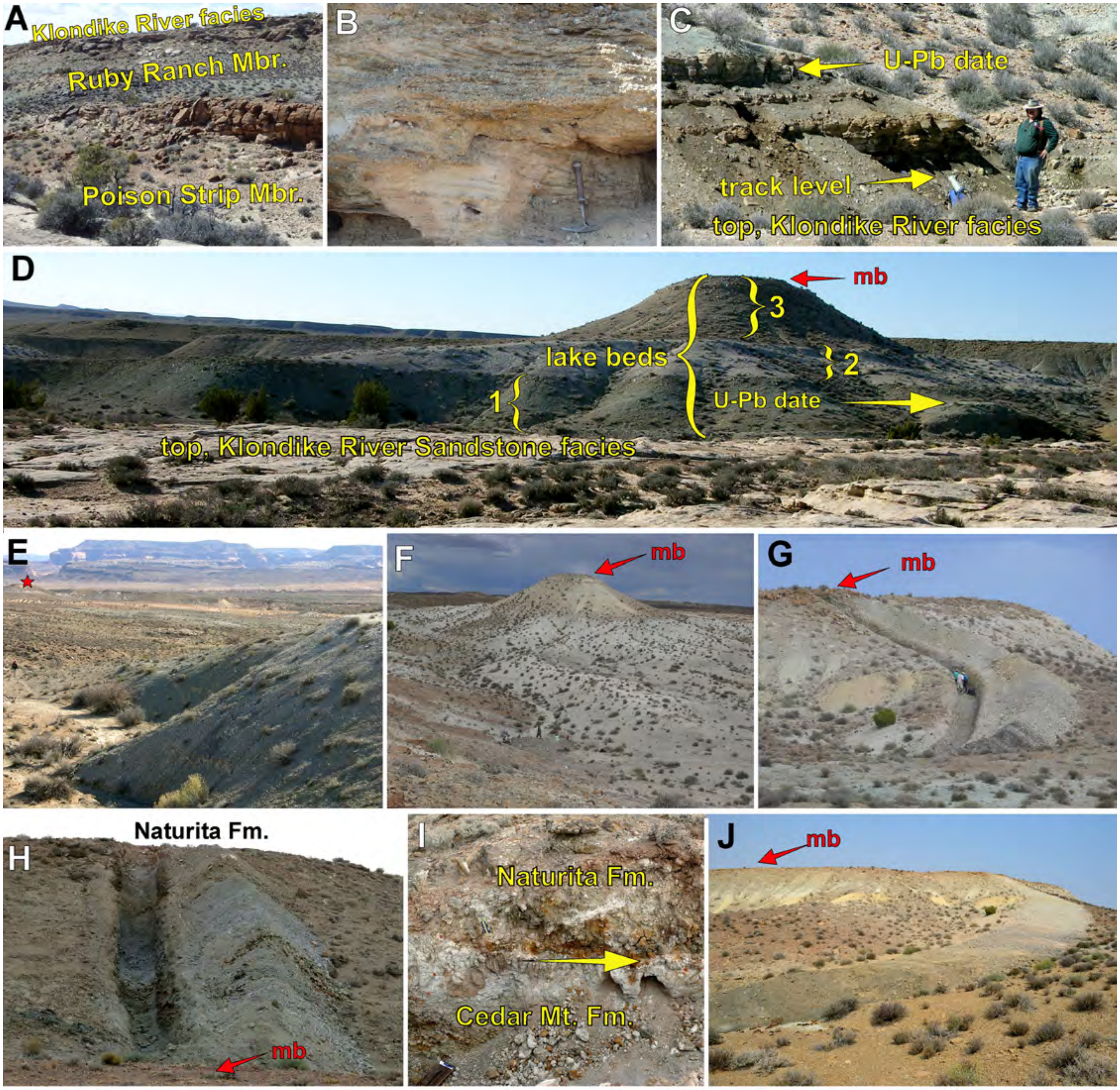

Figure 45. Caption on following page.

salt shifting into the axis of the anticline from the west. Doelling (1985, 1988; Doelling and Kuehne, 2013a) had speculated that salt tectonics continued in the northern Paradox Basin into the Early Cretaceous; these data support their hypothesis. Beyond our research on the section at the Klondike Bluffs Road area and research by Montgomery (2014) and research on the Mill Canyon Dinosaur Tracksite by Lockley and others (2014a, 2014b), there has been little research on the lacustrine strata in the Lake Carpenter facies. We and others have noticed that this sequence is nearly completely composed of highly smectitic clays in the northern end of

Figure 45 (figure on previous page). Upper Cedar Mountain Formation at the Klondike Bluff Section (KB, figures 44 and 11). (A) Upper part of middle section with dark-brown ribbon sandstone at base of Ruby Ranch Member cutting down into top of the lighter, more laterally extensive sandstone of the Poison Strip Member; Klondike River sandstone facies capping bluff above typical section of the Ruby Ranch Member. (B) Coarse-grained, trough cross-bedded Klondike River facies conglomerate with many large multi-centimeter, angular carbonate interclasts derived from underlying Ruby Ranch Member. (C) Basal organic-rich (coaly) Lake Carpenter facies with siliceous dolostone that correlates with or nearly with the Mill Canyon dinosaur tracksite. Position of siliceous dolostone sample for U-Pb dating that yields a proximately 113 to 112 Ma maximum age. (D) Well-exposed Lake Carpenter facies west of Moab airport viewed from east with three-fold division of well developed lacustrine Lake Carpenter facies: 1) low drab green organic shale, gray siliceous dolostone, sandstone, and plant debris; 2) middle interval weathering silvery gray (fresh dark olive black), well-laminated, calcareous shale, dolostone, and high-magnesium carbonates with fish debris; and 3) upper yellowish limestone and dolostone interval with scattered freshwater mollusks and fish debris capped by dark brownish marked dolostone. (E) View toward south-southwest along thalwag of Klondike River to Mill Canyon dinosaur tracksite designated by red star. (F) View of exposures of Lake Carpenter facies as viewed from the northwest. (G) Sampling track-hoed trench through Lake Carpenter for geochemistry and microfossils. (H) Upper trench below Naturita Formation. (I) Upper contact of Cedar Mountain Formation with basal conglomerate of Naturita Formation. (J) Reclaimed track-hoed trench; mb = dense, dark-brown dolostone marker bed.

the lake (Kirkland and others, 1997, 1999; Mori, 2009) and considered this to be a lens of the Mussentuchit Member preserved east of the San Rafael Swell. This is not compatable with our current understanding of these strata, as the first quartzite-rich conglomerate of the 3rd Cedar Mountain chronofacies (Hunt and others, 2011; Hunt, 2016) marking the base of the Muddy-Mowry sequence occur above the Lake Carpenter facies (figures 37, 45I). Perhaps, wind directions across the surface of the lake were predominately to the north, such that floating vesicular glass shards from volcanic ash falls tended to drift north, enriching this area in ash that altered to smectite. Future research on this system would prove or disprove this hypothesis.

Following our examination of the Klondike River and Lake Carpenter facies of the Ruby Ranch Member, we will return to US 191 and head south (left turn) for 2.5 miles where we will turn left onto the dirt road at Dalton Wells. We will drive a few hundred meters and park below the cottonwood trees to discuss the geological and paleontological history here.

Dalton Wells Quarry

The use of the plural term Dalton Wells, as opposed to the singular Dalton Well, has been researched by Brooks Britt, who found that use of the plural is consistent with use by the Dalton family and the local community. The use of the singular on the Merrimac Butte 7.5-minute quadrangle is an error on the part of the U.S. Geological Survey (Eberth and others, 2006). However, the use of the plural is being challenged by others (Kinneer and others, 2016). During the 1930s, a Civilian Conservation Corps (CCC) camp was established here, known as CG-32, Dalton Wells Camp. The site was also used briefly during World War II as a Japanese internment camp, of which the concrete slabs and cottonwood trees are the last remnants.

Southwest of US 191, the Moab fault cuts through the Cedar Mountain outcrop belt juxtaposing the Triassic-Jurassic Wingate Sandstone (Lucas and others, 2006; Lucas and Tanner, 2007; Kirkland and others, 2014) and the underlying Upper Triassic Chinle Formation on the west side of the fault against the Cedar Mountain Formation. This fault has been a conduit for fluids that have altered the adjoining strata (Chan and others, 2000; Garden and others, 2001), giving both the Morrison Formation and the Yellow Cat Member of the Cedar Mountain Formation their distinctive green color (Eberth and others, 2006).

The Dalton Wells Quarry is visible on the point at the west end of the escarpment, which is held up by the Poison Strip Member capping the less resistant beds of the Yellow Cat Member of the Cedar Mountain Formation above the much thicker Brushy Basin Member of the Morrison Formation to the northeast across Courthouse Wash (figure 47). The Dalton Wells Quarry is very significant in the history of paleontological research on

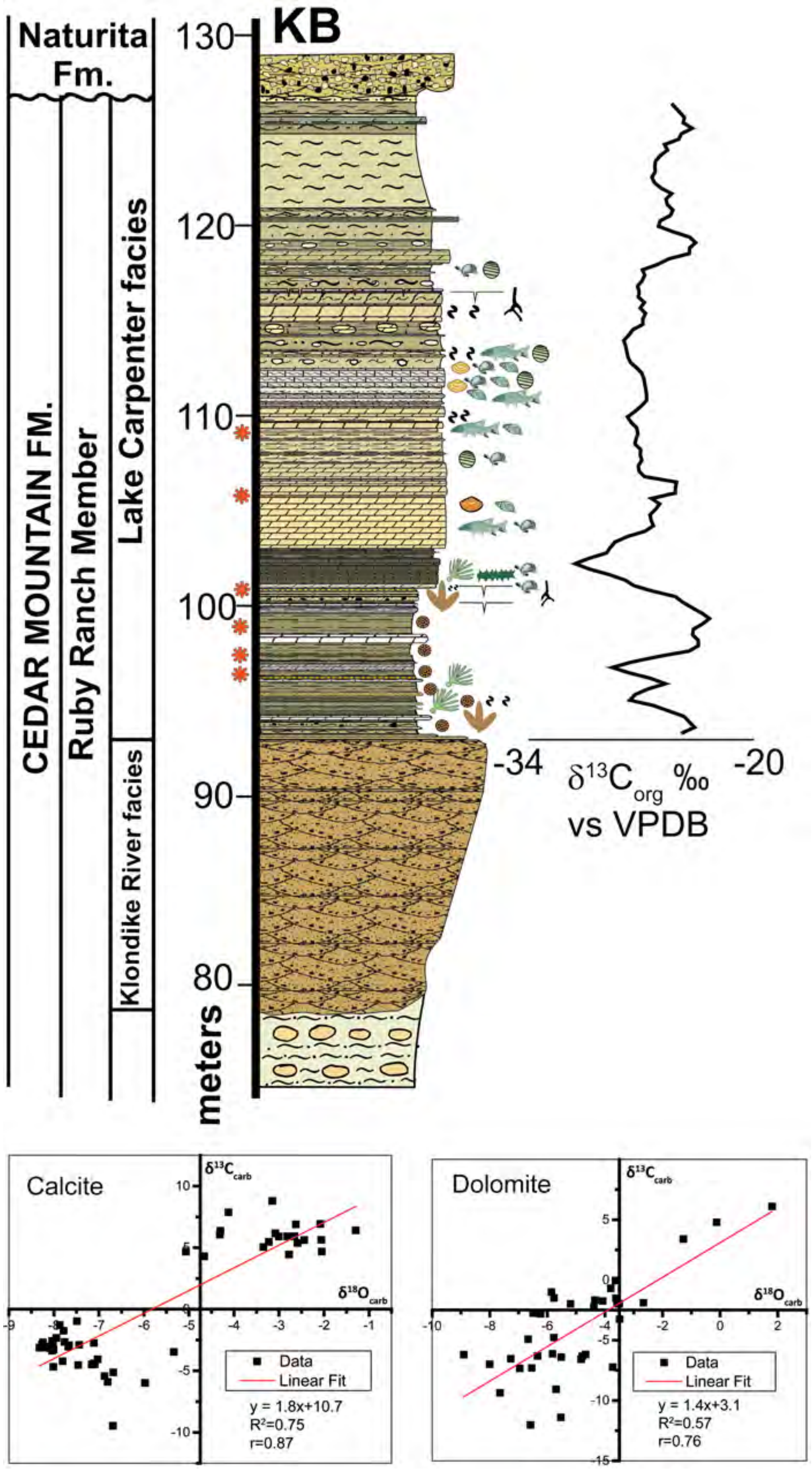

Figure 46. Detailed lithological profile of the upper Ruby Ranch portion of the Klondike Bluffs section (KB) with carbon isotope profile of bulk sedimentary organic carbon from Montgomery (2014). Also shown are the $\delta^{18}O$ versus $\delta^{13}C$ cross plots of bulk carbonate samples (both calcite and dolomite) showing positive covariance in their values.

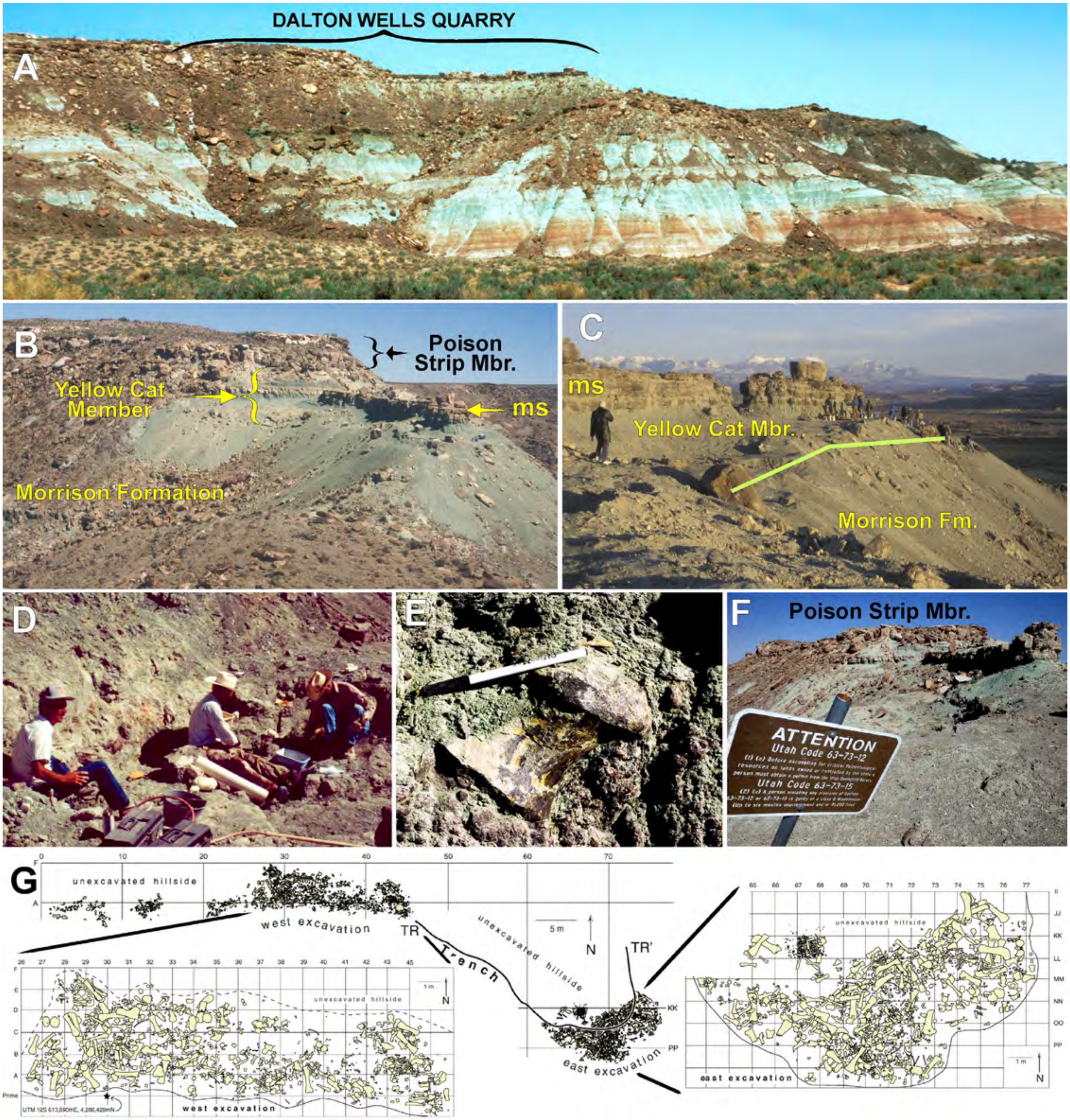

Figure 47. Dalton Wells Quarry. (A) Location of Dalton Wells Quarry near US 191. (B) View of the site from southwest. (C) View of site from northwest. (D) Brigham Young University excavation team in the 1990s pictured from right to left is Dee Hall, Brooks Britt, and Ken Stadtman. (E) Dinosaur vertebral centrum in situ. (F) Utah Fire, Forestry, and State Land's sign explaining state law forbidding the pillaging of fossil sites on state lands. (G) Quarry map from Britt and others (2009). MS = medial dinosaur track-bearing sandstone.

the Cedar Mountain Formation (Britt and Stadtman, 1997; Eberth and others, 2006; Britt and others, 2009) because: (1) it may be the first paleontological site discovered in the Cedar Mountain Formation and is certainly the first site discovered in the Yellow Cat Member, (2) it is one of the largest known single paleontological sites in the Lower Cretaceous of North America and is certainly the largest known in the Yellow Cat Member, and (3) with nine dinosaur taxa recognized, it preserves the most diverse single dinosaur fauna yet known from any single paleontological site in the Lower Cretaceous of North America. The quarry has been worked since the 1970s by BYU, and to date, more than 4200 dinosaur bones have been recovered and many thousands more await excavation. An area of only 215 m^2 has been excavated and it is estimated that the entire bonebed extends over 4000 m^2 (Eberth and others, 2006; Britt and others, 2009). The most abundant dinosaur is a yet to be named sauropod nick-named "Moabosaurus" with a minimum of 17 individuals (figures 17O and 17P). The locality is managed by the Utah Division of Forestry, Fire, and State Lands.

The Yellow Cat section is extremely thin at this site (figure 47) and, as on the entire west side of Arches National Park, there is no massive pedogenic carbonate in the Yellow Cat Member or for that matter, no carbonate beds at all. The base of the Yellow Cat is placed at the first concentration of chert pebbles, which is at the base of the bonebeds. Eberth and others (2006) interpreted the site to represent a 2-m-thick succession of four stacked bonebeds deposited in a back-bulge setting by subaerial debris flows (cohesive mudflows) triggered by intense rainfall or seismic events, which transported the bones over a relatively short distance. They interpreted the carbonate cementation of the poorly sorted host matrix to represent a calcrete formed through diagenesis and not paleosol development. We concur that there is no genetic relationship between the calcretes north of Arches National Park and the bonebeds at Dalton Wells. We consider that as opposed to a back-bulge model for depositional pattern at Dalton Wells, perhaps salt tectonics and the proximity to the Moab fault is in part responsible for this unusual sequence. The presence of *Utahraptor*, *Nedcolbertia*, *Cedarosaurus*, and *Gastonia* at the Dalton Wells Dinosaur Quarry supports its inclusion in the upper Yellow Cat Member as described above. Kirkland and Madsen (2007) erroneously assumed that there was no evidence of the lower Yellow Cat interval along the west side of Arches National Park, but beyond the basal pebble bed, there is no lower Yellow Cat Member at Dalton Wells.

Britt and others (2009) noted that there are mostly juvenile animals preserved at Dalton Wells. Additionally, they noted that there was an exceptional amount of bioerosion of the bones due to the activity of invertebrates.

From here we will return to US 191 and go north (turn right) for 2.3 km (1.4 miles), and, as we exit the narrows formed by the Poison Strip Member, turn left (carefully) onto the dirt Mill Canyon Road. We will follow this road for approximately 3 km (~2 miles), taking the left fork as we drive out of the dry wash onto the flats and continuing south until a right turn takes us into large parking area lined with bright red sandstone boulders. From here we will walk down the short trail to the Mill Canyon Tracksite.

Mill Canyon Dinosaur Tracksite

The Mill Canyon Dinosaur Tracksite (MCDT) was discovered by a local resident riding down the abandoned access road below the powerlines. The MCDT is in the Ruby Ranch Member of the Cedar Mountain Formation, located on BLM land near Moab, and is the largest and most diverse of the eight known Cedar Mountain tracksites. Although well known for its Lower Cretaceous vertebrate fauna, the Cedar Mountain Formation is lesser known for its dinosaur tracksites because few of its many tracksites have been described (Lockley and others, 1998, herein). Among the best known tracksites are the Arches National Park sites (Lockley and others, 2004; Martin and others, 2014) and another unnamed tracksite on Utahraptor Ridge (figures 19, 22I, and 22J) which has a large assemblage of what may be North America's oldest bird tracks (Lockley and others, 2015). Both are important locations and within a 20-km radius of the MCDT.

Preliminary findings from the MCDT site (Lockley and others, 2014a, 2014b) indicate the presence of at least eight named ichnotaxa including three distinct theropod track morphotypes, identified as *Irenesauripus*, a *Dromaeosauripus*-like form, and an unnamed ichnite. Poorly preserved bird tracks have also been identified. Sauropod tracks include *Brontopodus* and another morphotype of probable titanosaurid affinity, and manus-only sauropod undertracks. The ornithopod tracks at the site resemble *Caririchnium*.

The tracks are in the upper part of the Ruby Ranch Member. However, the trackbed is complex lithologically and best described as a light-gray, microcrystalline impure cherty dolostone, having a hardness of 5.5. The hardness of the track-bearing layer has contributed to its preservation. In fact, in addition to the main tracksite area (figure 48), which has at least 175 well-defined tracks and undertracks comprosing more than 20 trackways, there are two nearby areas, one to the north that has about 35 tracks in at least eight trackways (Lockley and others, 2014a, 2014b) and another one to the east that has about 30 tracks. Both of these areas are within about 100 m of the main site and are on the same sur-

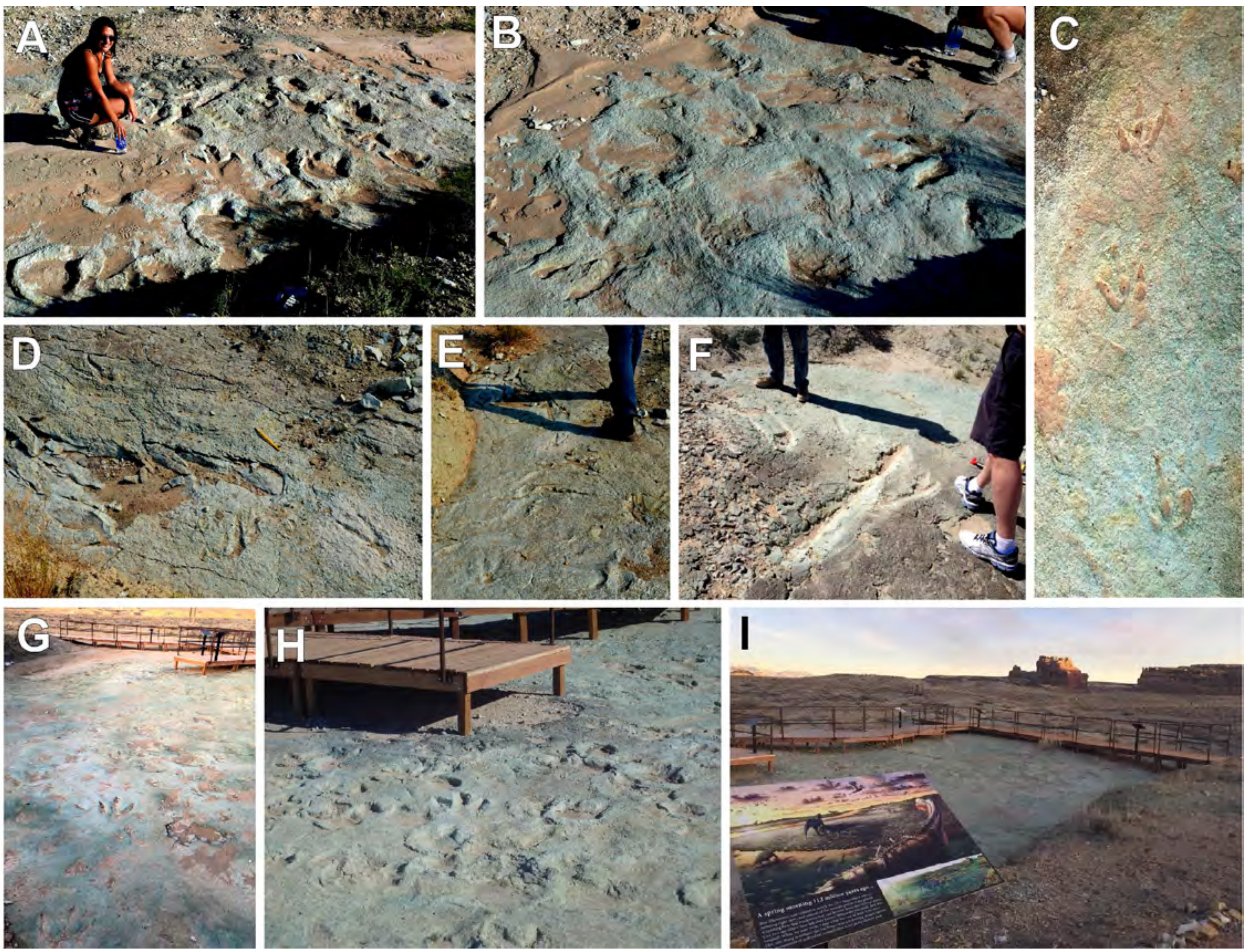

Figure 48. Mill Canyon dinosaur tracksite. (A) Soon after discovery, a sauropod-theropod dance floor. (B) More large theropod and small sauropod tracks. (C) A small theropod trackway; perhaps an ornithomimid (track length about 25 cm). (D) Dromaeosaurid trackway. (E) Another view of dromaeosaurid trackway. (F) Crocodilian resting trace. (G) Theropod heading for boardwalk. (H) site is all cleaned and ready for visitors. (I) Fully interpreted site was dedicated in 2016. Artwork in I by Brian Engh.

face, which is intermittently exposed over a large area between and around these sites.

The MCDT is one of six tracksites in different geological formations on federal land near Moab that have recently been developed for public visitation and interpretation. Partly with such developments in mind, the MCDT has been subject to special study using innovative strategies. First the site was considerably enlarged from the size of the original natural exposure, using mechanical excavation techniques, which are not often used at tetrapod tracksites. Unusually, for research in this region, this phase of work was funded through University of Colorado (Denver) by the Korean National Research Institute of Cultural Heritage. Second, the site was subject to a thorough photogrammetric survey which provided images for publications (e.g., Lockley and others, 2014b) and interpretative signs. Third, a boardwalk up to 80 m long and 2 m wide was installed over the site so that visitors can "walk with the dinosaurs" without stepping on or damaging the tracks (figure 48G to I). A shade ramada was also installed. Utah Friends of Paleontology and Moab Giants were community partners in these efforts during most phases of the project.

The MCDT has revealed a number of enigmatic traces that can broadly be described as slip and scratch marks. Some resemble swim tracks but cannot definitively be placed in this category. Likewise, the largest of these traces, a pair of elongate grooves, are only tentatively inferred to be of possible crocodilian origin (Lockley and others, 2014a). An herbivore coprolite was also found in the middle of the main site (Lockley and others, 2014b). The site has considerable potential for further excavation and future study.

From here we will return to US 191, drive north to I-70, and return to Green River, Utah, where we will spend the night.

Day 2 (AM) – Cedar Mountain Formation South of Green River, Utah

White Sands Missile Launch Complex

We leave Green River at the east end of town, crossing south over I-70 and turning left (east) on the frontage road. Abandoned steel buildings to the right were part of the (now decommissioned) Green River Missile Launch Complex, a part of the White Sands Missile Range. The site played an important part in the development of the Athena and Pershing cruise missiles as they were launched from here and crashed into White Sands, New Mexico. The army has turned this area over to the BLM, which keeps careful track of the area due to its heavy ATV usage and its scientific importance. Note, that the cuesta to the left (north) is held up by the calcarenites (transgressive carbonate sandstones) of the upper Turonian Juana Lopez Member of the Mancos Shale. After driving 5 km (3 miles) on the frontage road, turn right and proceed south on the Crystal Geyser Road.

Field crews of the Denver Museum of Science and Nature used the steel building on the right as their base of operations in the late 1990s. They recovered several isolated dinosaur bones on the dip slope formed by the basal conglomerate of the Naturita Formation (= Dakota Formation). Upper paludal and coastal sediments preserve a few resistant sandstone beds in this area and form part of the valley shaped by erosion of the basal Tununk Member of the Mancos Shale. Through much of eastern Utah and western Colorado, a lag of the small oyster *Pycnodonte newberryi* (often referred to as "Devils Toenails" and sometimes still incorrectly referred to the Jurassic genus *Gryphaea*) marks the base of the Tununk, and where the transgressive marine sandstone of the Naturita Formation (= Dakota Formation) are well preserved, the top of the Naturita (Young, 1960; Kirkland, 1996; Santucci and Kirkland, 2010). *Pycnodonte*, like *Gryphaea*, with which it is convergent, lived in shallow marine environments of normal salinity, low turbidity, and low sedimentation rates as it spent most of its life floating on its left valve on the substrate and had no ability to move on its own. Thus, it is characteristic of transgressive marine sequences (Kirkland, 1996).

The Crystal Geyser Road winds down section through the Cedar Mountain (figure 23G and H) and Morrison Formations for 2.7 km (1.7 miles), where the road turns west at an east-west-trending fault, where the Salt Wash Member of the Morrison on the north is against the Juana Lopez Member of the Mancos Shale on the south. The cold-water (CO_2) Crystal Geyser on the Green River and older Pleistocene spring and geyser carbonate deposits are associated with this fault (Kirkland and Madsen, 2007). Immediately past the bluff of Mancos Shale on the left, turn left onto the Crystal Geyser Safari Route. This road has been improved recently to facilitate the installation of a power line. After crossing the Mancos Shale for 1.3 km (0.8 miles), the road winds down and across Little Grand Wash up onto a bench formed by channel sandstones in the Poison Strip and Ruby Ranch Members. After about 0.5 km (0.25 miles), take the right fork and continue on the Crystal Geyser Safari Route. Continue to wind south and back around to the north to skirt a large ribbon sandstone in the Ruby Ranch Member. We will follow this exhumed channel sandstone on the right side (east) for the 0.8 km (0.5 miles) as we head south-southeast before dropping back down section to the level of the Brushy Basin Member. Continue south-southwest up a canyon rimmed by fluvial sandstone of the Poison Strip Member for about 0.62 km (1 mi). Pull over on a faint track and park here. The lower part of the Don's Ridge section was measured on Don's Ridge to the southwest and the upper part of the section was measured on the east side of the road (figure 49).

In this area, the Yellow Cat Member of the Cedar Mountain Formation can be divided into lower and upper sequences by a laterally continuous, calcareous, dark-brown sandstone (caprock) that may be encrusted locally by stromatolitic-looking mounds of carbonate (figures 16A-E and 49A). As with the lower Yellow Cat interval northeast of Arches National Park, the lower Yellow Cat in this area is characterized by common chert pebbles floating in fine-grained matrix and in lenses. However, paleosols are not nearly as well-developed here and the chert pebbles tend to be significantly larger.

The possible correlation of the caprock in the area of the Green River Missle Launch Complex with the gravelly, calcareous sandstone at the top of the calcrete at the Ruby Ranch Road section (figure 15C to E) needs to be tested. The excavation of vertebrate remains at sites in both areas will provide a biostratigraphic test of this correlation, as will paleomagnetic studies and acquiring more radiometric ages.

There are several important fossil sites within 1 to 2 km (mile) to the east that have been excavated and researched by the UGS in this area at the base of the Cedar Mountain Formation (figure 16A to E). The Suarez site was turned over to the Utah State University Eastern's Prehistoric Museum for excavation as discussed above. The Crystal Geyser site is currently being excavated by the North Carolina Museum of Natural History on the far side of the bench on which the UGS originally worked. Here, they have uncovered parts of a sauropod in addition to numerous bones of *Falcarius utahensis* (L.E. Zanno, North Carolina Museum of Natural History, personal communication, 2016).

Don's Ridge Dinosaur Sites

In 2005, while prospecting for fossil sites, UGS paleontologist Don DeBlieux found a relatively small area of less than 1 km^2 that preserves about a dozen bone-bearing sites at multiple stratigraphic horizons below the caprock identified at the Crystal Geyser Quarry. At least two bone-bearing intervals can be traced for several hundreds of meters and incorporate several individual sites (figure 50). The lowest interval is near the base of the lower Yellow Cat and consists mostly of broken sauropod bones in association with lenses of chert cobbles and carbonate mounds, which might represent spring deposits (Suarez and others, 2007b). Another zone of bonebeds is near the middle of the lower Yellow Cat and is also associated with lenses of chert cobbles and broken bones, but in contrast to the lower interval, preserves skeletal associations of iguanodonts, sauropods, and ankylosaurs. This area has become known as Don's Ridge.

The lower Yellow Cat is 9.3 m thick at Don's Ridge, which is more than four times thicker than in the area around the Crystal Geyser Quarry, and preserves much larger chert clasts than it does in the Crystal Geyser area to the east (figure 50C). The thickness of this interval makes it a prime candidate for paleomagnetic studies, which are being conducted by Kate Ziegler and Linda Donohoo-Hurley at the University of New Mexico. Ziegler (2008) and Ziegler and others (2007) recovered preliminary evidence that indicates the Yellow Cat was deposited, at least in part, before the magnetic long normal began at the base of the Aptian (Ogg and Hinnov, 2012).

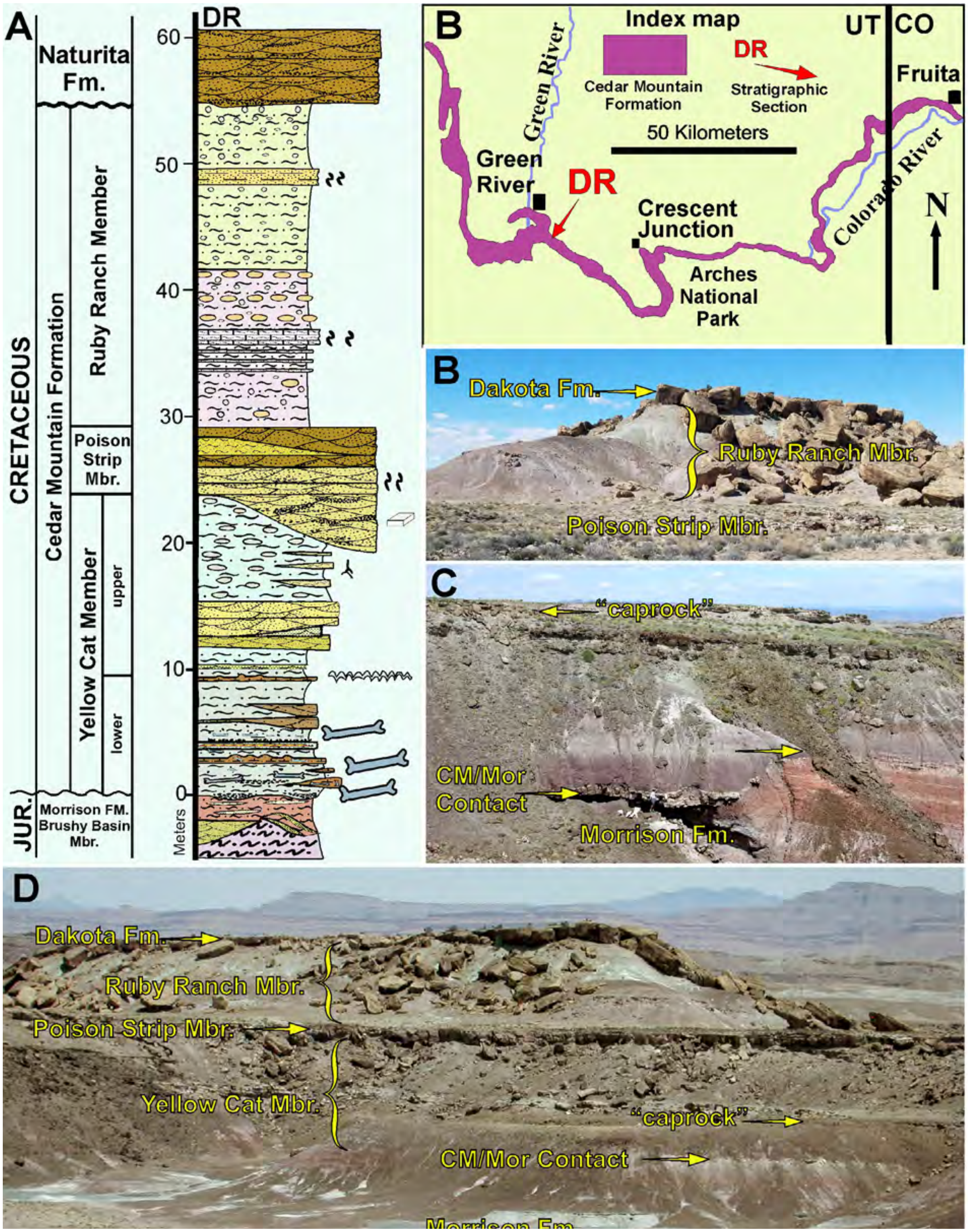

Figure 49. Don's Ridge section. (A) Cedar Mountain section at Don's Ridge (DR) measured roughly from 38°53'40.68"N, 110° 5'40.38"W to 38°54'22.20"N, 110° 5'29.51"W. Stratigraphic symbols after figure 10. (B) Index map for stratigraphic section. (C) Ruby Ranch Member of Cedar Mountain Formation at top of the section. (D) Unusual example of significant erosional relief on the surface of the Morrison Formation prior to Cedar Mountain deposition. (E) Cedar Mountain Formation north of Don's Ridge.

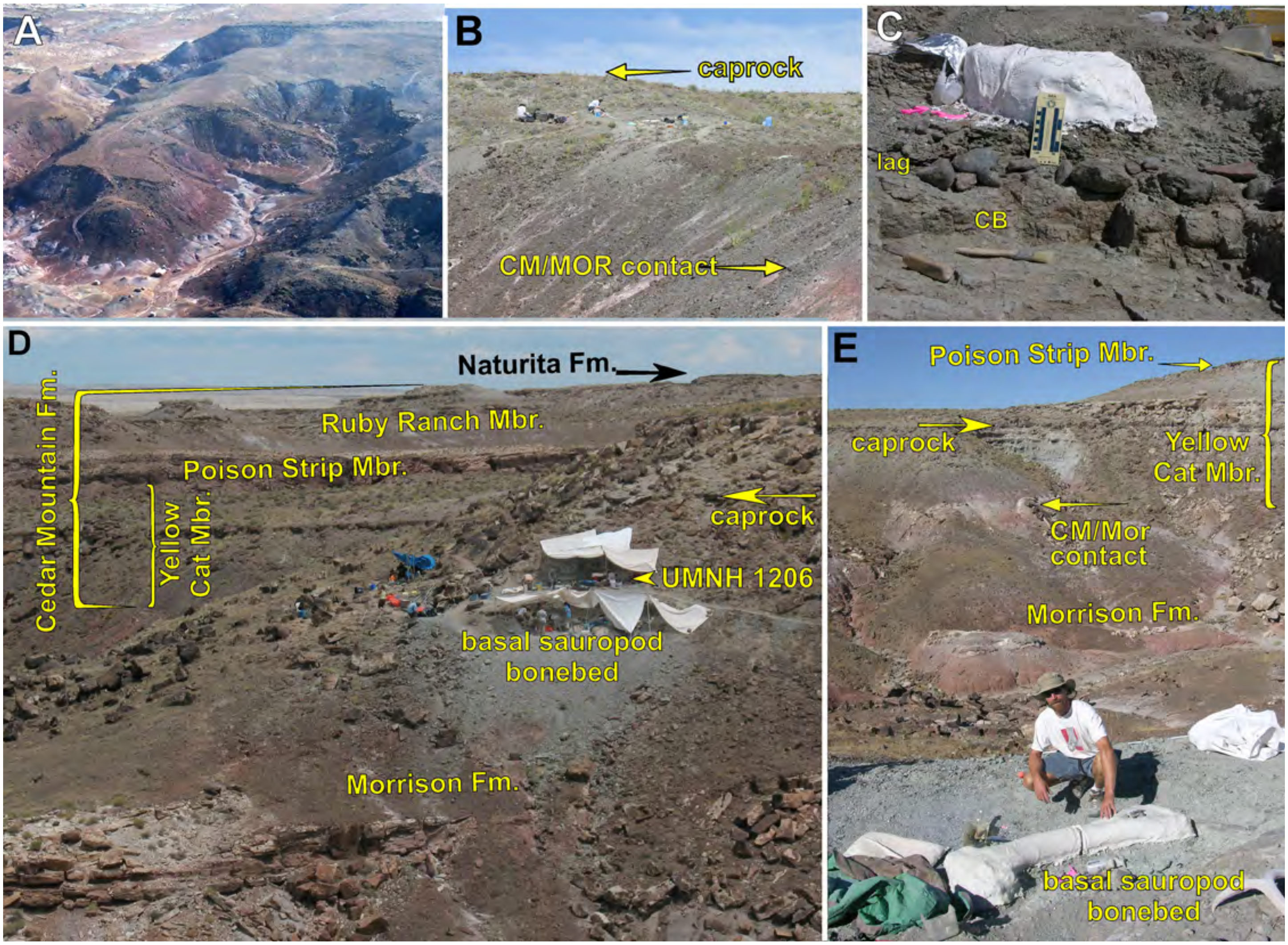

Figure 50. Don's Ridge Dinosaur sites. (A) Aerial view of Don's Ridge from northeast. (B) Lower Yellow Cat section at Don's Ridge south; CM/MOR = Cedar Mountain-Morrison Formations. (C) Upper dinosaur site at Don's Ridge south with cobble to pebble lag below bone layer resting on zone of thin chert layers (CB). (D) Cedar Mountain section as viewed from Don's Ridge north, *Iguanocolossus* type locality (UMNH 1206) above bonebed of mostly broken sauropod bones with chert cobbles. (E) Yellow Cat section viewed from *Iguanocolossus* type locality as Don DeBlieux poses with rare intact, jacketed sauropod humerus.

It is interesting that the lower Yellow Cat, as well as the entire Yellow Cat Member, pinches out a few kilometers to the west (figure 23G and H). Preliminarily, it is thought that the lower Yellow Cat interval at Don's Ridge represents a mixed-load river system developed on the unconformity at the base of the Cedar Mountain Formation (figure 49C). Additionally, the larger size of the chert clasts (having a maximum diameter of greater than 30 cm) suggests that perhaps the lower Yellow Cat at Don's Ridge has a genetic relationship with the Buckhorn Conglomerate in its type area, implying that the Buckhorn Conglomerate is older than the Poison Strip Member. Research at the Don's Ridge area is still ongoing and promises to be very productive geologically and paleontologically.

From here we will return to I-70 at Green River and drive west for 26 km (16.2 miles) before exiting at the Hanksville exit (Exit 149). As we drive west on I-70, we will drop down section from the Juana Lopez Member of the Mancos Shale through the Ruby Ranch Member of the Cedar Mountain Formation. It is important to note that the Naturita (= Dakota) is absent here as in many areas in the vicinity of the San Rafael Swell (Eaton and others, 1990; Kirkland and Madsen, 2007). At this exit we will turn right on the dirt road along the base of the Buckhorn- Morrison escarpment and drive west for approximately 1.6 km (1 mile) to have lunch and discuss the nature of the Cedar Mountain Formation in the Buckmaster Draw area.

Buckmaster Draw Section

Looking up the long slope formed by the Brushy Basin Member of the Morriosn Formation, the capping Buckhorn Conglomerate Member of the Cedar Mountain Formation is clearly visible. The large boulders along the road are also Buckhorn that have rolled down the slope. A stratigraphic section was measured to document the rapid thinning of the Cedar Mountain below the unconformity at the base of the Mancos Shale and to accurately locate and describe the upper contact. This was done a few kilometers north in the Buckmaster mining district. At this section, the Buckhorn Conglomerate is absent and the Yellow Cat facies of the Buckhorn Conglomerate forms the base of the section below the Ruby Ranch Member (figure 51). The basal Cedar Mountain contact is placed at the base of a thin conglomeratic mudstone that unconformably overlies a yellowish-orange-stained upper contact of the Morrison Formation. There is only 5.5 m of Yellow Cat facies with a well-developed zone of chert beds in the middle of the member below the carbonate-nodule-rich mudstone of the Ruby Ranch Member. Looking south, a thick cliff formed by beds of the correlative Buckhorn Conglomerate is visible above our lunch spot (figure 51E). To the north the Buckhorn Conglomerate forms the base of the section again 17 km north of I-70 and continues without a break to the north end of the San Rafael Swell.

The Ruby Ranch Member includes several ribbon sandstone beds in the area and is unconformably truncated by a pebble bed mixed with shells of *Pycnodonte newberryi* at the base of the Tununk Member of the Mancos Shale (figure 51A).

Day 2 (PM) – Cedar Mountain Formation West of Hanksville

Following lunch, we will proceed back south across I-70 and continue on SR 24 for 66 km (41 mi) to Hanksville. To the right, the flatirons of the Lower Jurassic Navajo Sandstone form the San Rafael Reef for most of the drive to Hanksville. The first 6.5 km (4 mi) we will drive on top of the Salt Wash Member of the Morrison Formation. Buckhorn Conglomerate caps slopes of the Brushy Basin Member of the Morrison Formation on the left (east). As we drop down section through the basal Tidwell Member of the Morrison Formation into the upper Summerville Formation of the San Rafael Group to the San Rafael River, we cross an approximately 40-km-wide saddle of Middle Jurassic San Rafael Group strata geographically separating Upper Jurassic and Lower Cretaceous strata on the eastern side of the Paradox Basin from correlative strata on the north end of the Henry Mountains Basin. An extensive dune field discontinuously covers these Jurassic strata across this saddle. There is a combination of active dunes and dunes stabilized by vegetation. This probably reflects an environment similar to that of the lower Campanian Djadokhta Formation in Mongolia's Gobi Desert. There is an abundance of small vertebrates (lizards, birds, and mammals) living in the high desert on the Colorado Plateau as there were in the Late Cretaceous of the Gobi Desert. Coyote and bobcat would reflect the Cretaceous carnivores like *Velociraptor* and *Oviraptor*, while the pronghorn would be analogous with herbivores such as *Protoceratops* and *Pinacosaurus*.

In Hanksville, we will turn right (west) on SR 95 toward Capitol Reef National Park. Following the Fremont River for the next 6 miles, we will slowly rise up section through the upper San Rafael Group to the Brushy Basin Member of the Morrison Formation. Here we will pull over well to the right side of the road to discuss the absence of the Cedar Mountain Formation on the east side of the Henry Mountains Basin.

Hanksville Section

Identification of the formations at the Hanksville section was the subject of considerable debate (Kirkland and Madsen, 2007). At this section, the Naturita Formation (= Dakota Formation) includes a lower conglomerate unit, a middle carbonaceous unit, and an upper condensed transgressive sandstone unit, a succession that is typical across much of the Colorado Plateau (Young, 1960; Kirkland, 1990, 1991). However, underlying the Naturita (= Dakota), Kirkland (in Kirkland and Madsen, 2007) argued that the light-colored interval below the Naturita Formation (= Dakota Formation) (figure 52) represented the Cedar Mountain Formation as it does in sections on the west side of the Henry Mountains Basin; whereas Madsen considered this interval the upper Morrison Formation, arguing that Cedar Mountain Formation was not preseved at this section.

During April 2005, the UGS Geologic Mapping Program organized a trip to define mapping units in the Cedar Mountain Formation for future mapping of geological maps at the 7.5-minute quadrangle scale. An ash was identified at this section a short distance below the contact with the Naturita Formation (= Dakota Formation) and Bart Kowallis of Brigham Young University offered to date it. Kowallis and others (2007) reported the age of the ash as Late Jurassic, confirming that the Morrison Formation directly underlies the conglomerate at the base of the Naturita Formation (= Dakota Formation) and validating Madsen's hypothesis (figure 52). Kowallis and others (2007) also proposed that the conglomerate at the base of the Naturita Formation (= Dakota Formation) might represent the Buckhorn Conglomerate, but the abundance of Eureka Quartzite clasts in the conglomerate identifies it as the Naturita Formation (= Dakota Formation) (Hunt and others, 2011).

Along this outcrop to the northwest, for about 10 km to approximately the latitude of the Morrison Hanksville-Burpee Quarry near Muddy Creek, the Naturita Formation (= Dakota Formation) appears to pinch out. Thirteen km to the northwest at the north end of the Henry Mountains Basin where the ford across Muddy Creek on the southwest side of the San Rafael Swell, a well-developed Cedar Mountain section is directly and unconformably overlain by the Tununk Member. A study of these stratigraphic relationships is very much a practical undertaking across this entire interval as there is a continuous, well-exposed outcrop belt. At the next stop, the Cedar Mountain section is much like that at Muddy Creek. The southeastern pinch out of the Cedar Mountain Formation in that area on the western side of the Henry Mountains Basin is south of Notom near the southern Wayne County line (figures 1 and 4).

From here we will drive west. For about the next 23 km we will cross Upper Cretaceous outcrops in the northern Henry Mountains Basin. For the most part, we will be driving on the Ferron Sandstone Member of the Mancos Shale capping the Tununk Member. This middle to upper Turonian delta complex is correlative to the shelf deposits represented by the Juana Lopez Member to the east. Extending the length of the Henry Mountains Basin and western San Rafael Swell, the Ferron is probably the best exposed large delta sequence in the world and a source of considerable organic fuel resources. It is a natural laboratory for researchers the world over. To the north is Factory Butte, which is formed by the Blue Gate Shale Member capped by the Muley Canyon Sandstone; both are members of the Mancos Shale (Eaton, 1990). Our Muddy Creek section is north of Factory Butte at the north end of the Henry Mountains Basin (figure 53).

Passing between the North and South Cainville Mesas, we will drive south along the Cainville Reef, which bounds the northwest side of the Henry Mountains Basin and the southeast side of the San Rafael Swell. For 10 km (6 mi), the Ferron Sandstone and Tununk Member are exposed on the left (east) and the Cedar Mountain Formation is exposed on the right. Note the absence of the Naturita Formation (= Dakota Formation) in this area. Following the westward curve in the road around the south end of the Caineville Reef, turn right into the west entrance to the Fremont River Ford.

Caineville Reef

Exposures of the Cedar Mountain Formation in this area are of particular interest because of rapid facies changes relative to the basal Buckhorn Conglomerate and the upper contact at the unconformity at the base of the Tununk Member.

Looking north across the Fremont River, a well-developed cliff of Buckhorn Conglomerate separates the underlying Morrison Formation from the Ruby Ranch Member of the Cedar Mountain Formation (figure 54A). Approximately 2.6 km (mi) to the northwest and

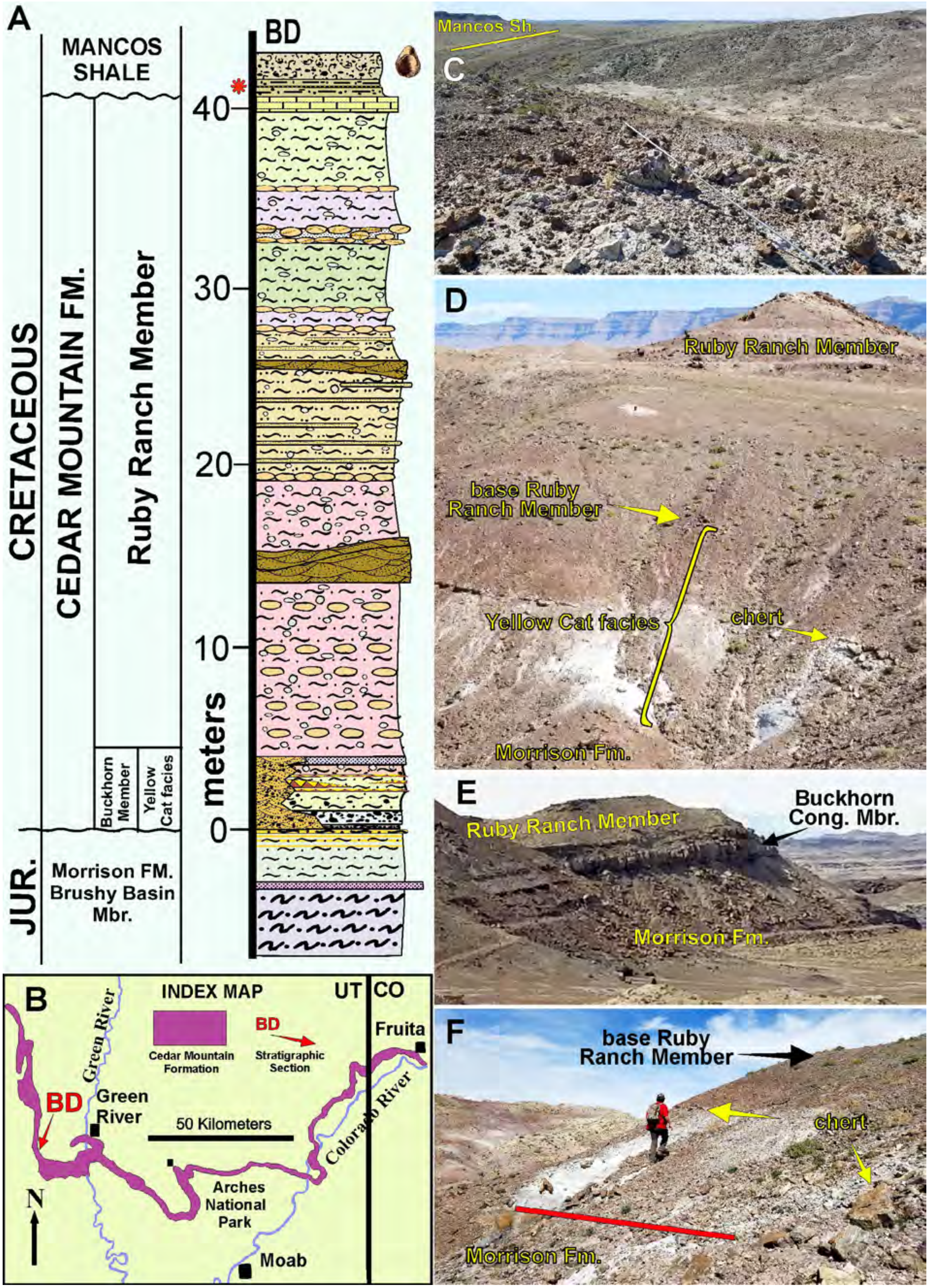

Figure 51. Caption on following page.

Figure 51 (figure on previous page). Cedar Mountain section along the eastern margin of the San Rafael Swell at Buckmaster Draw. (A) Stratigraphic section at near Buckmaster Draw (BD) measured from 38°58'17.19"N, 110°21'47.48"W to 38°58'18.33"N, 110°21'35.63"W. See figure 10 for explanation. (B) Index map for section. Stratigraphic symbols after figure 10. (C) Upper Ruby Ranch Member unconformably overlain by Tununk Member of the Mancos Shale. (D) Lower half of section with Yellow Cat facies of Buckhorn Conglomerate Member overlain by Ruby Ranch Member. (E) View to south from base of section showing well developed cliff-forming Buckhorn Conglomerate Member. (F) Yellow Cat facies of Buckhorn Conglomerate Member with basal pebbly mudstone resting on iron oxide stained upper contact of Morrison and well-developed chert beds near center of unit.

west of the East Hartnet Road, we excavated a partial skeleton of an ornithopod from near the top of the Cedar Mountain Formation, which is still under study. Although we only described the top of the section to put the skeleton into stratigraphic context, it was clear that a thick Ruby Ranch Member overlies a well-developed Buckhorn Conglomerate. Like elsewhere in the region, the Tununk Member unconformably overlies the smectitic transitional facies of the Ruby Ranch Member. McLlelland and others (2007) mapped the southern pinch out of the Naturita Formation (= Dakota Formation) just north of our excavation site. The Ruby Ranch Member is several times thicker than measured at the Muddy Creek section 32 km to the north-northwest toward the eastern pinch out of the Cedar Mountain Formation. A U-Pb age (zircon) for the base of the Ruby Ranch Member of 103.7 ± 2.6 Ma (Ludvigson and others, 2015) suggests that the upper Ruby Ranch was onlapping an unconformable surface on the Buckhorn Conglomerate (figure 53).

Along Caineville Reef, well-developed basal Cedar Mountain conglomerate beds come and go as discontinuous Buckhorn Conglomerate (McLlelland and others, 2007). However, as can be seen in these outcrops, a conglomerate caprock often occurs at the top of the sandy Buckhorn Conglomerate Member well above the unconformable contact at the base of the Cretaceous (figure 53D and F). Although Kirkland and Madsen (2007) have not studied the Cedar Mountain in this area to the same degree that they had in other areas, they proposed that the lower steep, light-colored interval consisting of stacked fine-grained sandstone and conglomeratic lenses (figure 54) represents the Buckhorn Conglomerate Member. This interval is similar to what is exposed just to the northeast of the Fremont River, and these beds represent a lateral facies of the main Buckhorn river channel. Another hypothesis we have considered is that, in this area, the coarse-grained strata correlative to the Poison Strip Member directly overlie strata correlative to the Buckhorn Conglomerate. Greenhalgh (2006) and Greenhalgh and Britt (2007) proposed that these fine-grained sandstone beds represent the Yellow Cat Member of the Cedar Mountain Formation interfingering with the Buckhorn Conglomerate. We concur that these strata are in fact correlative with at least the lower Yellow Cat, but we fail to recognize the characteristics we have noted elsewhere in the interfluvial Yellow Cat facies of the Buckhorn Conglomerate Member. For mapping purposes, splitting these units would be impractical.

The overlying pale-colored variegated mudstone preserves common pedogenic carbonate nodules and compares well lithologically with the Ruby Ranch Member of the Cedar Mountain Formation elsewhere. This section also compares well with the Cedar Mountain section north of Muddy Creek, which we have studied in more detail.

The Ruby Ranch Member of the Cedar Mountain Formation underlies the unconformity at the base of the Tununk Member in this area (figure 54). The Naturita Formation (= Dakota Formation) is completely removed by mid-Cretaceous erosion. Similar exposures are present in less accessible sections near Muddy Creek on the southwest side of the San Rafael Swell, and at the north end of Capitol Reef National Park on the west side of the Blue Flats. Eaton and others (1990) first documented this unusual contact at the top of the Cedar Mountain Formation on the west side of the San Rafael Swell near Ferron, Utah.

The basal Tununk Member at all of these sites is distinctive. It consists of a chert pebble conglomerate in a matrix of marine shale with shells of the marine oyster *Pycnodonte newberryi*, and at several sites, shark teeth. This conglomeratic bed is in turn overlain by a few centimeters, or tens of centimeters, of mudstone followed by a dense shell bed of *Pycnodonte newberryi umbonata*, a subspecies of *Pycnodonte* with a relatively smooth beak area that only occurs in the basal Turonian (Kirkland, 1996; Leckie and others, 1997). Within a meter of this *Pycnodonte* bed is the first thick (20 to 50 cm) volcanic ash (altered to bentonite) in the lower Turonian. The ^{40}Ar/^{39}Ar (sanidine) age of the volcanic ash is 93.25 ± 0.55 Ma (Obradovitch, 1993) and 93.46 ± 0.6 Ma (Kowallis and others, 1995). This important volcanic ash marker bed may be readily traced across the Western Interior in all marine sections (Elder and Kirkland, 1985; Elder, 1988, 1989, 1991; Kirkland, 1991; Kennedy and others, 2000).

Eaton and others (1990) proposed that the chert pebble layer at the base of the Tununk was sourced from chert pebbles originally deposited in the Buckhorn Conglomerate. On examing the lower Naturita Formation (= Dakota Formation) at Hanksville, we now propose that the source of the pebbles was more likely the basal conglomerate of the Naturita (= Dakota). The important thing to note at these sections is that there is convincing evidence that during one of the most rapid global eustatic sea-level-rise events in the Phanerozoic, proximal to the actively subsiding Cretaceous foreland basin, there was uplift along the San Rafael Swell in central Utah that exceeded both sea-level rise and regional subsidence (Eaton and others, 1990). The distribution of facies at the base of the Tununk Member needs to be mapped in detail across the San Rafael region to determine if this was simply a broadly developed forebulge or the reactivation of known Precambrian basement structures.

From here, we turn left (east) on SR 95 toward Hanksville and in just under 1.6 km (1 mile) , turn left again onto a dirt track on the south end of the Caineville Reef to get a different perspective on the relationships of the Buckhorn Conglomerate and its lateral facies changes (figure 54B and C). From here we will make our way back to our hotel in Green River, Utah, with additional stops if time permits (figure 54D and 54E).

Day 3 (AM) – Cedar Mountain Formation

Southwestern San Rafael Swell

Leave Green River, Utah, and drive west on I-70 west for 92.5 km (57.5 miles), crossing the San Rafael Swell to the rest area by milepost 103.5, where we will exit the interstate. We will make a few short stops while crossing the San Rafael Swell to appreciate the magnificent Triassic through Jurassic section exposed here.

Rest Stop – I-70 Section Overview

The rest area is built on light-colored transgressive marine sandstone beds of the Upper Jurassic Curtis Formation overlain by brownish-red shallow-marine strata of the Summerville Formation. The Summerville is overlain by the Morrison Formation. The marine Curtis lies on the regional J-3 unconformity developed on the top of the Middle Jurassic Entrada Sandstone as indicated by localized lenses of small chert pebbles on this surface. To the northwest, the Buckhorn Conglomerate, at the base of the Cedar Mountain Formation, caps the Morrison Formation (figure 8A). In this area, the Brushy Basin Member is similar in thickness to the sections on the west side of the San Rafael Swell, but the underlying Salt Wash Member is considerably thinner.

When we leave the rest area we will continue to the west on I-70; however, as we round the bend on the interstate in about 5 km (3 miles) at about milepost 98 we will slow down so that you may observe the intertonguing between the Buckhorn Conglomerate and the Yellow Cat facies of the Buckhorn described below and shown in figure 8. Unfortunately, it is illegal for a caravan of vehicles to stop and get out on an interstate highway so pay close attention to the Cedar Mountain Formation exposed in the cuts lateral to the Buckhorn Conglomerate on the right (north) side of I-70. The Ruby Ranch Member can be distinguished as a pale-purplish-pink mudstone with abundant carbonate nodules weathered out on the surface with a concave weathering profile in the lower slope. The overlying Mussentuchit Member exposed below the Naturita Formation (= Dakota Formation) has a convex weathering profile due to its high content of swelling clays. There is also a sharp but subtle color change to a pale olive gray.

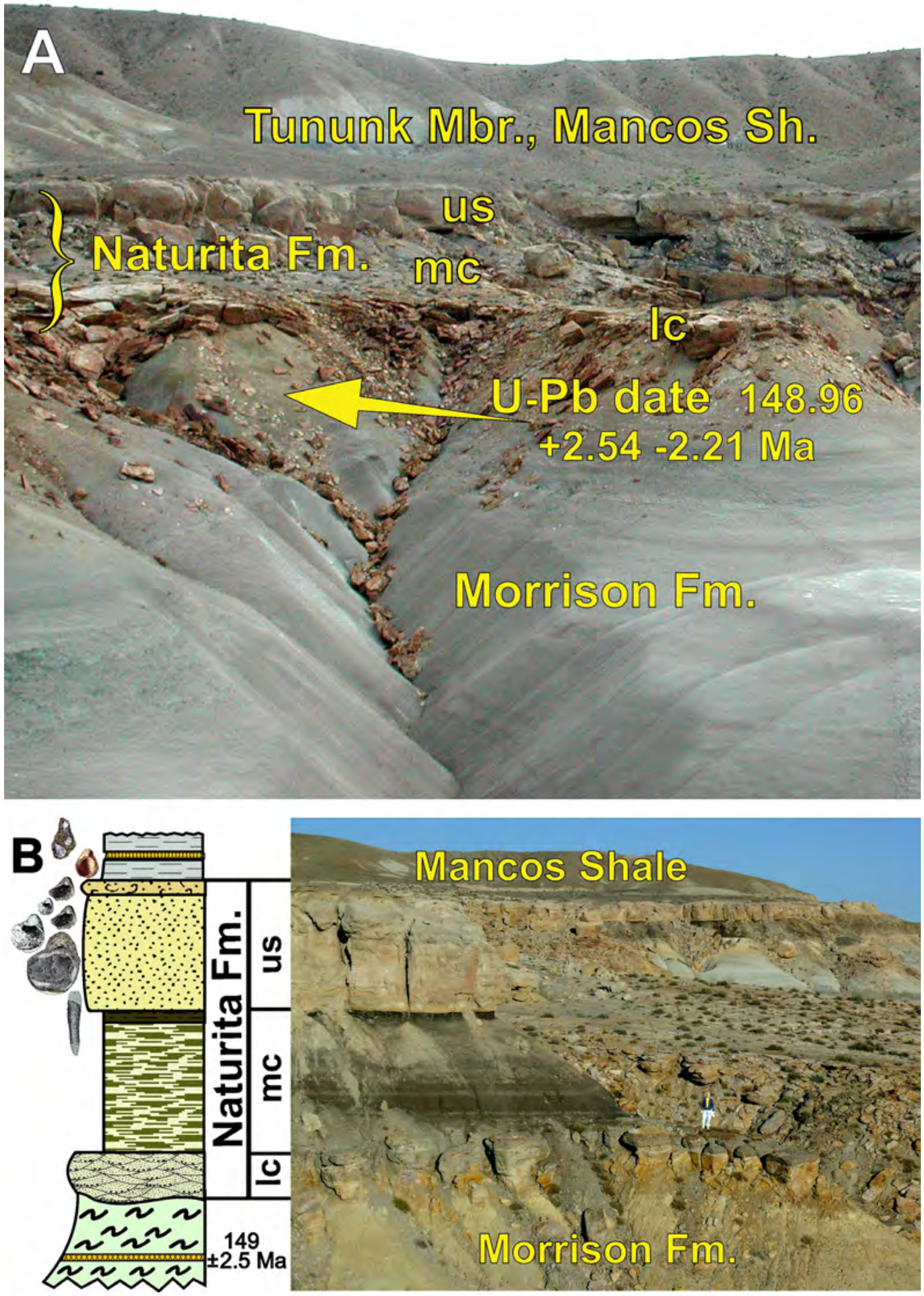

Figure 52. Hanksville section. Middle Mesozoic section west of Hanksville. (A) Contact between underlying Morrison Formation with Naturita Formation showing approximate position of radiometric date confirming that these smectitic strata are the upper Jurassic Morrison Formation and not a smectitic facies of the Cedar Mountain Formation (Kowallis and others, 2007). (B) Another view of section with the distribution of oyster species documenting the ecologic progression from freshwater, brackish water, beach, and shallow-shelf sand, reworked periodically by storm processes, to quiet shelf settings below storm wave base. Molluscan data from Kirkland (1990, 1991, 1996) and Santucci and Kirkland (2010). Abbreviations: us = upper sandstone member, mc = middle carbonaceous member, lc = lower conglomerate member. Stratigraphic symbols after figure 10.

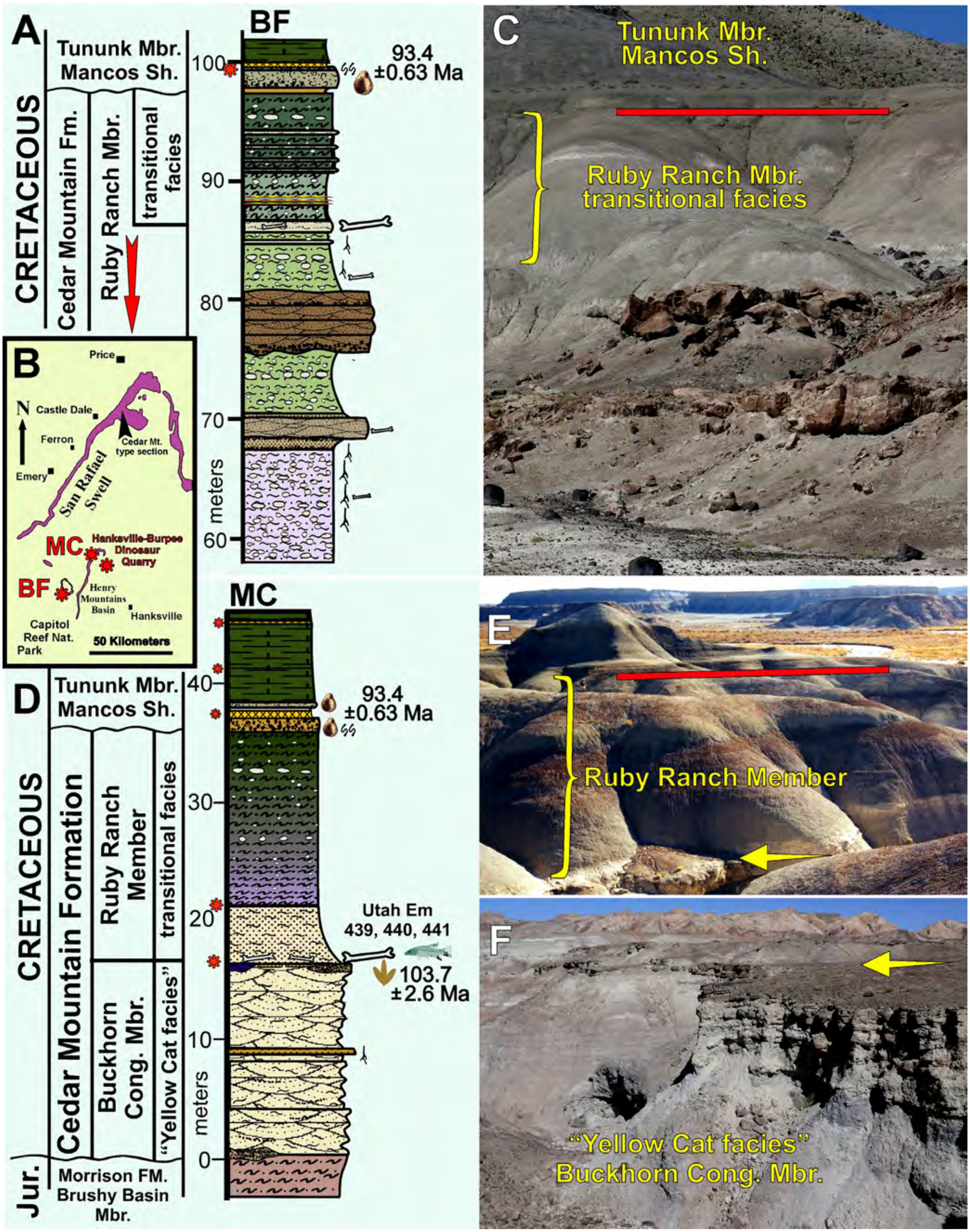

Figure 53. Caption on following page.

Figure 53 (figure on previous page). Cedar Mountain sections east of Capitol Reef National Park. (A) Upper portion of Cedar Mountain section measured on the southwest side of the Blue Flats (BF) west of the Hartnet Road measured from 38°17'38.15"N, 111°6'3.38"W to 38°17'32.63"N, 111°6'10.94"W. A much thicker Ruby Ranch Member is exposed here overlying a well-developed Buckhorn Conglomerate Member. (B) Index map for study areas. (C) Exposure of measured stratigraphic interval. (D) Cedar Mountain section measured to the north of the Muddy River Ford (MC) north and west of Wild Horse Road from 38°32'14.82"N, 110°54'4.45"W to 38°32'11.29"N, 110°53'57.41"W. (E) Ruby Ranch unconformably overlain by Tununk Member of the Mancos Shale. A thick volcanic ash marker bed (bentonite C of Elder (1988) overlies a mudstone-supported pebble bed at the contact. (F) Soft, fine-grained sandstone described as Yellow Cat interfingering with Buckhorn Conglomerate Member by Greenhalgh and Britt (2007) beneath a local dark-brown, calcareous pebbly sandstone marker bed. Stratigraphic symbols after figure 10.

Continue west for 10 miles, rising through the Upper Cretaceous section onto a bench formed by the Ferron Sandstone. Take exit 91 and turn right (north) at the bottom of the exit onto SR 10 to Emery. We will drive north to Emery on SR 10, but the Mussentuchit badlands are south of I-70 and worth seeing on a future trip. The badlands along Mussentuchit Wash are reached by turning south at this exit, driving up the hill, and following the road east above I-70 before taking the right fork south. After about 5.6 km (3.5 miles) on the Ferron bench, the road drops down through the cliff and turns back to the east across the Tununk Member. Drive about 3.7 km (2.3 miles) and take the next right fork that is just after crossing Willow Wash. Drive south on the Upper Last Chance Road—the Mussentuchit badlands (figure 32) are to the east below the Naturita (= Dakota Formation) escarpment for the next 4 km (2.5 miles). The Mussentuchit badlands are an important area for paleontological research initiated by the Oklahoma Museum of Natural History in the 1990s and carried on by the Utah State University Eastern's Prehistoric Museum, the Chicago Field Museum of Natural History, and the North Carolina Museum of Natural History. The BLM keeps a close watch on this area as well, and all paleontological research here must be done under BLM or Utah state paleontological permits.

However, we are going to drive north on SR 91 from Exit 10 for 25.7 km (16 miles) through the town of Emery before taking a right turn angling east toward Moore. After driving on this road for 4 km (2.5 miles), we will turn right once again on the Moore Cutoff Road to the east toward I-70. Head east for 4 km (2.5 miles) before the road drops down through the cliff formed by the Ferron Sandstone and continue on across the bench at the base of the Tununk Member and down through the Naturita and Cedar Mountain Formations. We will find a spot to turn around so that we may park along the westbound side of the road near the base of the Cedar Mountain section where we will be visible to any traffic. We will spend the rest of the morning exploring this important and accessible section.

Cedar Mountain Formation Along Moore Cutoff Road

The Cedar Mountain section along the Moore Cutoff Road is of particular importance because it is accessible by a paved route across the west flank of the San Rafael Swell crossing an unbroken section spanning the Middle Jurassic through Middle Cretaceous. With the spectacular Mesozoic section exposed along the road, it is studied by geology classes from across the nation.

A prominent cobble conglomerate near the top of the section has been pointed out to geology student after geology student as representing the Buckhorn Conglomerate. This suggested that the outcrop was noteworthy in being the only known area along the entire western San Rafael Swell where little or no Ruby Ranch Member was recognized between the Buckhorn Conglomerate and Mussentuchit Members of the Cedar Mountain Formation (Kirkland and others, 1997, 1999). The Ruby Ranch is thick to the north and south, and such a dramatic thinning in this area is at odds with the tectonic grain of the developing Cretaceous foredeep basin (see Currie, 2002). While nearly every geologist and paleontologist working on the Cedar Mountain Formation has commented to us on what a strange section of Cedar Mountain Formation this was, no one seriously doubted that this conglomerate was the Buck-

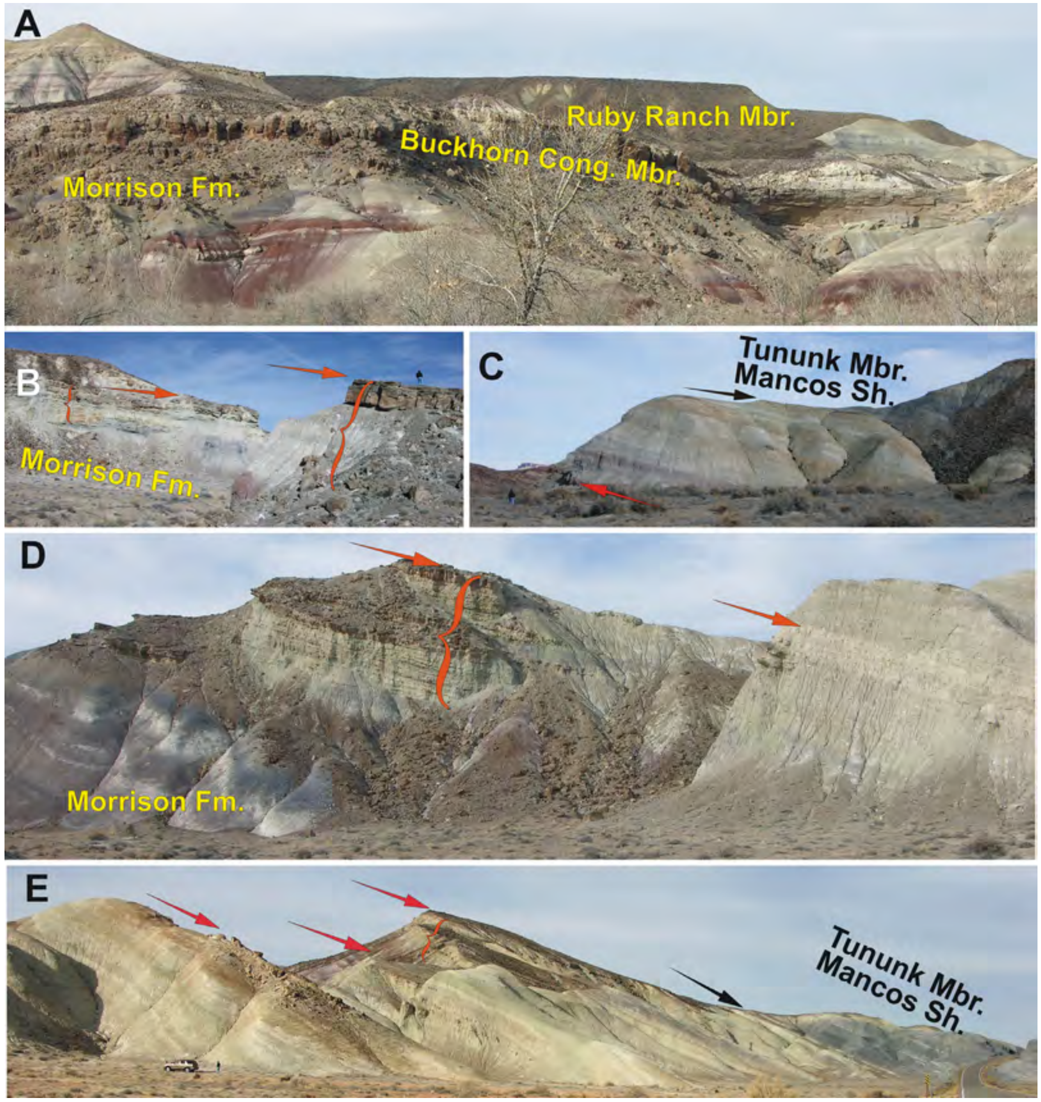

Figure 54. Cedar Mountain Formation along the Caineville Reef. (A) Buckhorn Conglomerate Member separating Brushy Basin Member of the Morrison Formation below from Ruby Ranch Member of the Cedar Mountain Formation above as exposed north of turnoff from SR 24 to ford across Fremont River east of Capitol Reef National Park (38°16'30.41"N, 111°5'22.02"W). (B) Exposure of basal Cedar Mountain Formation at the south end of Caineville Reef (38°16'27.56"N, 111°3'58.48"W) looking west. (C) Exposure of upper Cedar Mountain Formation at the south end of Caineville Reef looking north. (D) Exposure of basal Cedar Mountain Formation near middle of Caineville Reef (38°18'3.97"N, 111°2'38.97"W). (E) Exposure of Cedar Mountain Formation near middle of Caineville Reef. Red arrows indicate top of Buckhorn Member interval. Red bracket indicates interval representing Buckhorn Conglomerate Member. Black arrows indicate contact between Ruby Ranch Member of the Cedar Mountain Formation and Tununk Member of the Mancos Shale. Note the absence of Naturita Formation in this area.

horn Conglomerate.

For its importance as a geological reference section, the UGS picked the Short Canyon 7.5-minute quadrangle for a detailed geological map. During the fall of 2006, UGS geologists Hellmut Doelling and Paul Kuehne spent a day walking Kirkland back and forth across the quadrangle to show him what their mapping of Cedar Mountain units across this area had revealed to them. By the end of the day, they convinced Kirkland that there is a thick section of Ruby Ranch present every-

Figure 55. Caption to the right.

where under this major conglomerate bed, which can be traced from the north to south end of the map area. As is typical everywhere else, the Ruby Ranch Member here is largely non-smectitic and contains a great abundance of pedogenic carbonate nodules. Additionally, hiking down through the section several kilometers to the north along Short Canyon, a lower major conglomerate bed at the base of the Ruby Ranch Member was identified that almost certainly represents the Buckhorn Conglomerate. On the south side of the Moore Cutoff Road, we identified a cherty carbonate close to this same stratigraphic position (figure 55). At the time it was thought this might represent a spring deposit or calcrete developed on the unconformity at the base of the Cedar Mountain Formation.

The prominent conglomerate developed between the Ruby Ranch and Mussentuchit Members in this area reflects a river channel developed on the erosion surface (sequence boundary) indicated by the chert lag identified at this contact along the entire southwestern side of the San Rafael Swell. This conglomerate was mapped across the entire Short Canyon quadrangle and designated as the Short Canyon member of the Cedar Mountain Formation (Doelling and Kuehne, 2013b).

In April 2016, Kirkland examined a dinosaur track site previously noted as being in the Morrison Formation and realized that the track-bearing sandstone included a fair amount of very coarse grained sandstone. Kirkland hypothesized that bed may represent the base of the Cedar Mountain Formation. Additional evidence

Figure 55 (on right). Cedar Mountain section along the south side of the Moore Cutoff Road (SR 803) (MR) measured from 38°56'19.66"N, 38°56'19.66"N to 38°56'4.99"N, 111°5'3.58"W. Stratigraphic key, figure 10 and index map, figure 57A. Abbreviations of marker beds in figure 57: BCt = possible tongue or lense of Buckhorn Conglomerate 1.02 m thick, cb = 98 cm interval of thin chert beds in pebbly mudstone 153 cm below marked color change to thick (~16 m) overall reddish brown mudstone with abundant carbonate nodules, eb = interval of bioturbated, interbedded, en echelon grayish-orange, fine- to medium-grained sandstone and reddish mudstone, rmb = lateral extensively thick 50 to 100 cm sandstone, 262 cm below top of the reddish-brown interval, tb = basal gravelly, bioturbated sandstone with dinosaur track casts. Stratigraphic symbols after figure 10.

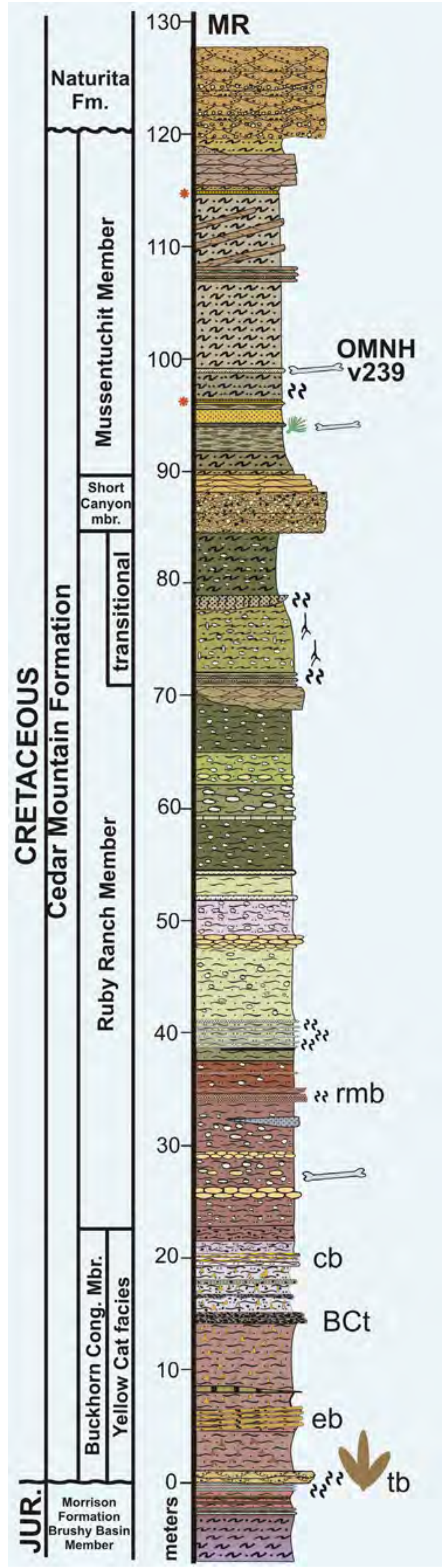

Figure 55. Caption on left.

that supported placing the base of the Cedar Mountain Formation here is that the track-bearing bed is above the highest smectitic mudstone typical of the Brushy Basin Member of the Morrison Formation, there is significant iron straining associated with this horizon, and the overlying mudstone beds are mottled. Arguments against placing the contact here are that the bed appears to be gradational with the underlying strata, a 1-m-thick pebble conglomerate occurs 14 m above the contact, and a cherty zone that is another 4 m above that. Furthermore, some of the tracks may represent stegosaurids, which are not known above the Jurassic in North America although there appears to be a number of iguanodont tracks, which are more abundant in the Cretaceous (figure 56).

The section discussed herein was described along the south side of the Moore Cutoff Road. The track bed may represent reworking of Morrison strata at the unconformity and, if these are indeed stegosaurid tracks, there is nothing against them representing a late surviving species. But it is possible that the pebble conglomerate represents more than a tongue or lens of the Buckhorn Conglomerate and actually represents the base of the Cedar Mountain Formation. Only further study of this interval across the area will fully determine this (figure 57).

If the track bed marks the base of the Cedar Mountain Formation, there is a total of 22.83 m of Yellow Cat facies of the Buckhorn Conglomerate below the base of the Ruby Ranch Member. The basal 14.66 m of the Ruby Ranch is dominated by red mudstone with abundant pedogenetic carbonate nodules that consolidate into calcrete zones at 3 and 6 m above the base of the Ruby Ranch. A laterally extensive sandstone marker bed occurs at 2.5 m from the top of the red bed interval. Across the road, well to the north, an extensive conglomeratic ribbon sandstone occurs at the top of the red mudstone sequence that in lateral view (from the road) resembled the Buckhorn Conglomerate, but is clearly too high in the section (figure 58).

Overlying the red mudstone is about 20 m of greenish mudstone interval capped by nearly a meter of consolidated septarian carbonate nodules. Overlying that is 3 m of pale-purplish-pink mudstone with

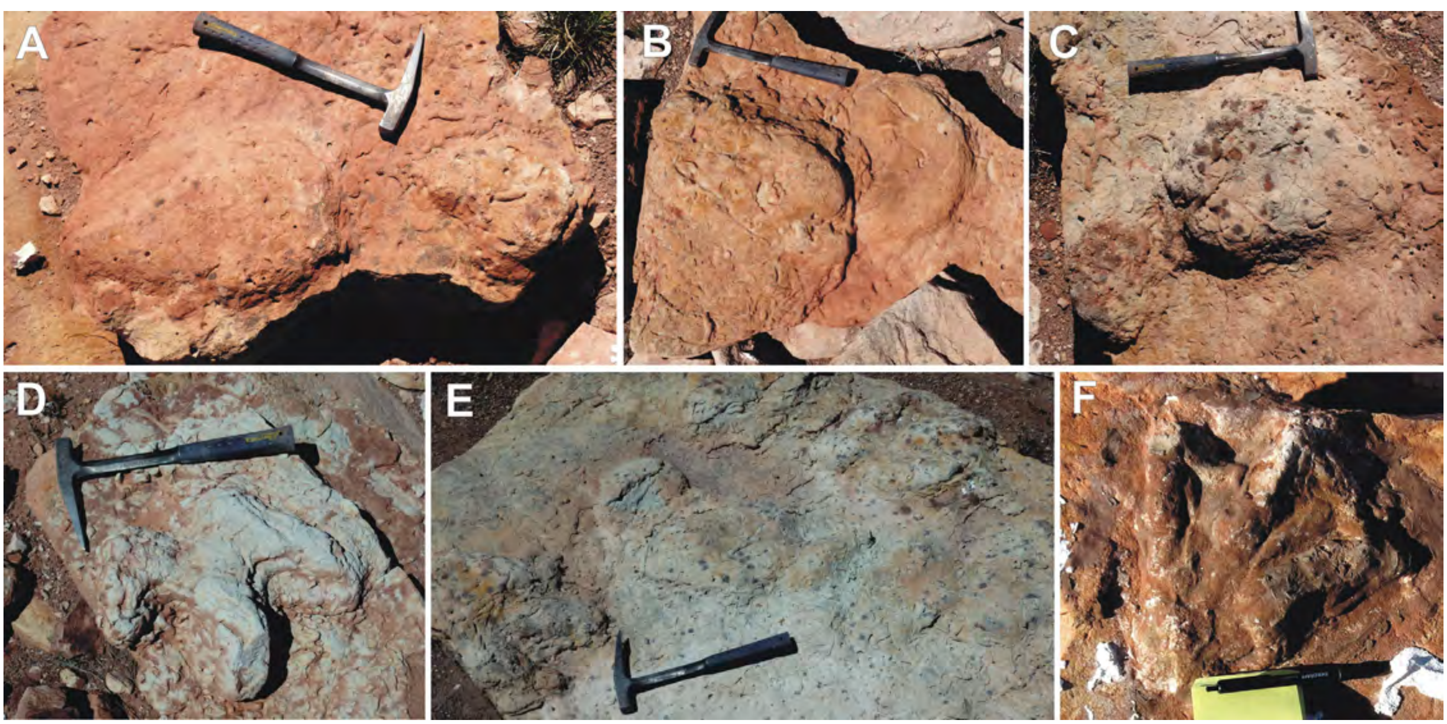

Figure 56. Dinosaur track casts at the base of the Moore Road section. (A-C) Pairs of pes (larger) and manus tracks pertaining to either a small sauropod or a stegosaur. (D) Iguanodont track. (E) Matched pair of iguanodont tracks defining a pace. (F) Theropod track.

abundant nodules capped by a very light-colored claystone marker bed that is 15 m thick and bounded by very fine grained sandstone splays. The splays averaged 0.4 to 0.7 m thick. The next overlying 13.5 m interval is once again dominated by greenish to olive-gray mudstone with pedogenetic carbonate. Two well-developed ribbon sandstone beds occur in the next 10 m as the mudstone beds begin to become slightly smectitic. The uppermost 5.6 m of the Ruby Ranch is dark olive-gray smectitic mudstone with common carbonate nodules representing the transitional facies of the Ruby Ranch and is sharply overlain by the Short Canyon member (figure 57I). Total thickness of the Ruby Ranch Member is 61.8 m.

The Short Canyon member consists of 3.7 m of quartzite-rich, trough cross-bedded pebble to cobble conglomerate capped by 1.4 m of very coarse grained, trough cross-bedded sandstone. The capping unit forms a broad bench below the smectitic mudstones of the Mussentuchit Member and a high escarpment holding up the thick section of the Ruby Ranch Member.

The overlying fine-grained portion of the Mussentuchit Member is 28.9 m thick and consists of highly smectitic mudstone that is often lignitic with a few beds of volcanic ash. The top 11 m contains a number of lenticular sandstone beds, some that appear to have an en echelon relationship with each other.

The base of the overlying fluvial sandstone of the Naturita Formation (= Dakota Formation) is sharp. These sandstone beds preserve abundant flattened casts and molds of tree trunks and branches. A mudstone pebble bed with *Pycnodonte newberryi* shells forms the base of the overlying Tununk Member of the Mancos Shale.

Geologically and paleontologically, the Cedar Mountain section along the Moore Cutoff Road needs to be further studied and sampled for chemostratigraphy. The hypotheses presented here need to be tested. However, it is likely that the new stratigraphic interpretation presented here is largely correct, as it certainly simplifies the facies relationships for the Cedar Mountain Formation on the western side of the San Rafael Swell.

From here we will drive back toward Moore, stopping for lunch at a site with Native American rock art and Turonian dinosaur tracks (Jones, 2001), which are preserved on fallen blocks of the Ferron Sandstone at an interpreted site along the side of the road. Following lunch, we will return to SR 10 and turn right (north) to drive 34 km (21 miles) north through the town of Castle Dale where we will turn right (east) on the Green River Cutoff Road. Drive about 24 km (15 miles) down section through the Upper and Lower Cretaceous (note that the type locality of *Eolambia* was less than 1 km (0.6 miles) south of this road, and to a flat plain formed in the valley on the Middle Jurassic. Turn left (north) on the Buckhorn Draw Road and proceed approximately 8 km (5 miles) to the type area of the Cedar Mountain Formation and Buckhorn Conglomerate.

Type Area of the Cedar Mountain Formation and Buckhorn Conglomerate

We will first briefly examine the Buckhorn Conglomerate, where large house-sized blocks have rolled down near the road. Then we will proceed about 0.5 miles to the dam at Buckhorn Reservoir, where the type section of the Cedar Mountain Shale was established by Stokes (1944, 1952). Unfortunately, a broad valley is formed between the basal conglomerate of the Naturita Formation (= Dakota Formation) and the Buckhorn Conglomerate such that much of the Ruby Ranch Member is covered. We will continue along the road for another 2.4 km (1.5 mi) as it turns back to the west and climbs through the low ridge formed by the basal conglomerate of the Naturita Formation (Short Canyon member equivalent). This is the area where Sorenson (2011) conducted research on exhumed channel sandstones and the lateral relationships between the Mussentuchit and Naturita (= Dakota). Climbing up through the Naturita (= Dakota) in this area, it is pretty clear that above what is mapped as Naturita (= Dakota) is an interval of smectitic mudstone characteristic of the Mussentuchit Member.

The Mussentuchit Member is difficult to separate from the underlying Ruby Ranch Member to the south and, if we had not found the pebble lag indicating the presence of a sequence boundary, many sedimentologists would have continued to consider the separation of the Ruby Ranch and Mussentuchit Members unjustified. However, in the northern part of its outcrop belt

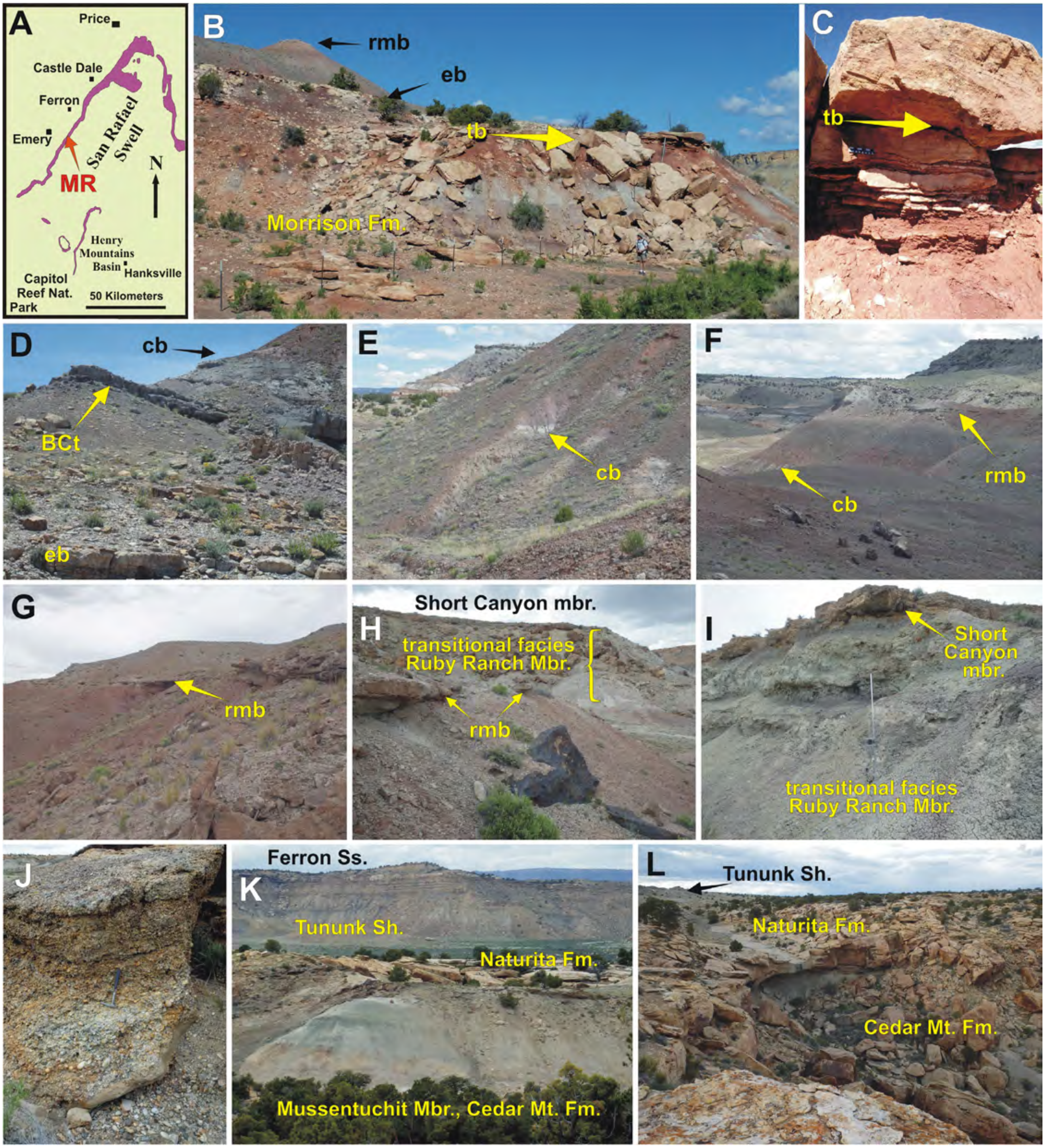

Figure 57. Caption on following page.

Figure 57 (figure on previous page). Cedar Mountain strata long the Moore Cutoff Road. (A) Index map for Moore Road area. (B) Basal, perhaps gradational contact, at base of the Cedar Mountain Formation. (C) Detail of contact with dinosaur track casts preserved under upper sandstone layer. (D) Yellow Cat facies of Buckhorn Conglomerate Member with thin Buckhorn tongue or lense (BCt) and overlying zone of thin chert beds (cb). (E) Base of approximately 16 m interval of reddish mudstone with numerous pedogenetic carbonate nodules and amalgamated carbonate nodule beds. (F) Overview of red interval to south of section. (G) Upper part of red bed interval in line of section. (H) Sandstone marker bed near top of red bed interval (rbm) with upper Ruby Ranch Member in distance. (I) Drab, smectitic upper Ruby Ranch mudstone with carbonate nodules below Short Canyon member. (J) Short Canyon member. (K) View west across bench formed by the Short Canyon member to the exposures of the Mussentuchit Member capped by fluvial sandstones of the Naturita Formation. (L) Sharp contact of basal fluvial sandstones of the Naturita Formation with underlying Mussentuchit Member. The sandstone beds preserve abundant log and branch impressions. Abbreviations as plotted against stratigraphic section in figure 55.

the Mussentuchit is part of the Naturita Formation (= Dakota Formation) overlying a contiguous basal Naturita conglomerate (Short Canyon member equivalent).

To most fully satisfy all the geologists working in the region, the most satisfactory solution is to consider the Mussentuchit Member a member of the Cedar Mountain south of the type area and as a member of the Naturita Formation (= Dakota Formation) north of the type area, where the basal conglomerate is continuous and contiguous with the Naturita Formation (= Dakota Formation) in total. This transition would seem to happen in this area (figure 59). Geological mapping in this area would pin it down more accurately. Farther to the north and east the Mussentuchit is not recognized within the beds of the Naturita Formation (= Dakota Formation) and would truly appear to be purely a product of foreland basin development on the west side of the San Rafael Swell.

From here, we will continue back to SR 10 for our return to Salt Lake City. If time permits, we can visit the Utah State University Eastern's Prehistoric Museum in Price, Utah, to examine some of the fossils from the Cedar Mountain Formation.

ACKNOWLEDGMENTS

All field paleontological research described herein was conducted under permits from the Bureau of Land Management (BLM), National Park Service (NPS), and State of Utah. Kirkland thanks Discovery Communications Quest Grants, BLM, NPS, Utah Friends of Paleontology, and UGS for funding. This publication reflects the research of a great many scientists referenced herein and the authors appreciate the countless discussions we have had with colleagues and students on these topics over the years in the field, on the phone, and at meetings. While no one else is held responsible for the ideas presented herein, none of this work was done in a vacuum and everyone's contributions are appreciated. We thank Sooz Kirkland, Martha Hayden, Ed Simpson, Doug Sprinkel, Mike Lowe, Tom Chidsey, Mike Hylland, and Stephanie Carney for reviewing the manuscript.

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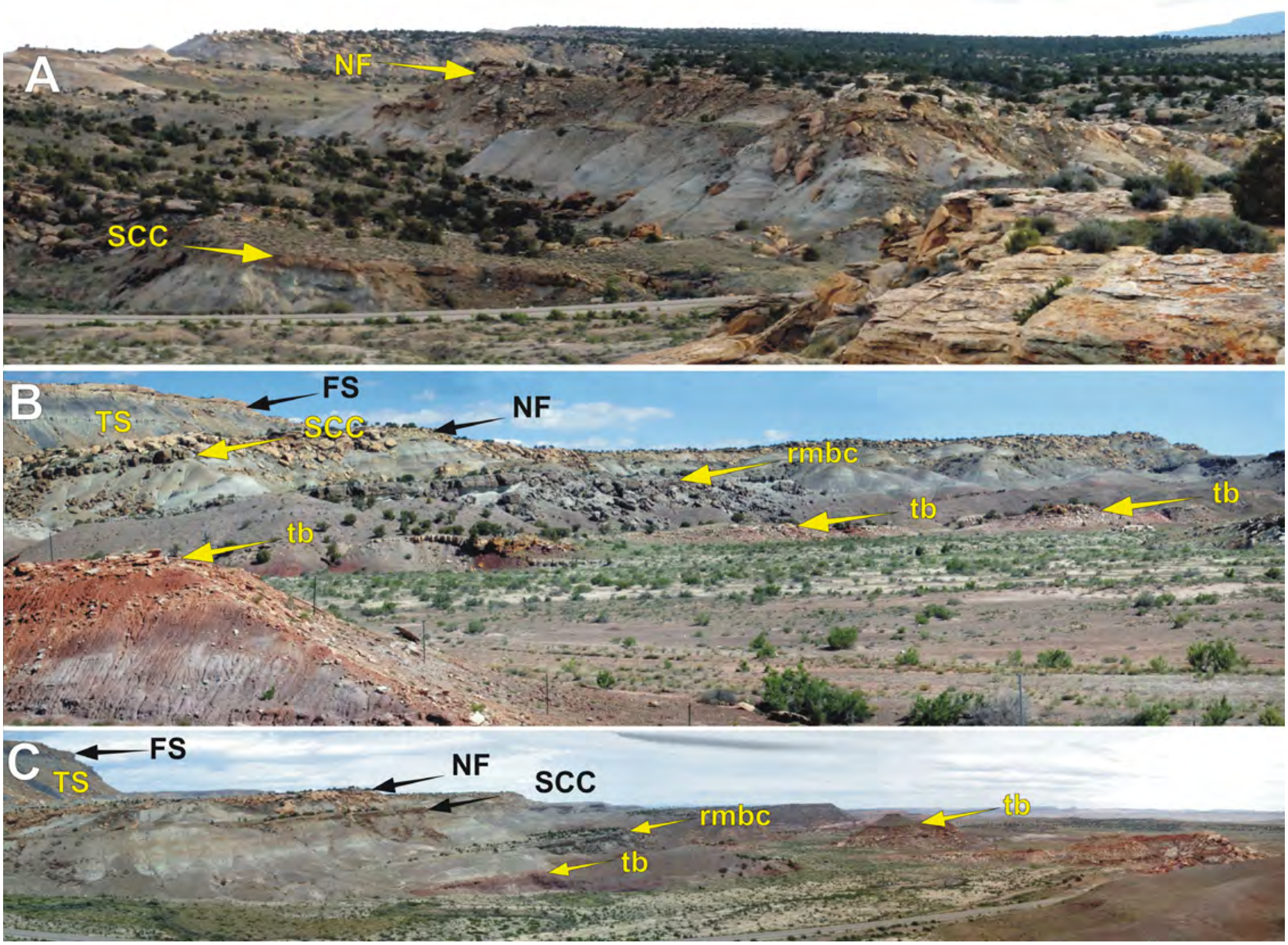

Figure 58. Panoramas of Cedar Mountain Formation along Moore Cutoff Road. (A) Panorama of Mussentuchit Member exposures south of road. (B) Panorama of Cedar Mountain Formation north of road from the southeast. (C) Panorama of Cedar Mountain Formation north of road from the Short Canyon escarpment in south. Abbreviations: FS = Ferron Sandstone Member of the Mancos Shale, NF = Naturita Formation, rmbc = large lenticular channel conglomerate at about position of red bed marker sandstone (rbm in figures 55 and 57) at top of red bed interval. SCC = Short Canyon member, tb = basal dinosaur track marker bed at top of smectitic Morrison Formation, TS = Tununk Member of the Mancos Shale.

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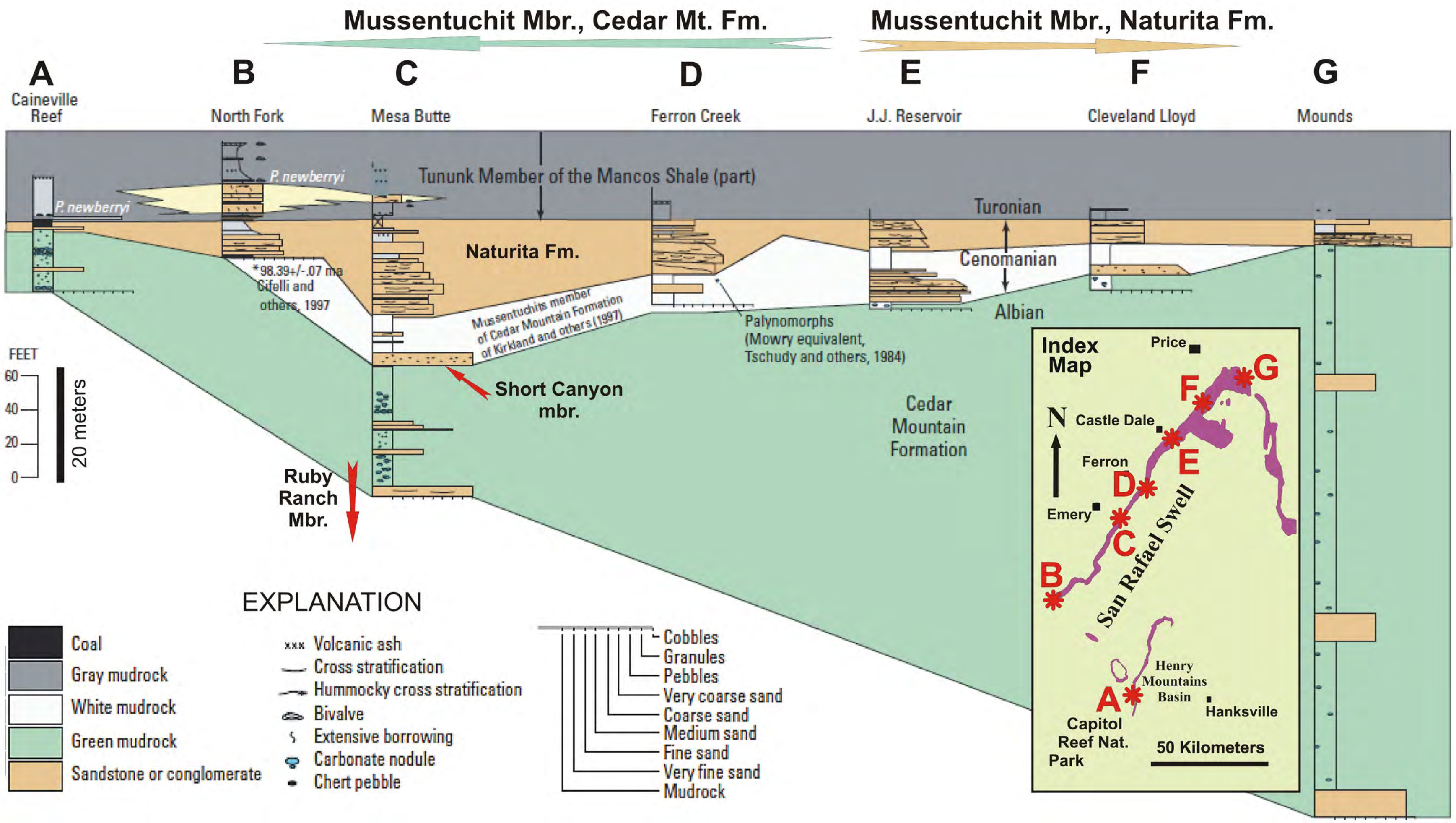

Figure 59. Panel diagram of Naturita Formation and bounding strata along the west side of the San Rafael Swell where we propose that the Mussentuchit Member be considered a part of the Cedar Mountain Formation south of its type area and part of the Naturita Formation north of the Cedar Mountain type area. Letters above sections keyed to locality map. Note that the Mesa Butte section, C, is just south of our Moore Road section for which we have calculated a considerably greater thickness for the Ruby Ranch Member (figure 55). Figure modified after Kirschbaum and Schenk (2011).

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