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GEOLOGY AND PALEONTOLOGY OF JURASSIC NATIONAL MONUMENT, UTAH

Kenneth Carpenter[1]

[1]*Museum of Natural History, University of Colorado, Boulder, Colorado 80302 USA*

ABSTRACT

Jurassic National Monument, Utah's newest national monument, encompasses the famous Cleveland-Lloyd Dinosaur Quarry on the north-end of the San Rafael Swell in Emery County. At only 1.3 square miles (3.4 km^2), the sedimentary rocks within the monument nevertheless record 38 million years of Utah's geologic history spanning the Late Jurassic and most of the Early Cretaceous. The sedimentary rocks record a shift from a warm, mesic climate in a landscape of scattered wetlands and ponds of the Brushy Basin Member of the Morrison Formation, to the dry, semiarid climate in a landscape of ephemeral rivers, floodplains and wetlands of the Ruby Ranch Member of the Cedar Mountain Formation. Thousands of disarticulated dinosaur bones from which numerous skeletons have been assembled have been recovered from the Cleveland-Lloyd Dinosaur Quarry, but only fragments of dinosaur bones have been found in the overlying Ruby Ranch Member.

INTRODUCTION

Jurassic National Monument on the northern end of the San Rafael Swell in Emery County is Utah's newest and smallest national monument (figure 1). It was established as part of the John D. Dingell, Jr. Conservation, Management and Recreation Act passed on March 12, 2019, by the 116th Congress (2019–2020) as Public Law 116-9, Part II, Section 1252. Its purpose was to "… conserve, interpret, and enhance for the benefit of present and future generations the paleontological, scientific, educational, and recreational resources of the area…" The monument encompasses 1.3 square miles (3.4 km^2) of federal land administered by the Bureau of Land Management and includes the Cleveland-Lloyd Dinosaur Quarry, which had been previously designated a Natural National Landmark in 1967 (Miller and others, 1996). The quarry is famous for producing over 16,200 bones of Late Jurassic dino-

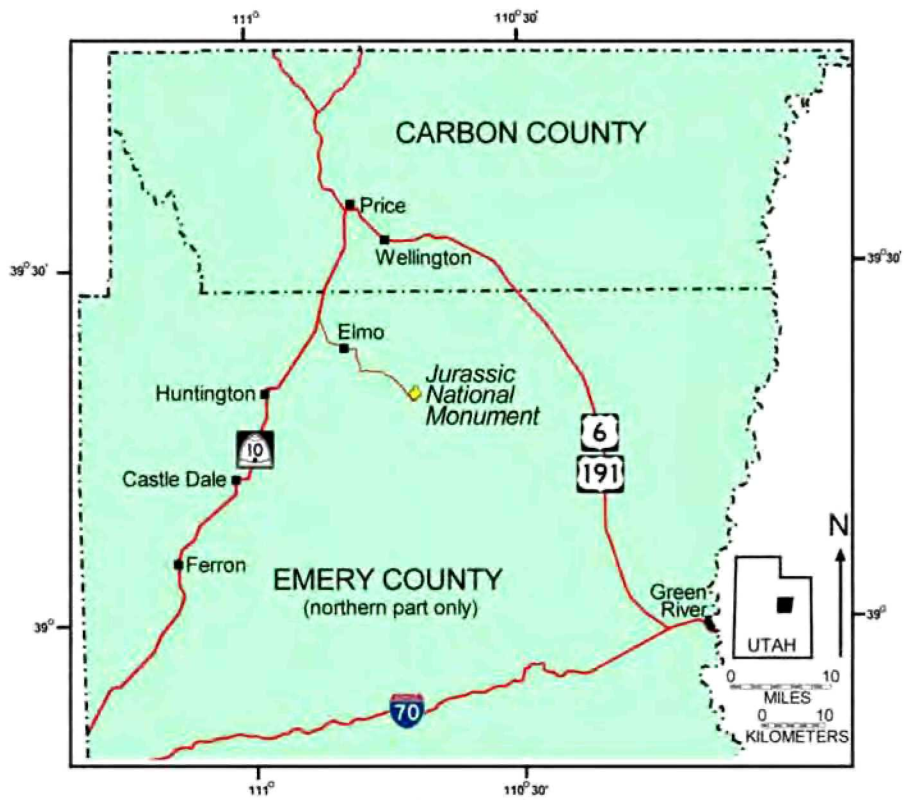

Figure 1. Location of Jurassic National Monument at the north end of the San Rafael Swell.

Carpenter, K., 2024, Geology and paleontology of Jurassic National Monument, Utah, in Sprinkel, D.A., Chidsey, T.C., Jr., Anderson, P.B., and Willis, G.C., editors, Geology of Utah's parks and monuments: Utah Geological Association Publication 28 (fourth edition), p. 299–318.

saurs from the Morrison Formation. The very irregular northern monument boundary roughly follows the 5760-foot (1755.5-m) contour to exclude the topographically flatter grazing land as a concession to grazing lease holders.

The San Rafael Swell, in which Jurassic National Monument lies, is a broad, asymmetric anticline extending roughly northeast-southwest in central Utah. It formed due to lateral compression during the Late Cretaceous and early Tertiary Laramide orogeny (80 to 55 million years ago [Ma]) (Yonkee and Weil, 2015). Subsequent erosion exposes about 7000 feet (2130 m) of marine to continental Permian to Cretaceous strata in spectacular cliffs, mesas, and deep canyons (Chidsey, 2013). Strata are gently to moderately dipping on the west side of the San Rafael Swell and steeply dipping on the east side where it forms the San Rafael Reef.

In the northwestern corner of the San Rafael Swell, erosion by Cottonwood Wash south of the monument and Sand Wash north of the monument, along with their associated unnamed tributaries, produced a cuesta of the Morrison and Cedar Mountain Formations, which forms the topographic core of Jurassic National Monument. The long and gentle northwestern slope of the juniper and grass-covered cuesta occupies almost three-quarters of the monument, whereas the steeper, southeast-facing escarpment is mostly barren except in the southern part of the monument (figure 2). The strata in the monument encompass part of the Brushy Basin Member of the Morrison Formation, and the Buckhorn Conglomerate and a part of the Ruby Ranch Members of the Cedar Mountain Formation (figure 3).

STRATIGRAPHY

Morrison Formation

The Morrison Formation in the San Rafael Swell overlies the Upper Jurassic Summerville Formation (Chidsey, 2013), and consists of the Tidwell Member at the base, the Salt Wash Member in the middle, and the Brushy Basin Member at the top (figures 3 and 4). Neither the Tidwell nor Salt Wash Members are present within the boundaries of the monument, so these strata are only briefly described.

Tidwell Member

Traditionally, the Tidwell Member on the Colorado Plateau was identified as the slope-forming strata between the underlying cliff-producing, marginal marine Summerville Formation and the overlying sandstone cliffs of the Salt Wash Member. In many places around the San Rafael Swell south of the monument, the lower part of the Tidwell Member consists of gray weathering, thickly bedded gypsum up to 46 feet (14 m) thick in large lenticular bodies a mile or more (1.6 plus km) in length (Carpenter, 2022). These lenticular bodies of gypsum formed in a complex of multiple playa lakes that developed distal to the ends of mega-alluvial fans radiating from remnants of the Elko highlands to the west (Thorman, 2011). Closer to the monument, the gypsum facies is absent because the playa lakes did not extend as far north. Here and other places where the gypsum is absent, the Tidwell commonly consists of a reddish or yellowish, discontinuous tabular sandstone called "Bed A" by O'Sullivan (1980). This sandstone is overlain by alternating, thinly bedded, fine-grained sandstone, siltstone, limestone, and mudstone composed of illitic clays and silt.

In most places on the western part of the Colorado Plateau where the thick gypsum beds occur at the base of the Tidwell Member, the Tidwell rests on angular unconformities of truncated anticlines at the top of the Summerville Formation (Trimble and Doelling, 1978; Carpenter, 2022); the unconformity is referred to as the J-5 unconformity by Pipiringos and O'Sullivan (1978). Where the gypsum beds are absent in the northern part of the San Rafael Swell and over much of the eastern part of the Colorado Plateau, the base of the Tidwell Member is more difficult to place. It has variably been argued that the contact with the underlying Summerville Formation is a disconformity at the base of Bed A (McKnight, 1940; Peterson, 1980; O'Sullivan, 1984) or that the contact is many places conformable (Craig and Shawe, 1975; Potter-McIntyre and others, 2016; Ejembi and others, 2021; Carpenter, 2022).

South of the monument, Bed A is discontinuous and the Tidwell Member lies conformably atop the underlying Summerville Formation where the sandstone is absent. Here, the gradation from laminated or very thinly bedded, orange-pink weathering siltstone beds of the Summerville Formation to the reddish weathering Tidwell Member occurs over a narrow span of less than a foot (less than 30 cm). The Tidwell Member near the monument is approximately 30 feet (9 m) thick.

Salt Wash Member

The Salt Wash Member on the Colorado Plateau typically consists of lenticular or tabular sheets of sandstone and some interbedded mudstone beds. Southeast of the monument, the Salt Wash Member is composed of well- to moderately well-sorted, white- to pale-gray, fine- to medium-grained sandstone and greenish-gray or gray mudstone. Some conglomeratic lenses occur, especially at the base of trough cross-stratification in the sandstone beds. The conglomerate clasts consist of Paleozoic marine limestone and multi-colored chert eroded from the Elko highlands and regions to the southwest. The coarser-grained strata were deposited as river channel sandstone and adjacent proximal over-bank deposits of levees and crevasse splays, and finer-grained strata as floodplain deposits. The base of the member is typically the first thick sandstone bed overlying the slope-forming Tidwell Member. By this definition, the base of the Salt Wash Member is not synchronous because the river channels swept across the landscape represented by the Tidwell Member at different times.

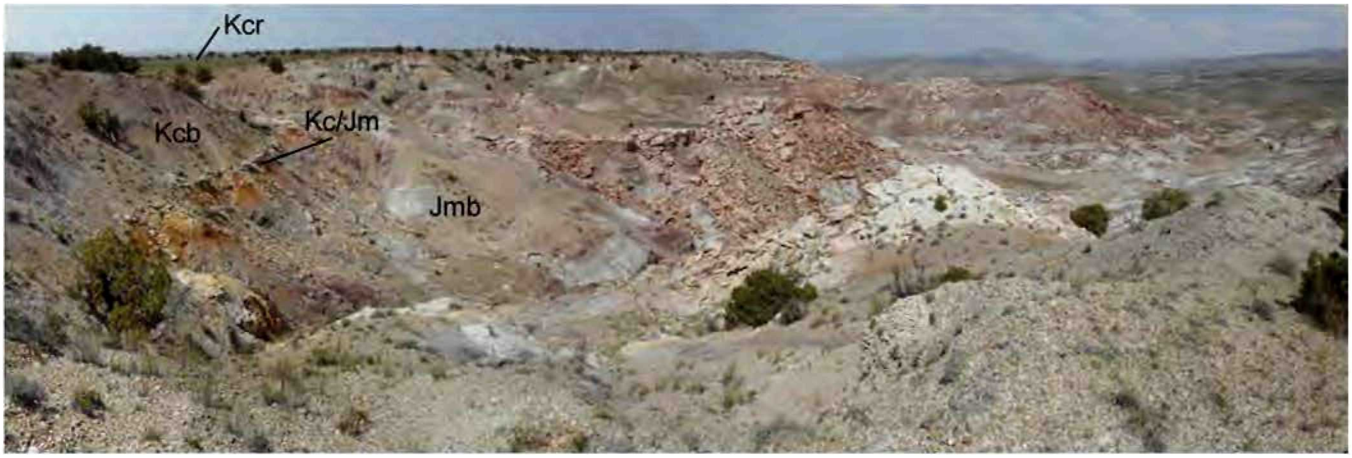

Figure 2. *View of the escarpment and flat upper surface of the cuesta held up by resistant Buckhorn Conglomerate Member of the Cedar Mountain Formation in the western part of Jurassic National Monument. Abbreviations:* **Jmb** *– Brushy Basin Member, Morrison Formation;* **Kc/Jm** *– Jurassic-Cretaceous boundary (K-1 unconformity);* **Kcb** *– Buckhorn Conglomerate Member, Cedar Mountain Formation;* **Kcr** *– Ruby Ranch Member, Cedar Mountain Formation.*

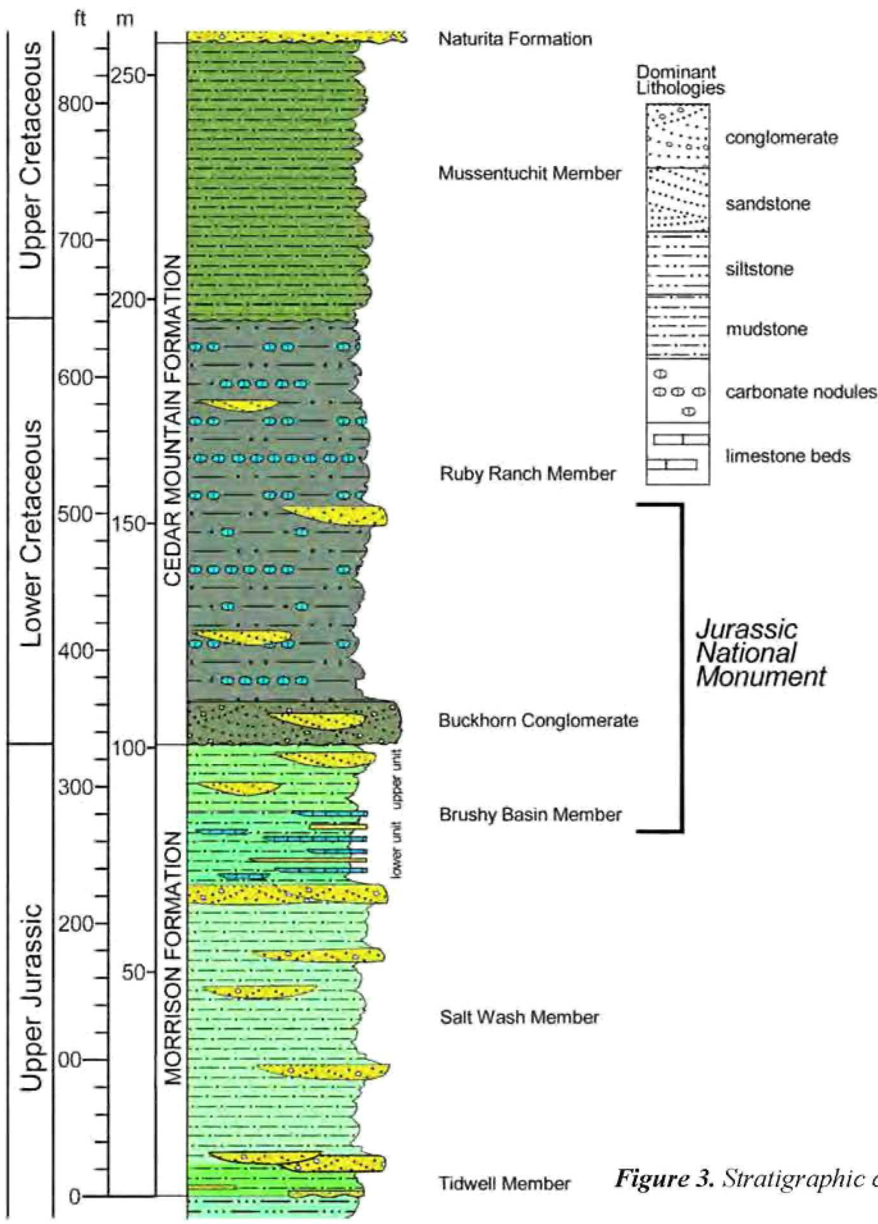

Figure 3. *Stratigraphic column of Jurassic National Monument.*

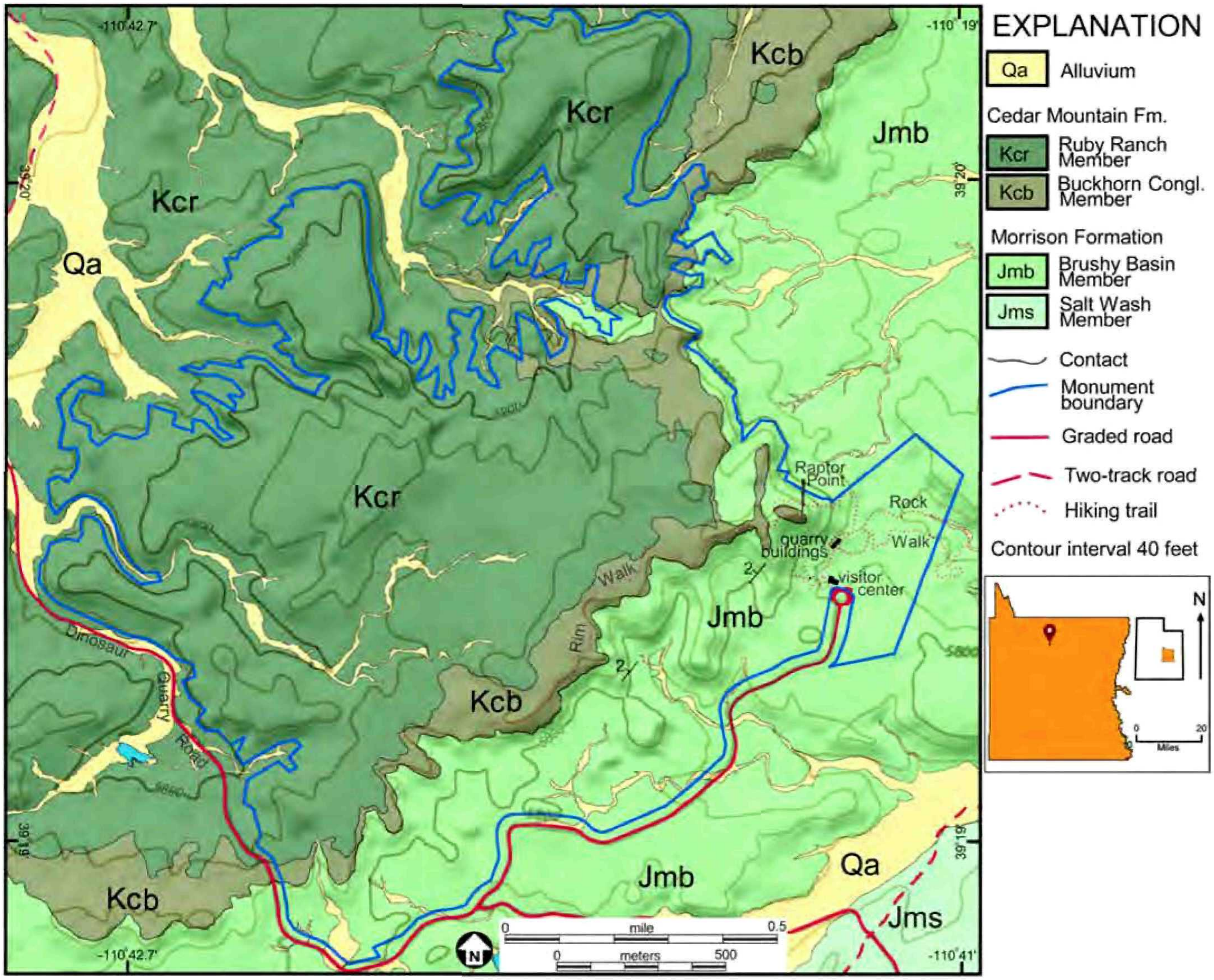

Figure 4. *Geologic map of Jurassic National Monument and surrounding areas. Mapping by author.*

The top of the Salt Wash is a widespread sandstone and a change from illitic clay mudstone to the volcanically derived smectitic clay mudstone of the Brushy Basin Member, which has a foamy or frothy appearance when weathered (figure 5A). This abrupt change in mudstone texture was due to the arrival of volcanic ash blown downwind of a subducting volcanic arc along the western margin of North America (Craig and others, 1955; Christiansen and others, 2015; Heller and others, 2015). Near the monument, the Salt Wash Member is about 217 feet (66 m) thick.

Brushy Basin Member

The Brushy Basin Member extends from Cottonwood Wash southeast of the monument up the face of the escarpment. The Brushy Basin Member is 105 feet (32 m) thick, with a gentle dip of about 2° northwest and a strike of 42° east. Radiometric dates at Little Cedar Mountain, about 11 miles (18 km) southwest of Jurassic National Monument, place the base of the Brushy Basin Member at 152.14 ± 0.51 Ma and the top at 150.00 ± 0.52 Ma (Trujillo and Kowallis, 2015). The Cleveland-Lloyd Quarry lies near the middle of the member, therefore the quarry strata are approximately 151 Ma. The member can be divided informally into two parts or units based on lithological differences (figures 3 and 5B). However, the thickness of the two units is not uniform across the escarpment and can vary by as much as 30 feet (10 m).

The informal lower unit consists of mudstone interbedded with multiple thin (4 to 50 inches [10–125 cm] thick) limestone beds and a few lenticular and tabular sandstone beds (figure 5B); most of the unit lies outside the southeastern monument boundary and can be seen along the Rock Walk Trail. The greenish-gray to gray mudstones are a mixture of smectitic clay and fine to medium grains of sand, composed of quartz, potassium feldspar, plagioclase, microcline, volcanic fragments, and biotite derived from volcanic ash (Bilbey, 1992; Christiansen and others, 2015). Based on studies of modern environments, the gray colors of the mudstone indicate that the ancient soils, or paleosols, were water saturated for at least a part of the year (Vepraskas and others, 2018).

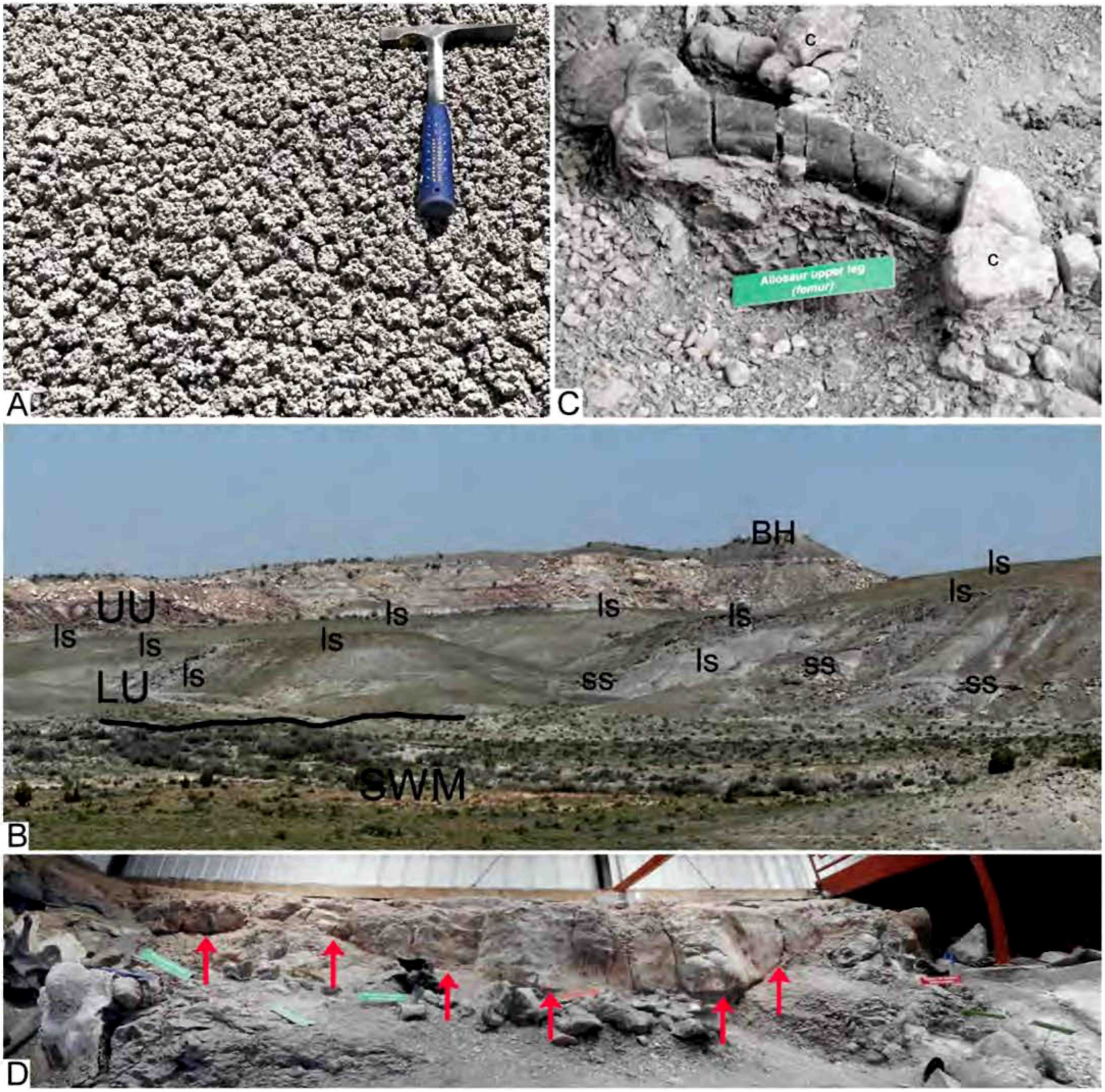

Figure 5. *Sedimentary features in Brushy Basin Member. (A) Characteristic popcorn or frothy texture of smectitic mudstone. (B) lower unit (LU) and upper unit (UU) of the Brushy Basin Member, Morrison Formation. Abbreviations: ls – limestone bed; ss – sandstone bed. (C) Carbonate nodule (c) overgrowth on fossil bone. (D) Uneven contact (red arrows) between overlying limestone and bone-bearing claystone. Thickest part of limestone is approximately 2.5 feet (0.75 m).*

The matrix of the Cleveland-Lloyd Dinosaur Quarry is a gray, calcareous, smectitic claystone, which is reported to have been up to 5 feet (1.5 m) thick during excavations (Miller and others, 1996). A series of 17 rock cores taken near the quarry by the Bureau of Land Management in 1982 shows that the claystone lies in a lens that thins towards the west and northeast. This lenticular cross section indicates a large pond, an interpretation supported by fossils of calcareous freshwater algae called charophytes and fossil aquatic gastropod shells (Madsen, 1976; Bilbey, 1998; Peterson and others, 2022). Calcium carbonate nodules occur among and adhering to the bones in the quarry (figure 5C). Laboratory studies and experiments have shown that such nodules form as a result of bacterial precipitation of dissolved calcium, which is used to dispose of metabolic waste (Berner, 1968; Yoshida and others, 2018).

The limestone beds are thin, tabular, and ledge and cuesta forming (especially near the visitor center and southeast of the road to the quarry). They are gray and commonly weather brown to yellowish-brown from their iron content. The upper and lower contacts of the limestone with the mudstone are abrupt and generally flat. However, the lower contact may be irregular, such as the limestone bed overlying the mudstone of the dinosaur quarry (figure 5D). This uneven base probably reflects that a hummocky surface existed at the time of the limestone deposition rather than differential compaction because of the uniformly flat upper surface of the limestone. Charophytes and aquatic gastropods occur, although not in great abundance (Bilbey, 1998, 1999; Suarez, 2003a). The limestone beds are 31 to 47% of silt and clay by mass (Suarez, 2003a), and typically grade laterally into the adjacent mudstone. This high percentage of silt and clay, the presence of root traces, and the lack of distinct shorelines suggests these limestone beds were deposited in palustrine wetlands with much of the water derived from overland flow from rainfall and riverbank overflow. In addition, rare earth element (REE) analysis, a form of geochemical analysis, of several widespread limestone beds at nearly the same stratigraphic level show that they are multiple, rather than one single, widespread bed (Suarez 2003a, 2003b).

The few sandstone beds in this informal unit are typically thin (less than 2 feet [60 cm] thick), tabular bodies, fine- to coarse-grained, calcite-cemented, and clay-rich, with sharp upper and lower contacts with the adjacent mudstone. Less common are lenticular bodies of trough cross-stratified, medium- to coarse-grained and occasionally conglomeratic sandstone; these conglomerates include different colored cherts and mud pebbles.

The upper informal unit of the Brushy Basin Member, best exposed on the escarpment, is predominately multicolored (variegated) smectitic and illitic mudstone interbedded with white to yellowish weathering sandstone lenses and sheets (figure 5B). It erodes rapidly, creating a steep escarpment and short, deep canyons. The erosion of the sandstone is predominately mechanical from the undercutting by erosion of the mudstone, and the subsequent collapse and fragmentation of sandstone blocks. This tends to create a rugged talus slope of sandstone blocks, such as seen above the visitor center.

The bands of the multicolored mudstone beds in the upper unit hold clues to the environmental conditions under which they were deposited. Many of the white banded mudstone have a higher sand content than the other colored bands and thus have a higher porosity, which allowed leaching of water-soluble minerals and organic material by groundwater during the Late Jurassic. These white bands are commonly associated with levee or crevasse splay sandstone, whereas other white bands are muddy sandstone channel fills as indicated by their lenticular cross section. The various shades of red and gray bands are associated with soil features and represent ancient soils or paleosols formed during the Late Jurassic (figure 6A; Demko and others, 2004). Other paleosols include discontinuous orange beds underlying sandstone (figure 6B). The orange is caused by the precipitation of oxidized iron, which is common in the hyporheic zone (Larson and others, 2013), the zone of water-saturated sediment adjacent to and below the active channel where water is exchanged with water in the channel. Solutes and nutrients, including organic material, may undergo chemical reactions that are not possible in the stream channel because the slow-moving hyporheic water has longer opportunity to interact with soil minerals and soil microbes. Experimental work and field observations have shown that microbes are an important source for the precipitation of some minerals, especially iron minerals (e.g., Brantner and Senko, 2014; Qin and others, 2020).

The thick sandstone bodies are fine- to very coarse-grained and are often conglomeratic at the base. Some of the sandstone beds have two or more stories as shown by upper lens of sandstone beds erosionally cut into the upper parts of underlying sandstone bodies. These erosional surfaces are occasionally conglomeratic, with gravel of chert pebbles in various shades of gray, as well as angular mud pebbles several inches in diameter. The sandstone may be massive, lacking any internal structure, but common sedimentary structures include trough cross-bedding, tabular cross-bedding, and lateral accretion surfaces typical of meandering rivers. Unionid freshwater clam resting traces occur in a sandstone above the visitor center (figures 6C and 6D). Clams are reported from other sandstone beds within the monument as well (Kantor, 1995). The average paleoflow of the channels was towards the southeast (Kantor 1995).

The sheet sandstones can be traced along the escarpment for long distances. Some merge into a larger sandstone body indicating that the sheet sandstones are coarse-grained overbank deposits, i.e., levees and crevasse splays (figure 7A). However, because both levees and crevasse splays share similar criteria (e.g., sharp bases, distal thinning and fining), distinguishing them is difficult without knowing if paleocurrents diverge from a common point indicative of a crevasse splay. The sheet sandstones commonly grade away from the thicker sandstone body into white mudstone over the span of several tens of feet as the amount of coarse grains decreases and the clay content increases. Internally, the sandstone beds may show no structure or be laminated and may preserve dinosaur tracks (figures 7B and 7C). The tops of the sheet sandstones are occasionally rippled.

Cedar Mountain Formation

The Cedar Mountain Formation unconformably overlies the Morrison Formation and occupies most of the surface geology of Jurassic National Monument (figure 4). The formation is divided into five formal members and one informal member on the eastern part of the Colorado Plateau of Utah (Kirkland and others, 1997; Doelling and Kuehne, 2013; Kirkland and others, 2016). They are from bottom to top: the Yellow Cat, Buckhorn Conglomerate, Poison Strip, and Ruby Ranch Members, and the informally named Short Canyon, and Mussentuchit Members. Radiometric dates from near the bottom and top of the formation indicate that the Cedar Mountain Formation spans from 140 to 98 million years, thus the formation is Early

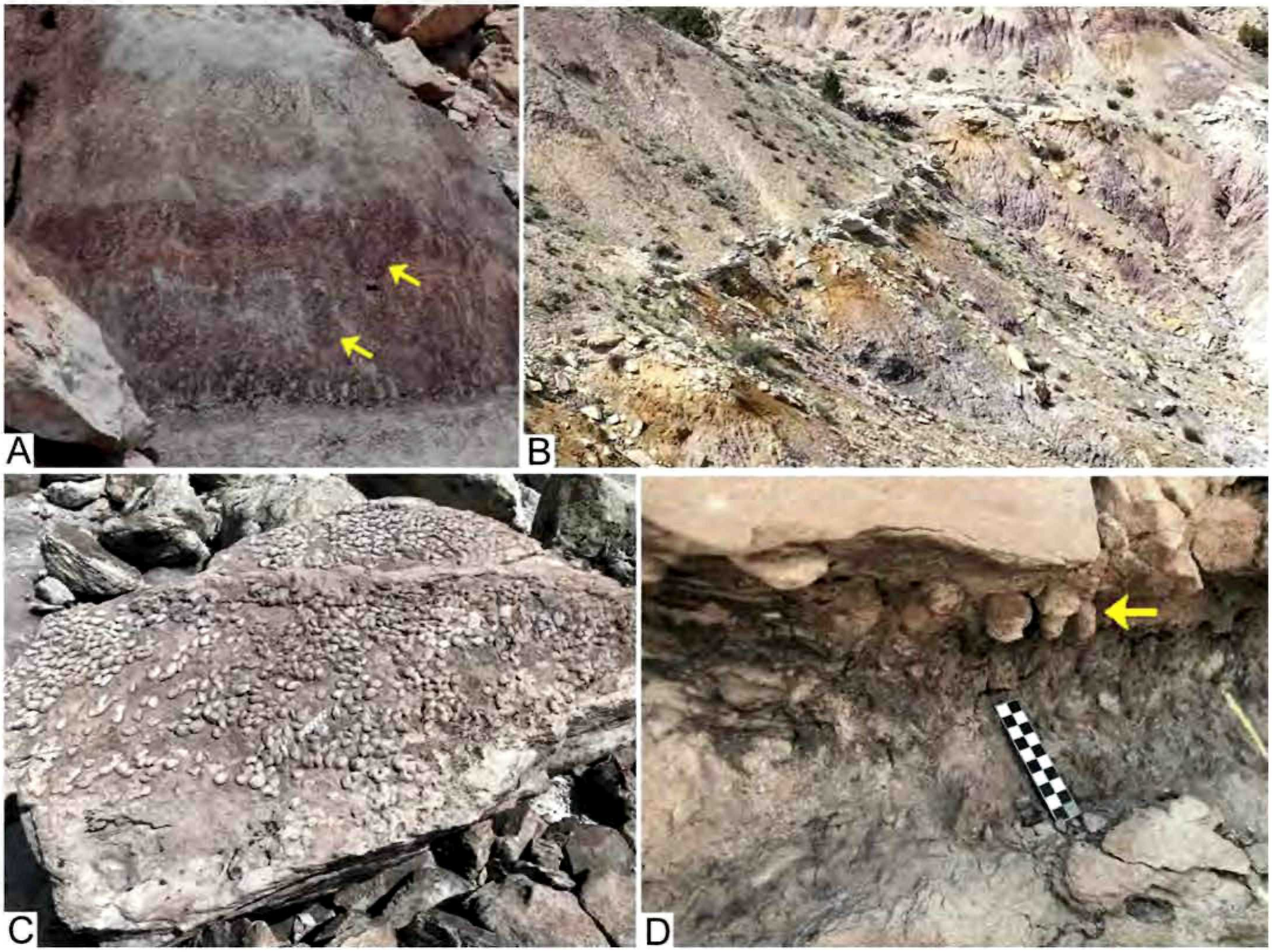

Figure 6. *Sedimentary features in Brushy Basin Member. (A) Gray and purple paleosol couplet. The upper gray paleosol is an iron and manganese depleted Gleysol, which formed under prolonged conditions of poor drainage resulting in reducing chemical conditions. The lower purple paleosol is the relocated (translocated) iron and manganese from the Gleysol deposit. Rhizoliths (root casts), extend from Gleysol downwards. Possible infilled vertebrate burrows at arrows. Height of couplet approximately 5 feet (1.5 m). (B) Redoximorphic mass (mineral deposit due to oxidation and reduction chemical reactions) paleosol horizon (yellow) in the former hyporheic (water circulation) zone below more porous sandstone and translocated manganese farther below in the purple. (C) Inverted sandstone cast of unionid clam resting traces. Scale (near center) in centimeters. (D) Natural occurrence of sandstone cast of unionid clam resting traces (arrow). Large slab in (C) originated here. Scale in centimeters.*

and early Late Cretaceous. However, at Jurassic National Monument, only the lower part of the Cedar Mountain Formation is present, the Buckhorn Conglomerate Member and the lower half of the Ruby Ranch Member (figure 3). The only fossils found to date from the Cedar Mountain Formation in the monument are wood fragments in the Buckhorn Conglomerate and dinosaur bone fragments in the Ruby Ranch Member (Casey Dooms, Bureau of Land Management, personal communications, 2003). Elsewhere, however, a large fossil record is known from the formation (Kirkland and others, 2016, 2023).

Buckhorn Conglomerate Member

The Buckhorn Conglomerate Member is resistant and forms the rim of the escarpment. Its base is irregularly scoured into the top of the Brushy Basin Member of the Morrison Formation, causing loss of an unknown amount of the Brushy Basin Member and of time. The Buckhorn Conglomerate is underlain by a discontinuous zone of iron oxide that was deposited in the hyporheic zone rather than being derived from a wetter climate at the end of the Jurassic or from weathering of an erosional surface before deposition of the conglomerate (figure 8A; see also figure 2). In addition, where the Brushy Basin Member beneath the Buckhorn is sandier, the rocks tend to be white due to leaching of water-soluble minerals and organic material by water seepage from the Buckhorn river(s), with the translocated minerals deposited below the bleached rock (figure 8B).

The conglomerate is up to 34 feet (10.5 m) thick in the

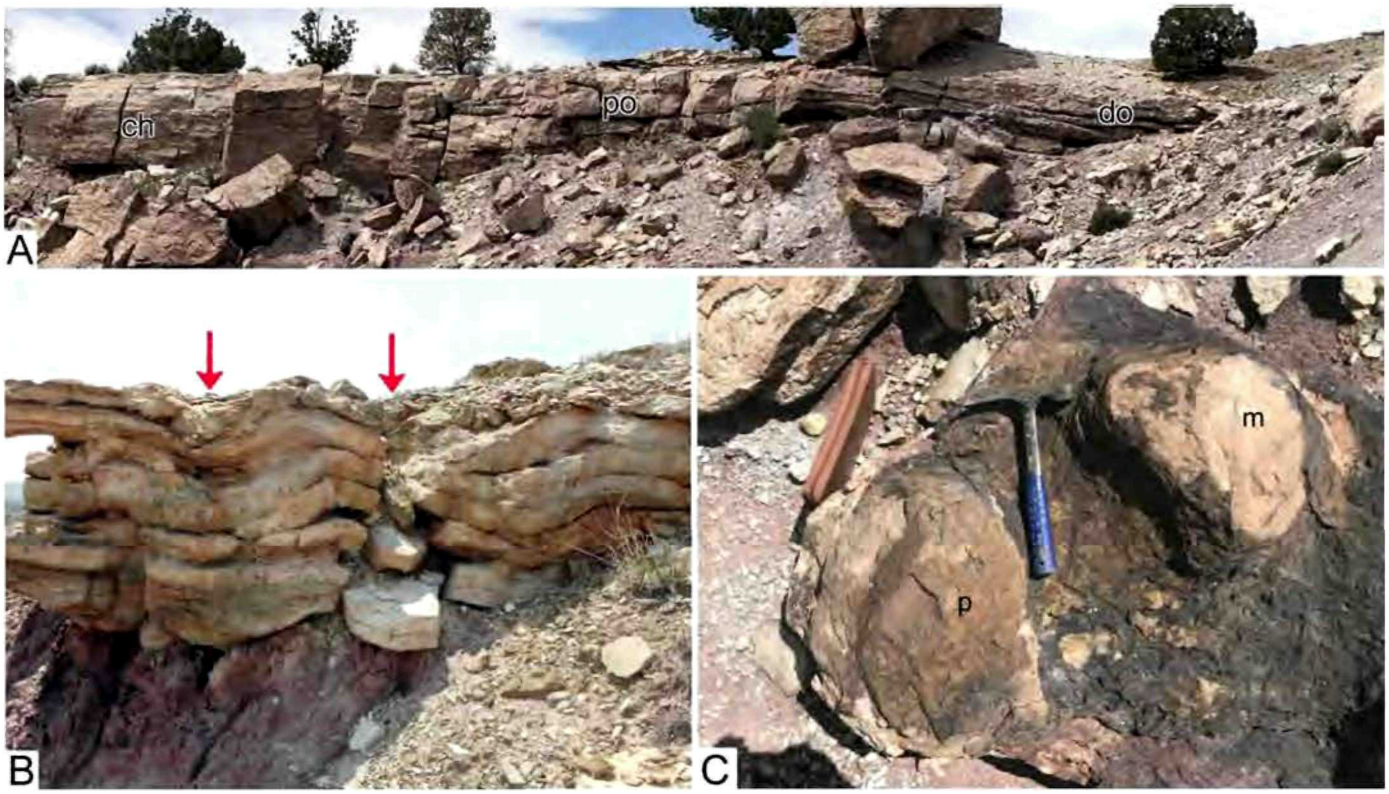

Figure 7. *Sedimentary features in Brushy Basin Member. (A) Sandstone channel (ch) grading into coarse-grained proximal overbank (po) to more distal overbank (do) separated by mudstone lenses of wanning overbank flow of a levee. (B) Sauropod track impression in stacked levee deposits. These beds can be traced to (A) indicating large tabular sheets of levees parallel to axis of channel rather than crevasse splays. (C) Sandstone casts of right fore and hind sauropod feet; the block originated from (B). Abbreviations: m – manus, p – pes. Rock hammer 11 inches (28 cm) in length.*

monument and is composed predominately of poorly to moderately sorted, subangular to rounded, white, red, brown, gray, and black pebble to cobble-size chert and quartzite (figure 8C; Stokes, 1944). Much of the conglomerate bed is poorly cemented, which causes the conglomerate to break down into a lag of gravel and cobbles on the cuesta surface as can be seen along the Rim Walk Trail or as a thin scree on the face of the escarpment (figure 2). Lenses of white to light-gray, medium- to coarse-grained sandstone (figure 8D) are present; some grade into conglomerate as seen at Raptor Point along the Rim Walk Trail above the quarry buildings. The Buckhorn Conglomerate was deposited in a broad, braided fluvial system flowing northeast from the rising Sevier orogeny to the west (Chidsey, 2013).

In the monument area, the top of the Buckhorn Conglomerate grades into the overlying Ruby Ranch Member within a 3- to 4-foot-thick (90–126-cm) zone of pale-red or pale-orange mudstone containing scattered or floating chert pebbles. For mapping purposes, the boundary is approximated where there is a sudden decrease in conglomerate size and red or orange mudstone first appear because these are easily seen on the surface. The change in grain size is especially noticeable on the gentle dip slope where the Buckhorn Conglomerate remains as lag on the surface (figure 8E).

Ruby Ranch Member

The Ruby Ranch Member is composed predominately of purplish-gray mudstone and abundant brown or brownish-gray carbonate nodules. In places, the nodules are so dense that they coalesce into thick beds (figure 9A). Geochemical and microscopic analysis of similar nodules elsewhere on the Colorado Plateau indicate nodule formation occurred in paleosols and ephemeral wetlands under semiarid conditions that was caused by the rain shadow effect of the Sevier Mountains rising to the west (Ludvigson and others, 2010, 2015). Many of the nodules are fractured and have calcite or chalcedony seams and some have a chalcedony septarian core (figure 9B). The nodules break up on the surface and, together with smaller spherical nodules, mantle the ground giving the surface a dark tint at a distance (figure 8C).

A few sandstone bodies are present, including a partially exhumed channel body near the northwestern monument boundary that is approximately in the middle of the member (figure 9C). Because of their resistance, the sandstone beds cap buttes and mesas on the cuesta surface (figure 8E).

In the vicinity of the monument, the Ruby Ranch Member is 255 feet (77.8 m) thick, but only the lower 151 feet (46 m) occur within the monument. The age of the Ruby Ranch ranges from the middle Aptian to middle Albian of the

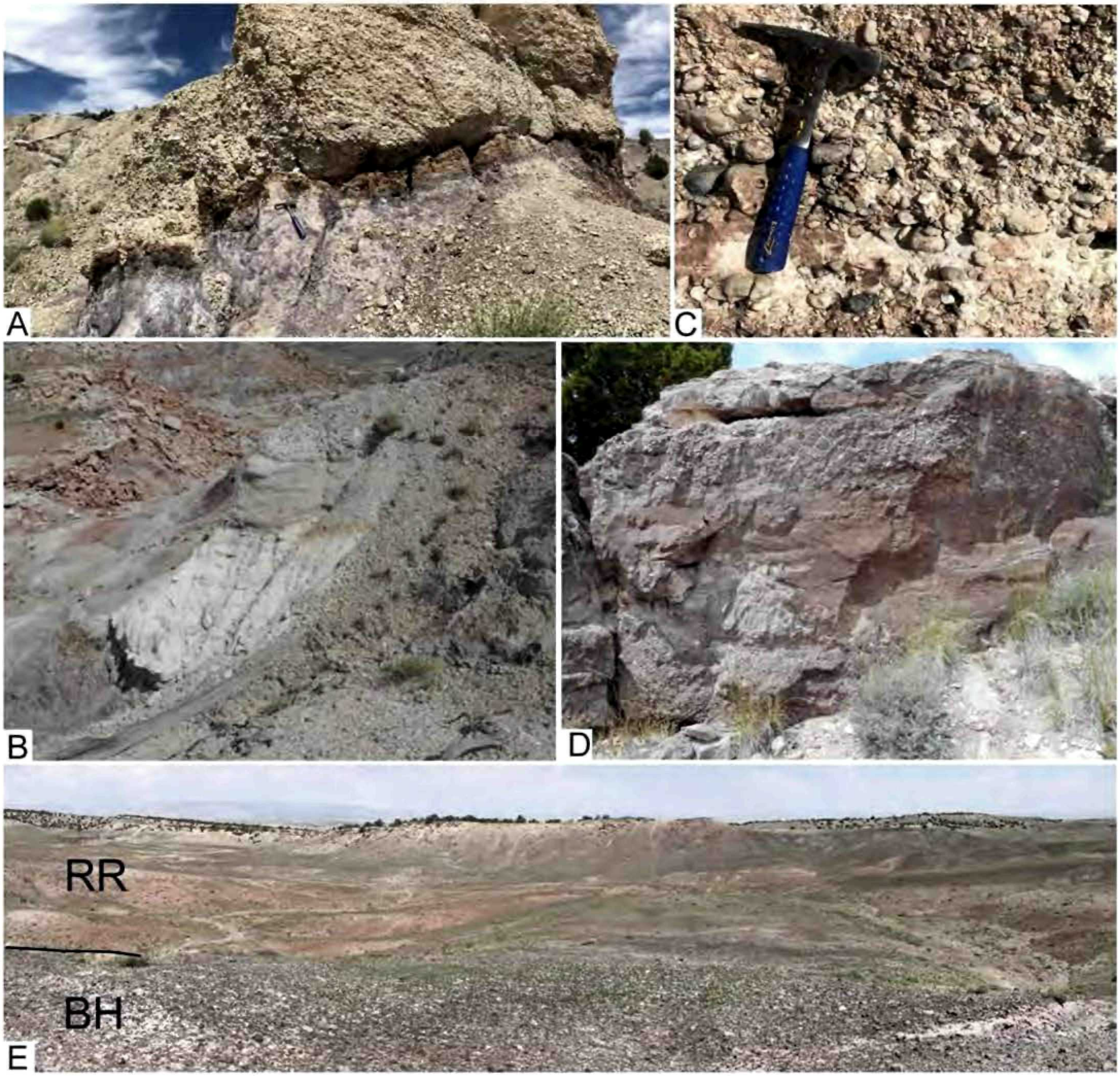

Figure 8. *(A) Irregular erosional contact between the Buckhorn Conglomerate Member of the Cedar Mountain Formation and mudstone of the Brushy Basin Member of the Morrison Formation. Note translocated iron (yellow) and manganese (pale purple) in the former hyporheic zone. (B) Contact between the Buckhorn Conglomerate Member of the Cedar Mountain Formation (gray) and a sandstone of the Brushy Basin Member of the Morrison Formation (white). Note zone of translocated iron (orange-brown) beneath Buckhorn Conglomerate and second zone below the bleached sandstone of the Morrison Formation. (C) Chert cobbles and pebbles of the Buckhorn Conglomerate. Hammer is 11 inches (28 cm) long. (D) Sandstone lens in the Buckhorn Conglomerate. Scale (upper center) in centimeters. (E) Top of the cuesta looking down the dip slope showing top of the Buckhorn Conglomerate (BH) and overlying Ruby Ranch Member (RR). The dark gray tint in the distant right is caused by covering of eroded carbonate nodules eroded from the Ruby Ranch Member.*

Early Cretaceous. A uranium-lead age of 119.4 ± 2.6 Ma has been reported from low in the Ruby Ranch Member (Ludvigson and others, 2010). This date was supplemented with carbon isotope fluctuations measured from carbonate nodules throughout the member. These fluctuations plotted as curves can be correlated with the better calibrated carbon isotope curves from marine rocks, which can be dated with invertebrate fossils. The carbon isotopes from the nodules show a peak of atmospheric carbon dioxide at approximately 111 Ma during the Aptian that may correspond to a major cycle of volcanic activity in the southern Indian Ocean (Ludvigson and others, 2015).

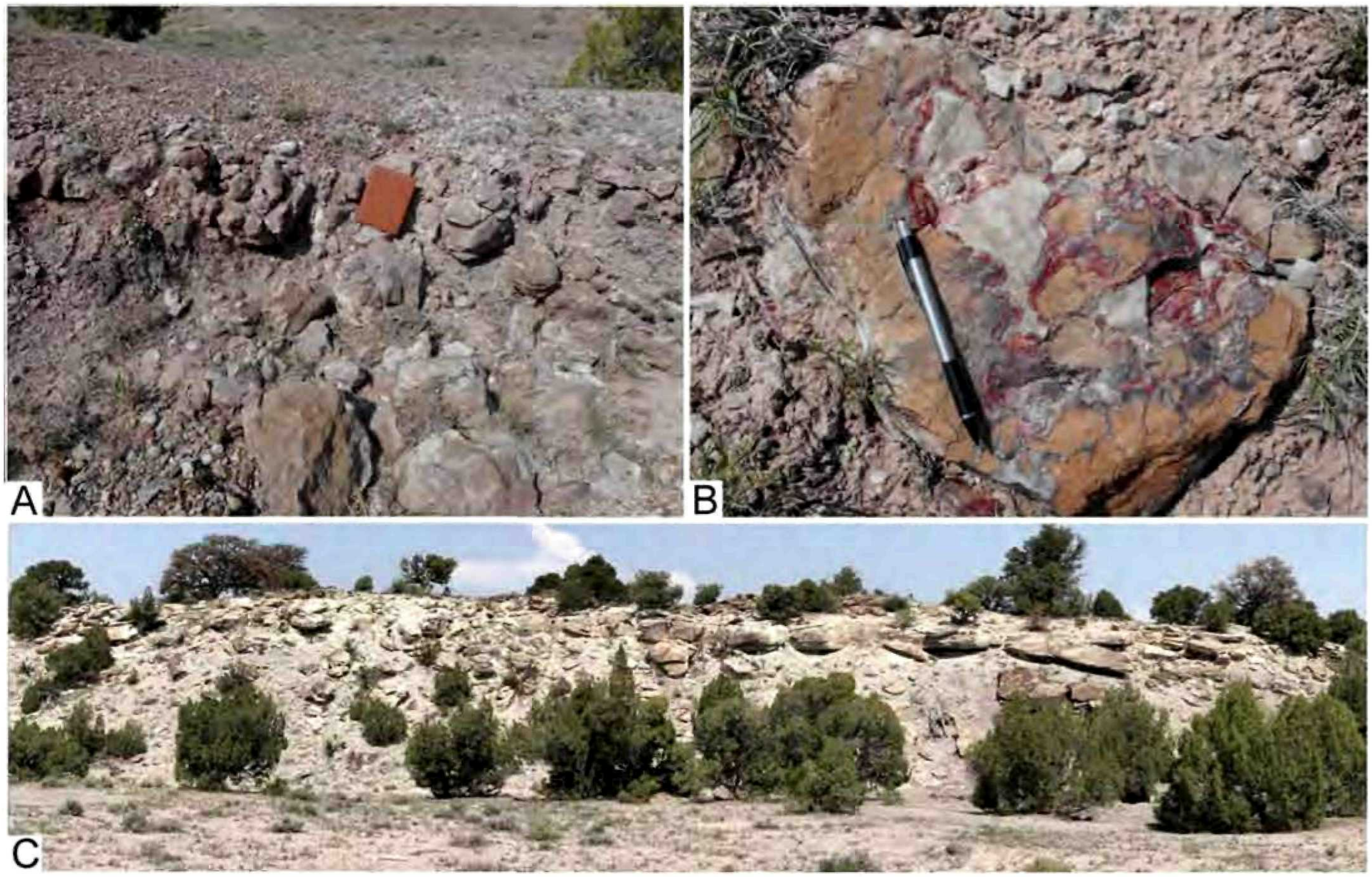

Figure 9. *(A) Carbonate nodule bed in the Ruby Ranch Member. Notebook is 11 inches (28 cm) tall. (B) Carbonate nodule with septarian core of chalcedony. Pencil is 5¼ inches (13.3 cm) long. (C) Partially exhumed sandstone channel in the Ruby Ranch Member.*

Surficial Deposits

Unconsolidated sand and gravel deposits occur along dry stream beds (figure 10A). Other unconsolidated deposits are not shown on the geology map (figure 4) because they are thin although they dominate the landscape in the monument. These include pediment surfaces of the cuestas where in-situ weathering of the bedrock has left a thin veneer of soil and rock debris, and talus slopes of rock debris and rockfall along the escarpment. Numerous small unnamed gullies, which carved canyons into the escarpment, are tributaries of Cottonwood Wash, an ephemeral wash outside the southern monument boundary. Similar small washes on the north side of the escarpment flow into Soap Wash.

These seemingly insignificant dry washes actually shaped the modern topography through erosion during sporadic summer rainstorms. The sediment deposits of these washes are predominately uncemented coarse-grained sands, pebbles, and boulders eroded from the more resistant sandstone and limestone beds of the Morrison and Cedar Mountain Formations. Finer grained sediments are deposited during the waning stage of flashfloods, especially when the flood has spilled out of the channel creating floodplains. Older alluvial deposits are present as terraces a few feet above the current washes (figure 10B). The ages of these older deposits are unknown but are assumed to be only a few thousand years old due to the rapidity of erosion.

STRUCTURAL GEOLOGY

The monument lies on the northwestern corner of the San Rafael Swell, a large, asymmetric anticline, with a gentle western dip (2 to 6°) and a steeper eastern dip (45 to 85°) (Chidsey 2013). Uplift of the San Rafael Swell is associated with a reverse fault developed in the underlying Precambrian rocks during the Laramide orogeny from lateral compression as the oceanic Farallon plate to the west slid beneath the North American plate (Karlstrom and others, 2022). Uplifting created numerous faults in the area (see figures 5 and 31 in Chidsey, 2013), but none of these occur within the monument boundary and did not shape the landscape. Instead, differential erosion of the gently dipping Buckhorn Conglomerate caprock and the soft underlying Brushy Basin Member created a cuesta with a steep southeast-facing escarpment and a northwest-facing dip-slope that is rolling due to the uneven erosion of soft mudstone of the Ruby Ranch Member. Several short canyons and ravines are cut into the escarpment face through the rapid erosion of the Brushy Basin Member mudstone. Large sandstone bodies in the Brushy Basin Member resist erosion and create spurs or ridges projecting from

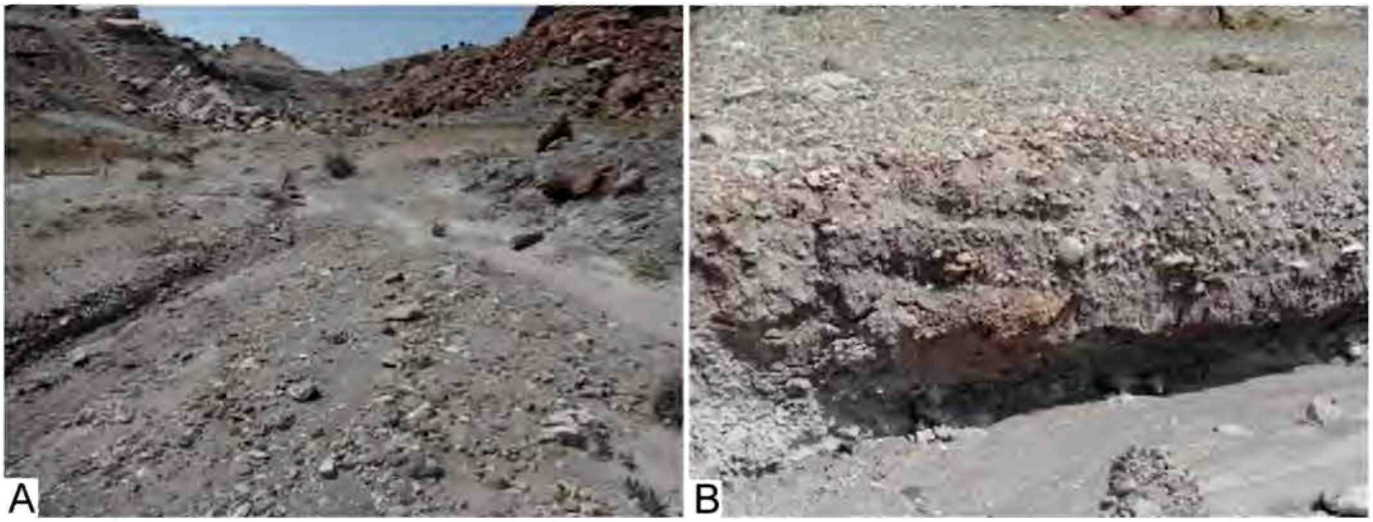

Figure 10. (A) Recent alluvium derived from the rocks in the background. Most of the cobbles are from the Buckhorn Conglomerate Member on the skyline. (B) Erosion through an older alluvial deposit (thickness about 2 feet [60 cm]). Most the cobbles are derived from the Buckhorn Conglomerate.

the escarpment with the short canyons developed between them.

GEOLOGIC HISTORY

The geologic history of Jurassic National Monument begins in the Late Jurassic with the start of deposition of the Morrison Formation following the northeastward regression of the Middle to early Late Jurassic Sundance seaway. The withdrawal left a very broad, low coastal plain that received sediments from the front of prograding fluvial mega-fans that built out from the Elko highlands to the west and from the Grand Canyon bight near the present-day Arizona-Nevada border (Carpenter, 2022). A vast sand sheet developed leeward of the fans across much of present-day Utah, analogous to the modern Gran Dieserto in Sonora, Mexico. A large complex of playa lakes developed contemporaneously south of the current monument. Continued progradation of the distal fan facies formed an interbedded, thin sandstone-siltstone-mudstone-limestone facies assemblage of the Tidwell Member. These strata indicate that the sediments were deposited in broad, very shallow fluvial and lacustrine environments. Thicker deposits of fluvial sandstone interbedded with overbank mudstones represented by the Salt Wash Member are the main bodies of the prograded fluvial mega-fans. Paleocurrent measurements of sandstone bodies indicate mega-fan sources lay to the west and southwest (Carpenter 2022), with deposition occurring in braided and meandering rivers and their associated floodplains. Fossil logs in the Salt Wash Member from elsewhere on the Colorado Plateau indicate forests of moderately tall conifers of 90 plus feet (28– m) growing in warm climates lacking strong seasonality in precipitation (Gee and others, 2019).

An increase of volcanism around 152 Ma in a broad belt along the western and southwestern margin of the North American plate deposited a great amount of volcanic ash downwind over what is now the Colorado Plateau (Christiansen and others, 2015). This influx of ash clogged rivers causing an increase in sedimentation on the floodplains (Heller and others, 2015). Alteration of the ash in the presence of water, a process called diagenesis, transformed it to smectitic clay, which is the dominant clay of the Brushy Basin Member. Frequent overbank flow caused pooling on the floodplain and the development of small wetlands and ponds, which are represented by the lower informal unit of the Brushy Basin Member (figure 11A). In one of the ponds, dinosaur skeletal remains amassed, although the mode of accumulation is controversial (see below and table 1).

A marked change in sediment deposition marks the transition to the upper part of the Brushy Basin Member. One or more rivers, which shed water and silt far onto the floodplain, depositing the lower unit, shifted to occupy the area now occupied by the monument (figure 11B) as is shown by large sandstone bodies, such as above the visitor center. Coarse-grained overbank flow deposited levees and small breaches deposited crevasse splays. More distally, flood waters deposited mud and silt. Fossil plants found elsewhere on the Colorado Plateau indicate a continuation of the warm and humid climate (Gee, 2020; Foster and others, 2023; Gee and others, 2023). This interpretation contrasts with the more arid climate that has been inferred from the sedimentary rocks of the Morrison Formation (Demko and others, 2004; Parrish and others, 2004). Support for elevated rainfall is indicated by the presence of large sandstone bodies, and the large clam beds indicate stable water flowed year-round (Good, 2004).

By the Early Cretaceous, the Sevier orogeny was uplifting mountains in western Utah and eastern Nevada. Gravel-filled braided river channels flowing from the uplifting highlands scoured into the top of the Brushy Basin Member and deposited the conglomerate and sandstone of the

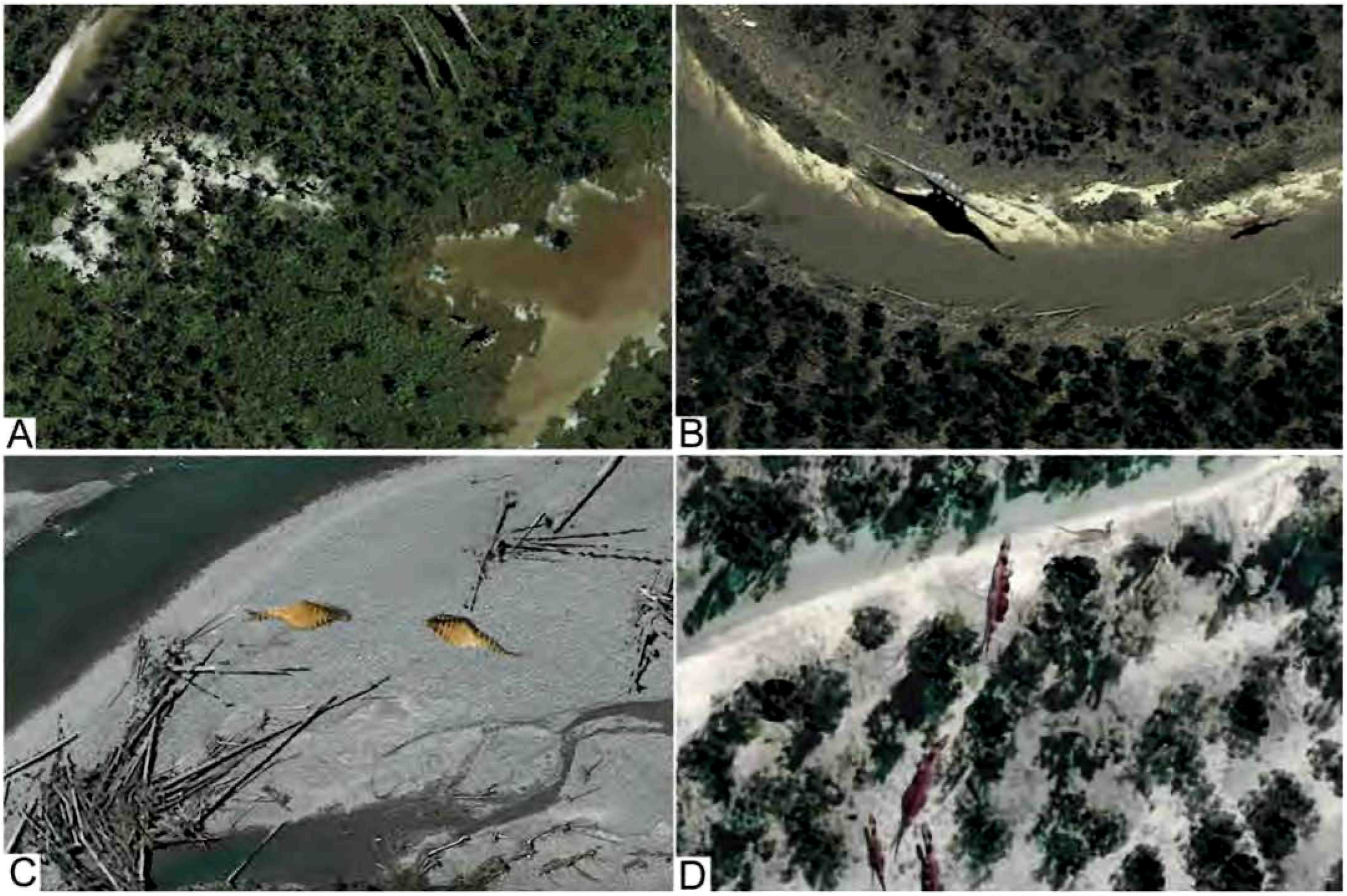

Figure 11. *Jurassic National Monument through time. Reconstructed aerial views during deposition of the major strata. (A) Lower unit of the Brushy Basin Member during which overbank flow from a river (upper left) created a pond on the floodplain (lower right). The* Diplodocus *sauropods that roamed this landscape were about 80 feet (24.5 m) long. Other dinosaurs include two* Stegosaurus *(lower center) and an* Allosaurus *(right of center) (B) Upper unit of the Brushy Basin Member dominated by fluvial system of channel and associated floodplain, The* Diplodocus *was about 80 feet (24.5 m) long, significantly larger than the approaching* Allosaurus. *(C) Buckhorn Conglomerate Member of braided river channels. The two armored ankylosaurs (genus unnamed) are about 10 feet (3 m) long. (D) Semiarid environment of the Ruby Ranch Member. Adult and juvenile iguanodontid dinosaurs (genus unnamed); adults were about 20 feet (6 m) long. Scale differs among the images.*

Buckhorn Conglomerate Member (figure 11C). Continued rise of the mountains blocked moisture-ladened winds resulting in a shift from the mesic conditions of the Late Jurassic to a strongly seasonal semiarid climate in Early Cretaceous in eastern Utah. This climatic change is evidenced by the extensive development of carbonate nodules in paleosols and in ephemeral pond deposits of the Ruby Ranch Member (figure 11D). Dinosaur fossils have been found at various sites in the Ruby Ranch and indicate the dinosaur fauna in the lower part of the member (Aptian in age) is different from the dinosaur fauna in the upper part (Albian in age), probably due to the isolation of North America from other continents until the end of the Early Cretaceous (Kirkland and others, 2023).

Except for the more recent alluvium in the wash bottoms, post-Ruby Ranch strata in the San Rafael Swell are not present within the monument boundaries but are preserved just to the north. These younger strata record renewed volcanism (Mussentuchit Member, Cedar Mountain Formation), then the encroachment of the Cretaceous Interior seaway (Naturita Formation) and its subsequent transgression over the area (Mancos Shale). Late Cretaceous withdrawal of the seaway coincided with the Laramide orogeny and the under-sliding of the Farallon plate beneath the North American plate during the Late Cretaceous–early Paleogene (Chidsey 2013; Karlstrom and others, 2022). Two major effects of the under-sliding plate were: (1) to elevate the Colorado Plateau and (2) to create several basins and anticlinal folds, including the San Rafael Swell, due to lateral compression caused by the drag of the Farallon plate on the underside of the North American plate. By the middle Cenozoic, erosion rather than deposition dominated on the plateau, and continues today. The effects of this erosion are seen today by the cliffs and canyons of the San Rafael Swell. It was erosion that exposed the fossil bones that became the Cleveland-Lloyd Dinosaur Quarry. The recent alluvium in the washes chronicle the

Table 1. *Comparison of the different hypotheses that have been proposed to explain the unusual concentration of fossil bones of the Cleveland-Lloyd Dinosaur Quarry arranged chronologically.*

Reference(s)	Hypothesis	Pros	Cons
Stokes (1945)	Dinosaurs died on bed of drying body of water and disarticulated by scavengers or trampling.	Dominance of *Allosaurus* due to scavenging behavior.	Little evidence on bone of scavenging.
Dodson and others (1980)	Predators mired in an oxbow lake.	Explains the dominance of carnivores.	No evidence of a channel that was cut off. Little evidence on bone of scavenging. No explanation for scattering of bones.
Stokes (1985)	A localized boggy spot beneath a shallow pond analogous to quicksand, but of clay.	Dispersal of disarticulated bones by water circulation. The input water is mineral rich and fossilized the bones.	Does not explain dominance of one species.
Hunt (1986)	Catastrophic mortality and later transport by sheet flood to site.	Fluvial transport sorting explains the under-representation of some bones. Scattering of bones during transport.	Lack of siliciclastics from fluvial transport with bones.
Bilbey (1992)	Predator trap and trampling by other dinosaurs.	Dominance of *Allosaurus* due to predatory behavior.	Little evidence for predation.
Richmond and Morris (1996; also Morris and others, 1996)	Predator miring of pack-hunting *Allosaurus* in flood pond between anastomosing channels.	Dominance of *Allosaurus* due to pack-hunting.	No evidence presented for an anastomosing river. Little evidence on bone of scavenging. No explanation for scattering of bones.
Bilbey (1998)	Predator trap in muddy lake sediments.	Abundance of carnivores, scattering of bones from decomposed carcasses.	Little evidence for predation.
Bilbey (1999)	Predator trap of volcanic mud in a spring-fed pond.	Distribution of bones by trampling and water circulation.	No evidence for a spring. Little evidence on bone of scavenging.
McGee (1999)	Separate events of predator trap and fluvial concentration.	Explains dominance of *Allosaurus* and mix of other dinosaurs over time.	Lack of siliciclastics with bones; unable to differentiate events. Little evidence on bone of scavenging.
Suarez (2003a)	Drought accumulation.	Explains the Light Rare Earth Element signature.	Does not explain dominance of one species or scattering of bones.

Table 1 (continued). *Comparison of the different hypotheses that have been proposed to explain the unusual concentration of fossil bones of the Cleveland-Lloyd Dinosaur Quarry arranged chronologically.*

Reference(s)	Hypothesis	Pros	Cons
Gates (2005)	Multiple drought events at an ephemeral pond where *Allosaurus* congregated.	Scattering of bones by scavengers and trampling.	Does not adequately explain dominance of one species.
Hunt and others (2006)	Miring of some animals and semi-disarticulated skeletons transported by sheetflood to site.	Sorting explains the under-representation of some bones. Scattering of bones from transport.	Lack of siliciclastics from fluvial transport with bones.
Peterson and others (2017)	Attritional accumulation in an ephemeral pond by flood.	Abraded bone fragments from seasonal reworking and redeposition. Hyper-eutrophication explains geochemical signature.	Lack of siliciclastics with bones. Does not explain dominance of one species.
Reddick (2018)	Not a predator trap when compared with La Brea tar pits.	Attritional accumulation of bones.	Questionable validity for comparative population curves based on femur lengths of *Allosaurus* and dire wolf.
Moore (2019)	"Bloat and float" carcasses in an ephemeral pond.	Wide distribution of bones from individual carcasses.	Does not explain dominance of one species.

on-going erosion of the cuesta and temporary deposition of sands, gravels, and cobbles. Movement of the alluvium downstream to Price River is incremental from the heavy rainstorms of the summer.

PALEONTOLOGY

Brief History of Jurassic National Monument

Jurassic National Monument was created around the Cleveland-Lloyd Dinosaur Quarry, a site that was first excavated by the University of Utah in 1929 (figure 12A). Excavations continued for three years; it was apparent early that the site was unusual because of the high proportion of bones of *Allosaurus*, a large carnivorous dinosaur from the Late Jurassic. Excavations at the site by Princeton University from 1939 to 1941 (figure 12B) sought to collect enough bones for a mounted dinosaur skeleton. It was at this time that the site received its moniker named after Cleveland, Utah, the nearby hometown of William Stokes who led the Princeton excavations, and Malcolm Lloyd, a Princeton alumnus who partially funded the field work. World War II interrupted further excavations and it was not until 1960 that excavations were resumed by William Stokes, then at the Department of Geology, University of Utah. Stokes and James Madsen, curator of the geology department's Museum of Earth Sciences. They developed the Cooperative Dinosaur Project in which funding museums and universities would receive a fossil skeleton for exhibit (figures 12C and 12D). Intensive excavations took place for the five years of the project and then sporadically up to the present by the Utah Museum of Natural History (now the Natural History Museum of Utah), Utah Division of History, Brigham Young University, and the University of Wisconsin-Oshkosh. Archival records show that about 16,211 dinosaur bones have been excavated from 3370 square feet (313 m^2), making it one of the richest concentrations of dinosaur bones in the world (figure 13).

As a result of the scientific importance of the site, the Cleveland-Lloyd Dinosaur Quarry was designated a National Natural Landmark in 1967. Two metal buildings were erected over part of the site in 1976 for protection of the fossils and security of in situ exhibits (figure 14). In 2019, the area was designated Jurassic National Monument under the management of the Bureau of Land Management.

Figure 12. *(A) First excavations at what became the Cleveland-Lloyd Dinosaur Quarry; photograph taken September, 1929. Courtesy Marriott Library Photo Archives. (B) Princeton University excavation in 1941. (C) University of Utah Cooperative Dinosaur Project excavation in 1962. Courtesy Museum of Natural History of Utah. (D) Tables of mostly Allosaurus bones (taken in about 1970), University of Utah Cooperative Dinosaur Project, from the Cleveland-Lloyd Dinosaur Quarry. Courtesy Marriott Library Photo Archives.*

Fossils of Jurassic National Monument

The Cleveland-Lloyd Dinosaur Quarry contains the richest concentration of fossils in the monument but is not the sole occurrence. Freshwater invertebrates occur in limestone beds of the lower part of the Brushy Basin Member, and clams, dinosaur bones, and trace fossils occur in its sandstones, as summarized below. A list of taxa is given in table 2.

Plants

Plants include four different morphotype species of the calcareous reproductive structure of freshwater algae (charophyte oogonia). They occur in both the quarry claystone and limestone beds. Modern charophytes grow in still or slow moving, calcareous freshwater. Other plants include fragments of the woody parts of trees, including shoots found in limestone and wood found in limestone, siltstone, sandstones, and conglomerate throughout the monument. Root traces (rhizoliths) of unknown plants are commonly seen in paleosols.

Gastropods

Gastropods occur in many of the limestone beds. Most are small, but nowhere are they abundant. The assemblages include both gill-breathing or prosobranch snails (*Amplovalvata, Viviparus*), and lung-breathing or pulmonate snails (*Gyraulus, Lymnaea*). Prosobranch snails occur in well-oxygenated, perennial standing water, and pulmonate snails occur in both perennial standing water and in oxygen-poor, ephemeral ponds (Evanoff and others, 1998). Feeding traces from possibly one of these snails are known from the surfaces of river channel sandstone.

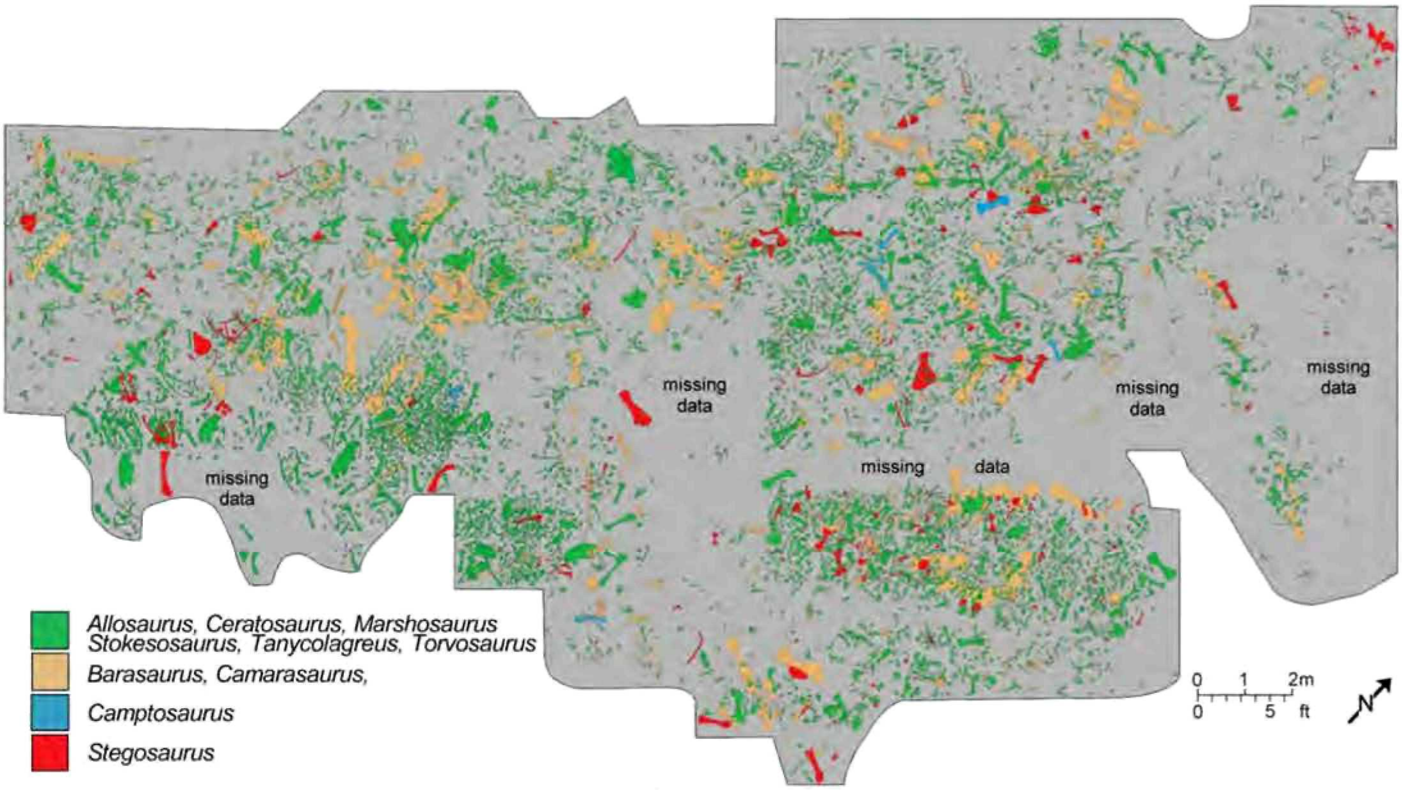

Figure 13. *Map showing distribution of bones excavated at the Cleveland-Lloyd Dinosaur Quarry, 1960–1990. Based on maps in Miller and others (1996).*

Unionid Clams

Unionid clams are known from resting traces at the interface between overlying sandstone and mudstone. The clams originally occupied a floodplain pond, which was buried by a crevasse splay represented by the sandstone when a nearby river flooded and breached its banks. The absence of shells indicates that the clams were able to free themselves (Good, 2004). These freshwater clams prefer well-oxygenated, perennial fluvial or standing water. Today, unionid clams have a parasitic larval stage on a fish host, which suggests that fish were present in the rivers, although no fossils have yet been found.

Crustaceans

Crustaceans are represented by the tiny shells of ostracods or seed clams. At least two different shell types are present in some of the limestones.

Arthropods

Arthropods are known only by the tracks and burrows (trace fossils or ichnofossils) made in the sediments of fluvial sandstones. These trace fossils provide important clues for the presence of organisms not represented by body fossils (shells, bones, etc.) and help to fill out the paleoecosystem. The recent discovery of arthropod body fossils from the Brushy Basin Member elsewhere on the Colorado Plateau should give better insights into the potential trace makers at Jurassic National Monument (Lara and others, 2023).

Dinosaurs

Dinosaurs are represented by bones from fourteen species from the Cleveland-Lloyd Dinosaur Quarry (figure 15). It has long been known that the bones of the carnivorous dinosaur *Allosaurus* dominates the site numerically, although the reason for this has long been the topic of much debate (table 1). Many of the hypotheses center around the inferred predatory or scavenging behavior of the dinosaur around a drying water hole, while other hypotheses focus on fluvial concentration in a topographic low on the floodplain. Each hypothesis has its adherents, but the lack of testability makes the hypotheses speculation.

A benefit of having so many specimens of *Allosaurus* is that individuals of different size categories, hence ages, are represented (figure 16). Based on growth rings in the bones, the youngest individuals are estimated to have been about a year old, whereas the oldest about 19 years old (Bybee and others, 2006). The largest bones suggest that *Allosaurus* might have lived a maximum of 28 years.

Currently, there is no other site in the Morrison Formation that has provided a large data set for age and growth studies. Future plans by the Bureau of Land Management are to erect a new, larger protective building over the quarry, to develop the bones in situ, and to expand interpretative displays of this unique site.

Table 2. *Taxonomic list of fossils excavated and studied from Jurassic National Monument.*

KINGDOM PROTISTA
DIVISION CHLOROPHYTA
CLASS CHAROPHYCEAE
Family Characeae, calcareous freshwater algae
Aclistochara bransoni (ref. Peterson and others, 2022)
Latochara collina (ref. Peterson and others, 2022)
Porochara fusca (ref. Schudack and others, 1998)
Stellatochara obovate (ref. Peterson and others, 2022)
KINGDOM PLANTAE
CLASS CONIFEROPHYTA
Order Coniferales
Family uncertain
Behuninia provoensis, short shoot (ref. Suarez, 2003a updated)
CLASS GINKGOOPSIDA
Order Ginkgoales
Family uncertain, wood (ref. Suarez, 2003a)
KINGDOM ANIMALAE
PHYLUM MOLLUSCA
CLASS BIVALVIA
Order Unionida
Family Unionidae
Vetulonaia sp freshwater clam (ref. Good, 2004)
CLASS GASTROPODA
Order Architaenioglossa
Family Cyclophoridae, freshwater snail
Amplovalvata sp. (ref. Suarez, 2003a)
Family Viviparidae, freshwater snail
Viviparus sp. (ref. Madsen, 1976)
Order Heterostropha
Family Lymnaeidae, freshwater snail
Lymnaea ativuncula (ref. Suarez, 2003a updated)
Lymnaea morrisonensis (ref. Suarez, 2003a updated)
Family Planorbidae
Gyraulus veternus, freshwater snail (ref. Suarez, 2003a updated)
PHYLUM ARTHROPODA
CLASS OSTRACODA, seed shrimp
Order Podocopa
Family Limnocytheridae
Theriosynoecum wyomingense (ref. Suarez, 2003a)
Helmdachia sp. (ref. Schudack unpublished)
PHYLUM CHORDATA
CLASS REPTILIA
Order Testudines
Family Pleurosternidae
Glyptops plicatulus, freshwater turtle (ref. Bilbey, 1992)
Order Crocodylomorpha
Family Goniopholidae
Amphicotylus?, crocodile (ref. Bilbey, 1999 updated)
CLADE[1] SAURISCHIA
Clade Theropoda
Family Ceratosauridae
Ceratosaurus dentisulcatus (ref. Madsen and Welles, 2000)
Family Megalosauridae
Torvosaurus sp.? (ref. Foster, 2003)
Family Allosauridae
Allosaurus fragilis (ref. Madsen, 1976)
Family Stokesosauridae
Stokesosaurus clevelandi (ref. Madsen, 1974)
Family Coeluridae
Coelurus sp.? (ref. Carpenter and others, 2005a)
Family Piatnitzkysauridae
Marshosaurus bicentissimus (ref. Madsen, 1976)
Family unknown
Tanycolagreus topwilsoni (ref. Carpenter and others, 2005b)
Clade Sauropoda
Family Haplocanthosauridae
?*Haplocanthosaurus* sp. (ref. Madsen and others, 1995)
Family Camarasauridae
Camarasaurus sp. (ref. Madsen and others, 1995)
Family Diplodocidae
Apatosaurus sp.? (ref. Foster and Peterson, 2016)
Barosaurus lentus (ref. Madsen and others, 1995)
Diplodocus sp. (ref. Foster, 2003)
CLADE ORNITHISCHIA
Clade Ornithopoda
Family Camptosauridae
Camptosaurus dispar (ref. Bilbey, 1992 updated)
Clade Stegosauria
Family Stegosauridae
Stegosaurus sp. (ref. Bilbey, 1992)
ICHNOFOSSILS, trace fossils
KINGDOM ANIMALAE
PHYLUM MOLLUSCA
CLASS BIVALVIA
Order Unionida
Family Unionidae, resting trace (ref. Good, 2004)
CLASS GASTROPODA
Order and family uncertain, feeding trace (ref. Hasiotis, 2004)
PHYLUM ARTHROPODA
CLASS MEROSTOMATA
Order Xiphiosura
Family uncertain
Kouphichnium isp freshwater horseshoe crab tracks (ref. Hasiostis, 2004)
CLASS INSECTA
Order Trichoptera
Family Limnephilidae?
Tektonargus kollaspilas, caddisfly larva tube (ref. Hasiotis, 2004)
Order Diptera
Family Chironomidae?, midge burrow (ref. Hasiotis, 2004)
Order Coleoptera
Family Cicindelidae
Cylindricum isp insect burrow (ref. Hasiotis, 2004)
Family Heteroceridae
Steinichnus isp beetle or cricket burrow
(ref. Hasiotis, 2004)
PHYLUM CHORDATA
CLADE SAURISCHIA
Clade Theropoda
Family uncertain
(ref. Gierliński and Sabath, 2008)
Grallator, small theropod track
(ref. McClosky and others, 2023)
Clade Sauropoda
Family uncertain (re. Hasiotis, 2004)
Brontopodus, large sauropod track
(ref. McClosky and others, 2023)
Parabrontopodus, large sauropod track
(ref. McClosky and others, 2023)
CLADE ORNITHISCHIA
Clade Ornithopoda
Family uncertain
(ref. Gierliński and Sabath, 2008)
Dinehichnus, small ornithischian track
(ref. McClosky and others, 2023)
Clade Stegosauria
Family uncertain
Stegopodus czerkasi, stegosaur track
(ref. Gierliński and Sabath, 2008)
FOSSIL EGG
PHYLUM CHORDATA
CLADE SAURISCHIA
Clade Theropoda
Family Prismatoolithidae
Preprismatoolithus coloradensis, *Allosaurus* egg?
(Hirsch and others, 1989, updated)

[1]Clade is being used increasingly in dinosaur paleontology and groups dinosaurs by their presumed common ancestor and descendants. The reason being that the traditional Linnean system allowed unrelated dinosaurs to be grouped together, thus implying a false evolutionary relationship.

Figure 14. *(A) Metal buildings erected over part of the quarry (center) and visitor center (left). (B) Interior of the north quarry building showing viewing platform overlooking excavations. Photograph by Veronica Krantman, Bureau of Land Management.*

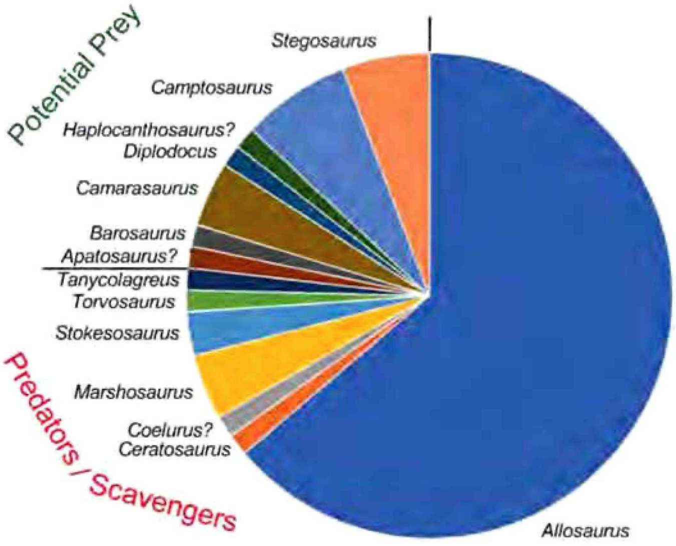

Figure 15. *Pie chart showing the relative proportions of the dinosaurs from the Cleveland-Lloyd Dinosaur Quarry. The unusual dominance of* Allosaurus *individuals at the site is readily apparent. Data in part from Foster (2003).*

Figure 16. *Arrangement by size of* Allosaurus *thigh bones (femora) from the Cleveland-Lloyd Dinosaur Quarry as an indication of growth, from very young (possibly a year old) to adult. Based on an exhibit at the Prehistoric Museum, Price, Utah.*

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