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SEDIMENTOLOGY, STRATIGRAPHY, AND DEPOSITIONAL ENVIRONMENT OF THE CRYSTAL GEYSER DINOSAUR QUARRY, EAST-CENTRAL UTAH

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ABSTRACT

The Crystal Geyser Dinosaur Quarry, near Green River, Utah, is located at the base of the Lower Cretaceous (Barremian) Yellow Cat Member of the Cedar Mountain Formation. The quarry preserves a nearly monospecific accumulation of a new basal therizinosauroid, *Falcarius utahensis*. We used field descriptions and petrographic analysis to determine the depositional environment and development of the quarry strata. Results of these analyses suggest that the quarry represents multiple episodes of bone accumulation buried by spring and overbank flood deposits. Evidence for these previously undescribed spring deposits includes calcite macroscopic structures within the quarry strata—such as pisolites and travertine fragments—and calcite micromorphologies—including radial-fibrous, feather, and scandulitic dendrite morphologies and tufa clasts. At least two episodes of bone incorporation are preserved in the quarry based on their stratigraphic position and lithologic associations. The unique depositional setting in and around the Crystal Geyser Dinosaur Quarry appears to have been favorable for the preservation of vertebrate fossils and provides insight into early Cretaceous environments in North America.

INTRODUCTION

The Crystal Geyser Dinosaur Quarry (CGDQ) is located south of Green River, Utah, (Fig. 1A) at the base of the Lower Cretaceous Yellow Cat Member of the Cedar Mountain Formation. The CGDQ strata are Barremian in age, and the quarry is one of the earliest Cretaceous dinosaur sites in North America (Kirkland et al., 1997, 2005a, 2005b). The quarry is the site of a very dense, nearly monospecific accumulation of bones from a new therizinosauroid dinosaur species, *Falcarius utahensis* (Kirkland et al., 2005b). This unusual theropod dinosaur has small leaf-shaped teeth that suggest a transition from a carnivorous to omnivorous or herbivorous diet (Kirkland et al., 2005b). Therizinosauroids are mostly known from Asia, with the exception of the Late Cretaceous species, *Nothronychus mckinleyi*, discovered in New Mexico (Kirkland and Wolfe, 2001; Clark et al., 2004). The number of skeletal remains at CGDQ (probably >100 individuals) makes this the most prolific therizinosauroid fossil locality in the world. Because the basal Cedar Mountain Formation contains the oldest known dinosaur-bearing Cretaceous deposits in the United States, the CGDQ and other fossil localities in the Cedar Mountain Formation are an important source of information for understanding Early Cretaceous paleoenvironments (Kirkland et al., 1999; Kirkland, 2005).

This is the first study of the depositional environment of the CGDQ. The purpose of this study is to document the sedimentology and stratigraphy of the CGDQ and surrounding area. We use these observations to determine the environmental setting of the CGDQ and the development of the bone accumulations.

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GEOLOGIC SETTING

The Cedar Mountain Formation is composed of five members (Fig. 1B): the basal Buckhorn Conglomerate, Yellow Cat, Poison Strip Sandstone, Ruby Ranch, and Mussentuchit Members (Stokes, 1952; Kirkland et al., 1997). The Buckhorn Conglomerate crops out only on the west side of the San Rafael Swell and is not present in the study area. Instead, the Yellow Cat Member and CGDQ unconformably overlie the Upper Jurassic (Tithonian) Morrison Formation. The Cedar Mountain Formation was originally thought to be unfossiliferous, compared with the underlying Morrison Formation (Stokes, 1952); several paleontological sites, however, have recently been discovered (Kirkland et al., 1997, 1999; Kirkland, 2005). The Yellow Cat Member is considered Barremian in age based on vertebrate and charophyte assemblages (Kirkland et al. 1997, 2005a) and palynology (D. Eberth and B. Britt, personal communication, 2002). Thus, the unconformity encompasses about 20–25 myr. The contact in this area is typically characterized by a well-developed, pedogenic and groundwater calcrete, lag gravel, and a change in mudstone from the bright colors of the Morrison Formation to the more drab colors of the Cedar Mountain Formation (Aubrey, 1998; Currie, 1998; Stikes, 2003; Demko et al., 2004). The remainder of the Yellow Cat Member is characterized by mauve to pale green mudstones interbedded with thin limestone beds, nodule horizons, and sandstone lenses. Kirkland et al. (1997) suggested that the Yellow Cat Member was deposited in a semiarid to monsoonal climate, based on the presence of carbonate and barite nodules.

METHODS

We conducted fieldwork for 7 weeks in July–August 2004. We measured 10 stratigraphic sections in and adjacent to the CGDQ along the crest of the mesa (Fig. 1A) from the Morrison-Cedar Mountain Formation contact to the top of the extensive ledge-forming unit that caps the mesa. This caprock is widespread and has been traced 600 m to the northwest and 300 m to the east; however, its full lateral extent is currently unknown. Within the study area, the Morrison-Cedar Mountain Formation contact is, in places, indistinct and difficult to identify. As a result, we dug trenches from the caprock down to strata that could positively be identified as Morrison, typically by the appearance of red smectitic claystone to silty claystone with pale green to pale blue mottles.

In all measured sections, individual beds were characterized based on their color, lithology, sedimentary structures, and fossil content. Bed description included color determined using the Munsell Soil Color Chart (Munsell Corp., 1975), grain size, sedimentary structures, and presence and abundance of fossil material. From each bed, oriented samples were taken for thin-section analysis. We made and analyzed a total of 125 thin

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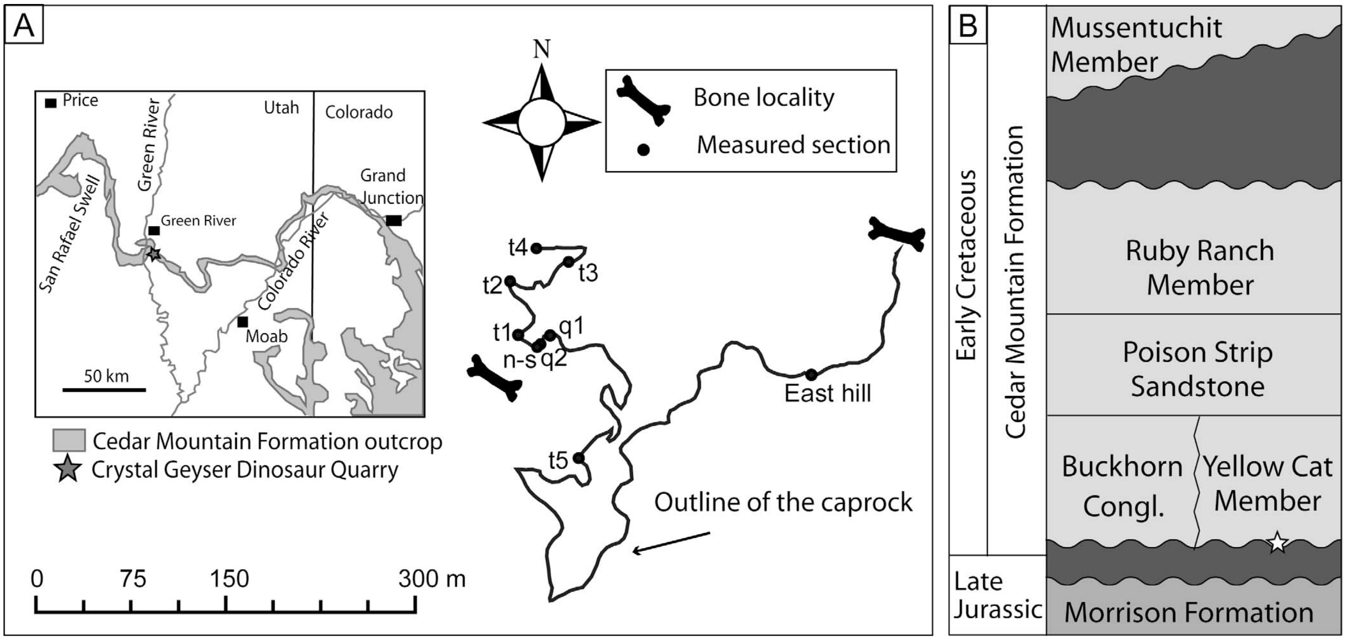


FIGURE 1—Geographic and stratigraphic location of the CGDQ. A) Distribution of the Cedar Mountain Formation in eastern Utah, location of CGDQ, and study area map. Study area map shows outline of the caprock (line) and locations of measured sections (dots), including Quarry Profile 1 (q1), Quarry Profile 2 (q2), Trench 1 (t1), Trench 2 (t2), Trench 3 (t3), Trench 4 (t4), Trench 5 (t5), East-Hill Trench (east hill), and the North-South Trench (n-s). B) Stratigraphy of the Cedar Mountain Formation (from Kirkland et al., 1997). CGDQ = Crystal Geyser Dinosaur Quarry.

sections. Where possible, we cut thin sections from each bed of a measured section into horizontal and vertical orientations.

DESCRIPTIONS OF PROFILES

We measured two sections in the active quarry: Quarry Profile 1 (q1) in the northeast corner and Quarry Profile 2 (q2) in the southwest corner (Fig. 1A; see also Suarez et al., 2007). In addition, two trenches lateral to the quarry—North-South (n-s) and Trench 1 (t1)—have bone-bearing horizons similar to the active quarry (Figs. 1A, 2). The North-South Trench is a vertical section just to the southwest of q2, and Trench 1 is located about 10 m to the northwest. Trench 3 to the northeast has similar stratigraphy but does not contain dinosaur bones. In addition to the quarry sections, we also measured four distal sections: Trench 2 (t2), Trench 4 (t4), Trench 5 (t5), and the East-Hill Trench (east hill), all of which lacked dinosaur bones and were stratigraphically different (Fig. 3). Trench 2 and 4 are the farthest to the northwest and north of the quarry, respectively. Trench 5 is to the south, and the East-Hill Trench is to the southeast (Fig. 1A).

Quarry Sections

The quarry strata can be divided into a basal carbonate bed, a middle bone-bearing mudstone with limestone lenses, and an upper unit of mudstones, muddy sandstones, and limestone lenses that contains some bone fragments but is otherwise unfossiliferous. This sequence is capped by a dense siliceous limestone. The stratigraphy varies somewhat laterally between sections, especially within the upper unfossiliferous unit.

The basal micritic limestone is light gray (10R7/1 to 5Y7/1) to white (N8) and contains poorly sorted dinosaur bones, claystone clasts, pisoids, travertine fragments, and chert pebbles. Within Quarry Profile 2, isolated pisoids and clusters are commonly present as opposed to micritic limestone (Figs. 4A–B). In those locations associated with pisolites, many bones rest directly on the erosional surface atop the Morrison Formation. Many of these bones have distinct east-west orientation (Suarez et al., 2007). Within the micritic limestone, bones tend to be at high angles (with respect to bedding) and exhibit a greater abundance of spiral fractures. Toward the east, the basal limestone contains fewer pebbles and less bone material.

The overlying bone-bearing sandy-to-gravelly mudstone is bluish gray (5PB6/1) or reddish gray (10R5/1), or both, with light greenish gray (10GY8/1) mottles and contains pisolite clusters and fragments, claystone clasts, and isolated chert pebbles (Figs. 4C–D). Bones at the base of the unit tend to be significantly fractured compared to those higher in the section. Gravel is more abundant at the base of the mudstone but is also present up to 50 cm above contact. Carbonate nodules and concretions are present throughout the unit and tend to form a distinct horizon about 50–60 cm above the Morrison Formation, as well as toward the top of the unit. Many concretions formed around bone (Fig. 4E) or older calcite nodules. At the top of this unit, very sparse, carbonate-filled root traces and vertically oriented bones are truncated by an erosional surface (Fig. 4F).

Overlying the erosional surface is a unit of interbedded sandy mudstone to muddy sandstone with lenses of micritic to sandy micritic limestone. The micritic carbonate horizons and lenses above the erosional surface are white (N8), some of which have pale-red (10R7/3) mottles. These limestones lack any significant structures or fossils, although chert pebbles are occasionally found. The sandy mudstones and muddy sandstones are usually light greenish gray (5-10GY8-7/1). In q1, the muddy sandstone is characterized by low-angle cross-beds. The silicified, dense, gray (2.5Y6/1) micritic limestone caprock is present in all profiles. The caprock has varying amounts of matrix-supported coarse sand grains but, otherwise, no obvious structures.

Distal Sections

Prominent changes in the lithostratigraphy are seen farther from the quarry (Fig. 3). Similarities in the measured sections to the north and northwest (Trenches 2 and 4) include thinner and more discontinuous basal carbonates and capping siliceous limestones that are more sandy than the quarry sections. The section in Trench 2 (Fig. 5A) consists of a 3 cm discontinuous micritic limestone within a light greenish gray (10GY8/1) sandy mudstone overlain by a 12 cm grayish red purple (5RP4/2) granular carbonate. The granular carbonate grades to a pale-

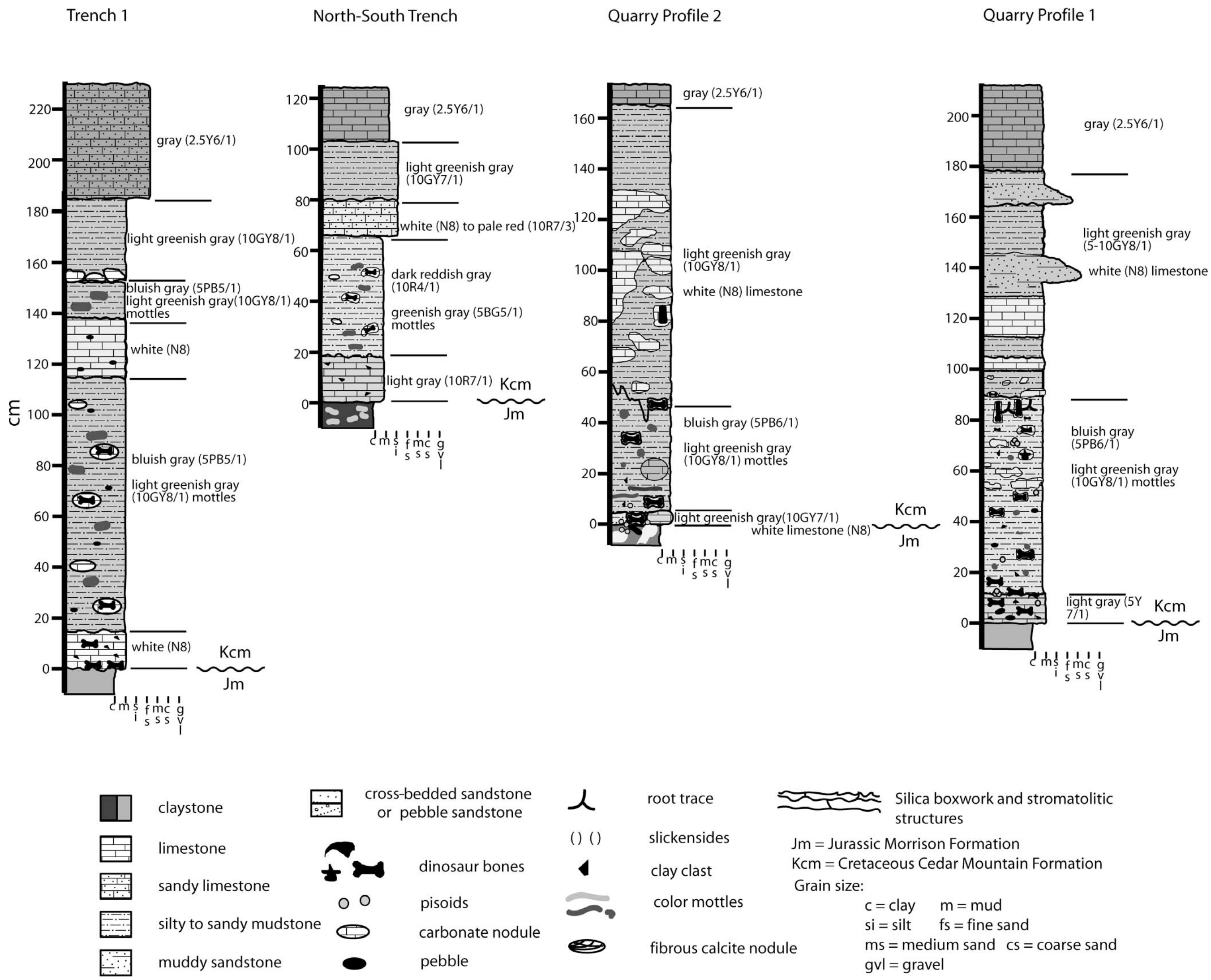


FIGURE 2—Measured sections of quarry profiles.

green (5G7/2) sandy mudstone (33 cm) with carbonate concretions that is capped by a gray (2.5Y6/1) sandy limestone. The basal carbonate in Trench 4 is a thin 4–5 cm zone of isolated and micrite-cemented pisoids (Fig. 5B). Overlying the basal carbonate is a 12-cm-thick layer of weak red (10R4/2), slickensided claystone, which grades into a thicker (122 cm) weak-red (10R4/2), fractured, silty mudstone. Fractures are filled with pale-green (5G7/2) to bluish gray (5PB5/1) carbonate. The fractures intersect to form a boxworklike pattern (Fig. 5C). Flat, lenticular, fibrous calcite nodules often occur in the top 15 cm. Overlying the fractured silty mudstone is a pale-green (5G7/2) sandy mudstone with lenticular carbonate concretions capped by a gray, coarsening upward sandy limestone.

Sandstones dominate to the south and southeast. The base of Trench 5 is marked by a white (10YR8/1) micritic limestone with weak red (10R4/4) mottles and septarian-like sparry calcite veins; it is overlain by a 258-cm-thick sandstone unit. The lowermost 78 cm are laminated light greenish gray (10GY8/1) with horizontal dusky red (10R3/4) to weak red (10R5/3.5) mottles developed along laminae. The sandstone changes gradually in color, and the middle 78 cm is a weak red (10R5/3.5) sandstone with light greenish gray (10GY8/1) mottles. The uppermost 102 cm consist of light-greenish gray (10GY8/1) sandstone with weak red (10R5/3.5) mottles. The East-Hill Trench section lacks a basal carbonate. Instead, a pale green (5G8/2) sandy mudstone (50 cm) with carbonate concretions overlies the Morrison Formation. At this site, the Morrison is a pedogenically altered claystone with slickensides. The paleosol contains carbonate nodules and drab-haloed root traces that appear to be infilled by the pale green sandy mudstone from the overlying unit.

The caprock at both locations is gray (10YR6/1) and very sandy. At Trench 5, the unit is 55 cm thick and grades from a calcite-cemented gravelly sandstone at the base to a sandy limestone at the top. At the East-Hill Trench, the ledge-forming caprock unit is 114 cm thick and consists of four fining-upward, cross-bedded, carbonate-cemented sequences of pebble conglomerate to fine sandstone. Micritic nodules become common toward the top. The very top of the unit is a thinly bedded, sandy micritic limestone with interspersed small knobby structures composed of black-stained chalcedony (Fig. 5D).

PETROGRAPHIC ANALYSIS

Quarry Sections

The basal carbonate matrix is composed of micrite to microspar. Claystone clasts are commonly surrounded by a thin halo of microspar and, less commonly, by fibrous calcite (Fig. 6A). Within the carbonate are domains covered with in situ growth of fibrous calcite. In addition, numerous clasts contain similar fan-shaped radial calcite and scandulitic-dendrite calcite crystals (Jones and Renaut, 1995; Figs. 6B–C). Several carbonate clasts are brecciated and contain void-filling fibrous or acicular

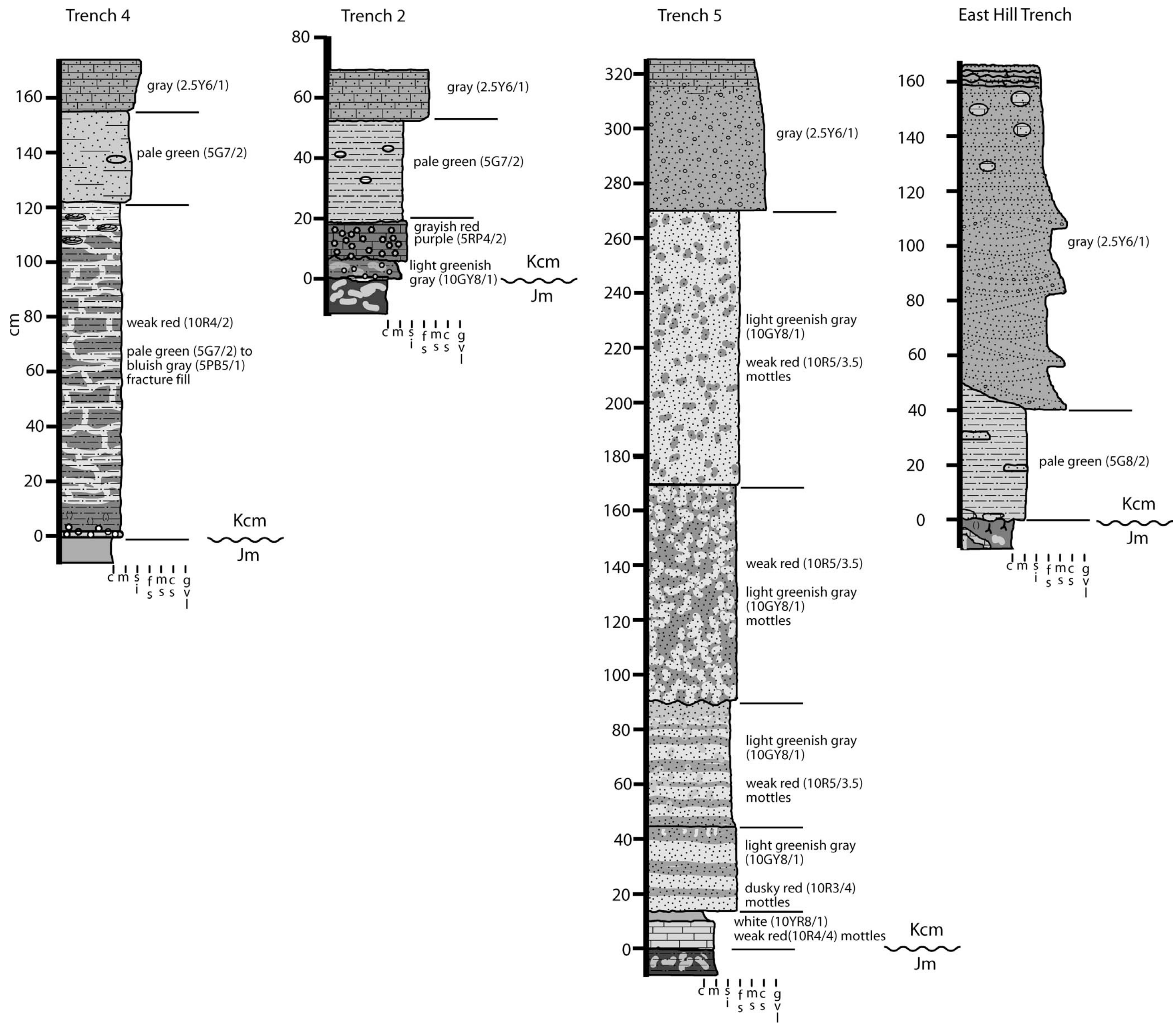


FIGURE 3—Measured sections distal to the quarry. See Figure 2 legend (in figure) for symbols.

radial calcite. All pisolites consist of radial fibrous calcite, and some exhibit banding defined by alternating layers of light and dark separated by thin iron oxide laminae (Fig. 6D). Isolated pisoids are encrusted with a thin layer of micrite.

The bone-bearing beds are composed of weakly birefringent clays and calcareous muds with abundant quartz and chert. The noncalcareous portions of the mudstone are moderately to strongly relict bedded and commonly contain micrite glaebules. Pisoids have radial calcite fabric, some resembling calcite-feathered crystals of Fouke et al. (2000) or calcite-feathered dendrites of Jones and Renaut (1995; see Fig. 6E). Within carbonate clasts composed of intermixed micrite and sparry calcite, micrite commonly has a clotted texture (Fig. 6F). Some micritic clasts and quartz grains are surrounded by fibrous radial calcite. Nodules within the bone-bearing beds are typically micritic, with some quartz sand grains and veins of coarse sparry calcite. Nodules within concretions typically have iron oxide stains on the outside of the nodule. Within the iron-stained nodules, calcite veins and bone fragments tend to be more abundant. In the bone-bearing beds, most bones are encrusted by micrite or microspar. Cracks between the encrusting micrite and the bone, and cracks within the bones, are filled with secondary sparry calcite. In the bones, Haversian canals contain spherical iron oxides and sparry calcite.

Petrographic features in the mudstone horizons above the erosional surface are similar to those in the bone-bearing beds. Carbonate horizons above the bone-bearing beds consist of silty-to-sandy micrite. These carbonates also have micritic glaebules, pisolites, and pisolite fragments and, rarely, bone fragments. The caprock generally consists of micritic mudstone with sand-sized quartz grains. The caprock at Quarry Profile 1 displays a fining upward of micritic clasts. Fibrous calcite surrounds some of the micrite clasts, quartz grains, and chert fragments. Circumgranular cracks filled with sparry calcite are common in micrite clasts. Diagenetic dolomite occurs in some voids between the carbonate clasts.

Distal Sections

The basal carbonates in the northern sections (Trenches 2 and 4) are composed of micrite, and at Trench 2 the carbonate shows distinct reddish bands that under the microscope are identified as iron oxide cements and grains. The top of the discontinuous carbonate has prominent yellowish

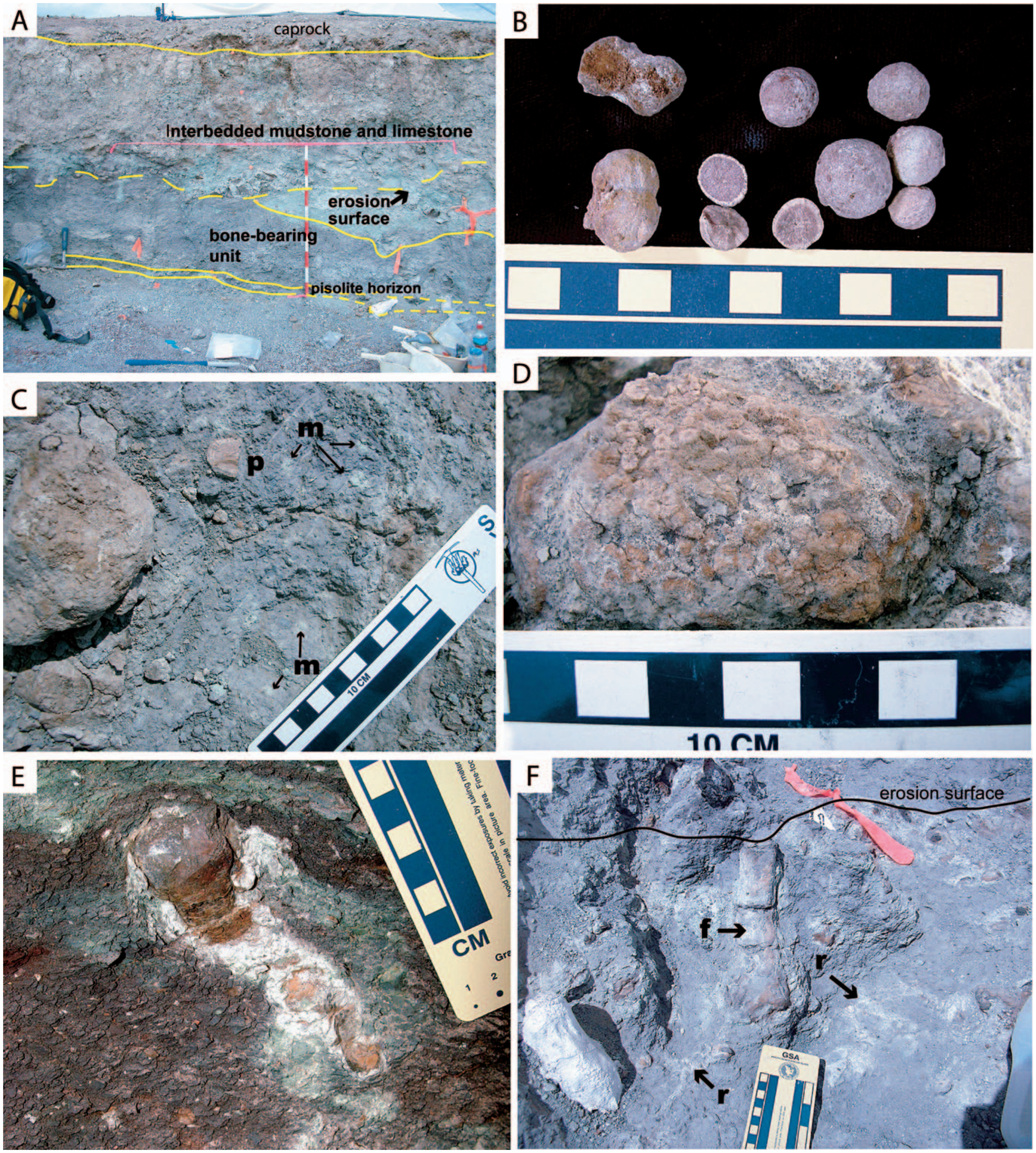


FIGURE 4—Photographs of quarry profiles. All scales except A in cm. A) High wall of Quarry Profile 2; small dashed lines = covered pisolitic horizon; long dashed line = erosion surface on SW side of the quarry. Color change from bluish gray, bone-bearing units (below) to light greenish gray, unfossiliferous units (above) occurs at variable depths. Scale in 10 cm intervals. B) Pisolites from base of Quarry Profile 2. C) Bone-bearing mudstone in Quarry Profile 1 showing light greenish gray mottles (m), a pisolite fragment (p), and carbonate nodules. D) Cluster of pisolites in Quarry Profile 1. E) Metatarsal lightly encrusted with calcium carbonate in North-South Trench. F) Top of bone-bearing units in Quarry Profile 1. f = vertically oriented, carbonate-encrusted femur, which is truncated by an erosional surface; r = branching carbonate-filled root traces.

brown staining. At Trench 4, there are domains of micrite intersected by boxwork textures (Fig. 7A) and pisoids with radial fibrous calcite fabric (Fig. 7B).

The granular carbonate in Trench 2 consists of clasts of large (0.5–3-mm-long) calcite crystal clusters and fine sand and silt within a micrite-cemented matrix (Fig. 7C). The edges of some of the larger crystals have haloes of fibrous calcite. The overlying sandy mudstone contains weakly birefringent clays that are strongly relict bedded. Concretions are composed of quartz sand and pisoids cemented with fibrous calcite and micrite.

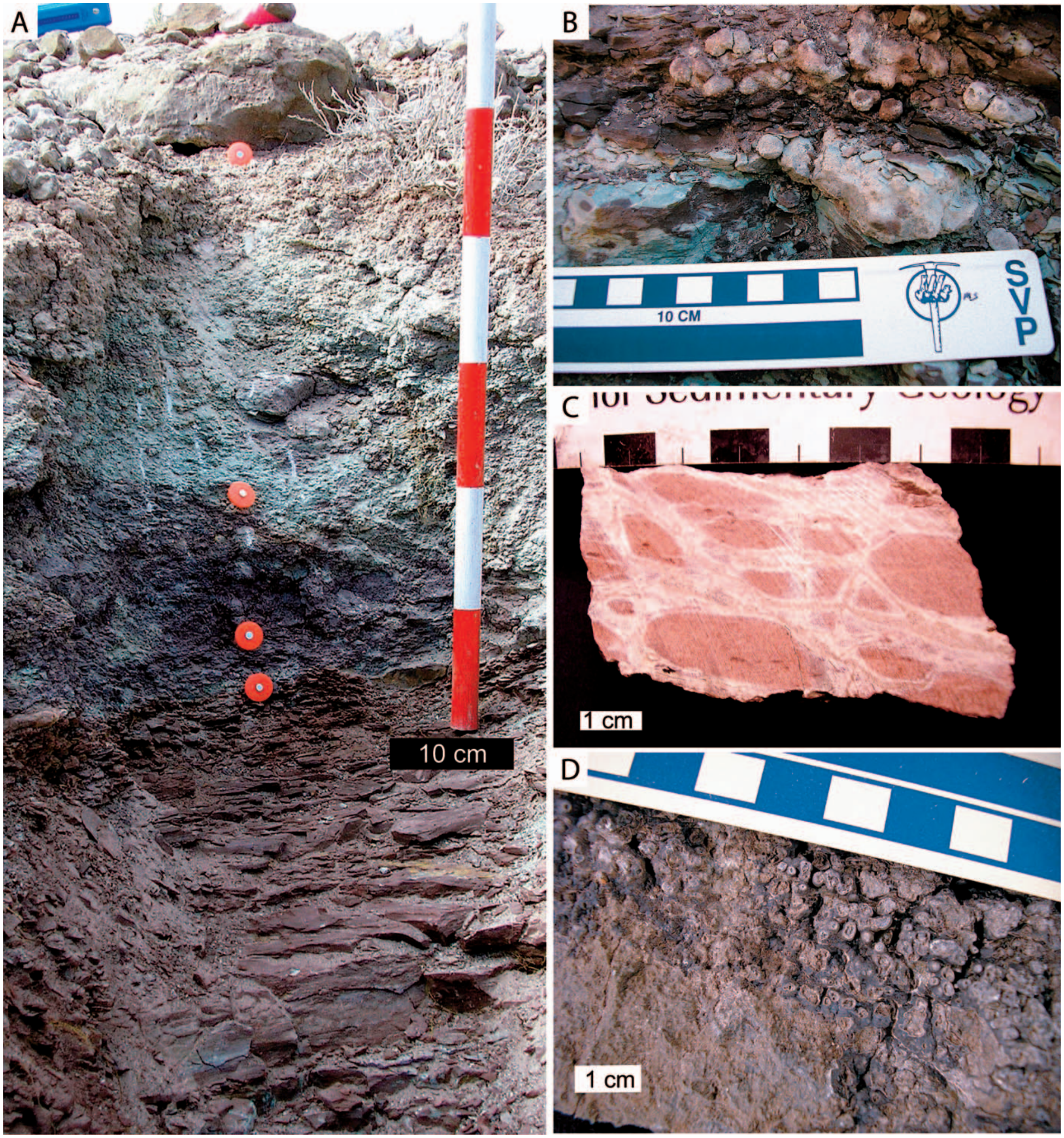


FIGURE 5—Photographs outside the quarry. A) Photograph of Trench 2; round pins = boundaries between lithologic sections. Purple unit (delineated by second and third pin) is the granular carbonate. Scale in 10 cm divisions. B) Pisolitic horizon in Trench 4. C) Calcitic veins filling fractured silty mudstone, forming a boxworklike structure in Trench 4. D) Small chalcedony knobby structures at the East-Hill Trench.

At Trench 4, fractures of the brecciated silty mudstone are filled with calcite and small, isolated sphaerosiderites (Fig. 7D). The calcite fill consists of microcrystalline calcite, isolated acicular calcite crystals, and spherulitic acicular crystal arrays with pseudouniaxial extinction patterns. Sphaerosiderites, about 250 μm in diameter, are engulfed within the calcite (Figs. 7D–E). The sphaerosiderites are brownish orange, display pseudouniaxial extinction, and tend to have slightly more relief than the micritic matrix. The nodules in the upper part of the bed are comprised of interwoven, fibrous, boxwork calcite, especially toward their centers, with vermiform kaolinite in some of the voids (Fig. 7F). The texture is more micritic toward the edge of the nodules. The caprock at Trenches 2 and 4 consists of micritic limestone with quartz sand, and clotted micrite clasts, some with circumgranular cracks.

To the south, the basal carbonate at Trench 5 consists of coarse micrite to microspar with veins of sparry calcite. Some of these sparry calcite crystals are faintly zoned. The sandstone beds contain birefringent, translocated clays around quartz grains and authigenic vermiform kaolinite (Fig. 8A). There are also some carbonate glaebules and iron oxide staining.

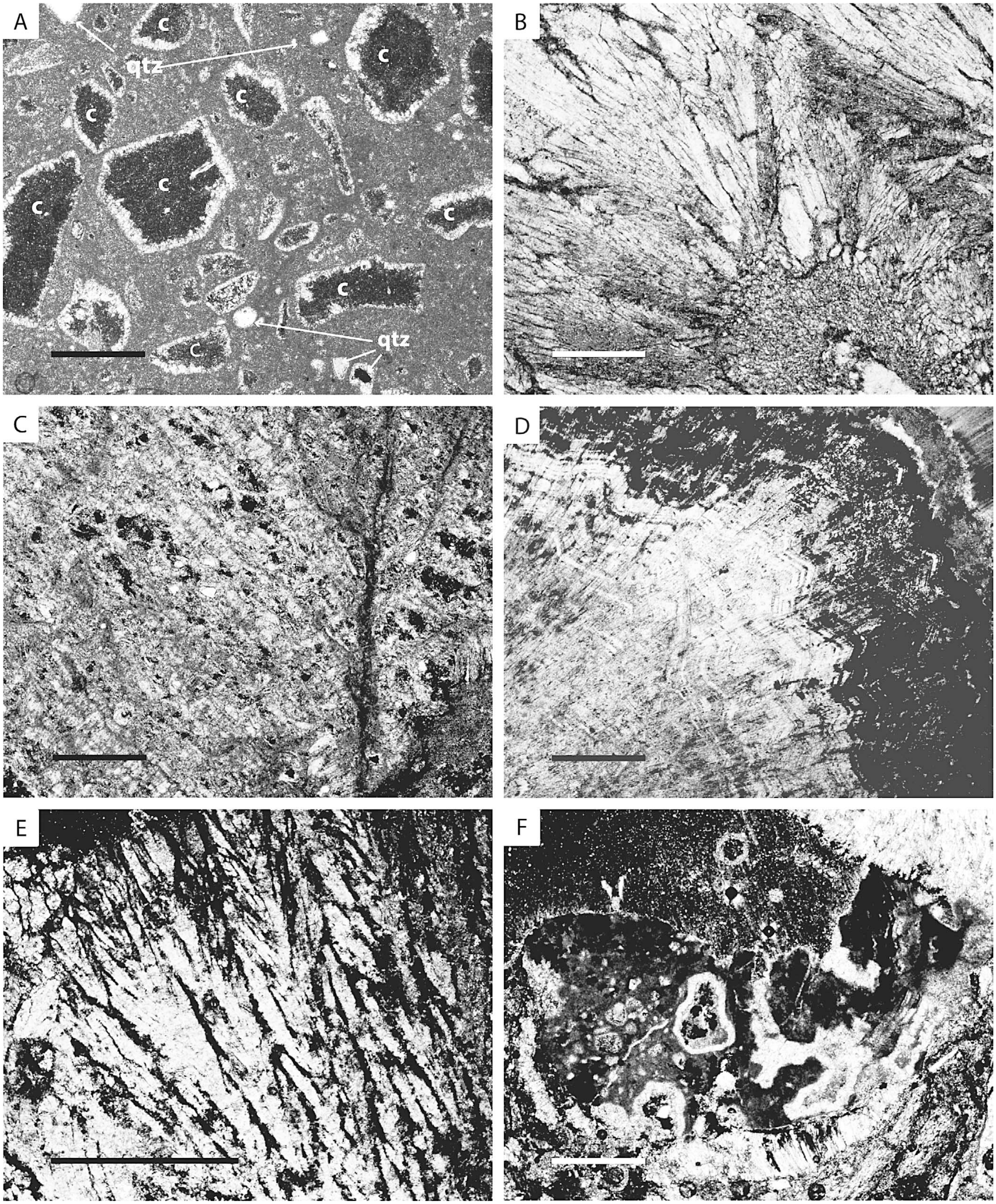


FIGURE 6—Photomicrographs of samples from the quarry, cross-polarized light. All scales = 500 μm. A) Horizontal thin section of quartz grains (qtz) and claystone clasts (c) within a micritic matrix from the basal carbonate of Quarry Profile 1. B) Vertical thin section of fan-shaped fibrous calcite, from the basal carbonate of Quarry Profile 1. C) Horizontal thin section of scandulitic dendrite. D) Unoriented thin section of an isolated pisolite from Quarry Profile 2. E) Vertical thin section of calcite resembling the calcite feather dendrites of Jones and Renaut (1995) or Fouke et al. (2000) within a cluster of pisolites in Quarry Profile 2. F) Vertical thin section of a clotted micrite clast within the mudstone of Quarry Profile 2.

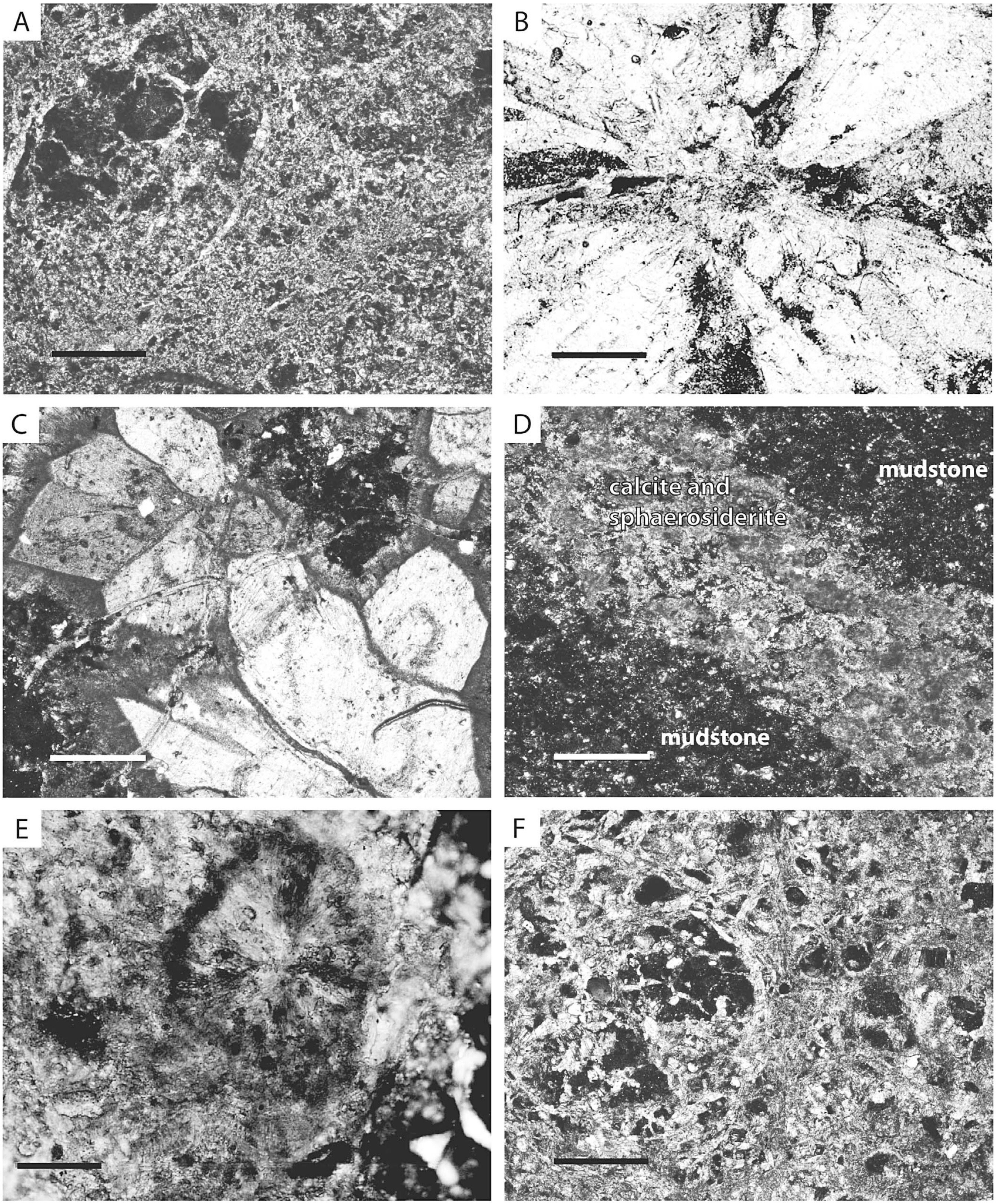


FIGURE 7—Photomicrographs of Trench 4 and Trench 2, cross-polarized light. All scales except E = 500 μm. A) Vertical thin section of the pisolitic horizon at the base of Trench 4 showing a boxwork texture of fibrous calcite and iron oxide stained micrite. B) Vertical thin section of calcite crystals radiating from the center of a pisolite at the base of Trench 4. C) Vertical thin section of the granular carbonate of Trench 2, revealing calcite crystal clusters and fine silt and sand grains cemented by micrite. D) A vertical thin section of a fracture filled with calcite and sphaerosiderite in Trench 4. E) Horizontal thin section of sphaerosiderite, showing pseudouniaxial extinction from Trench 4. Scale = 100 μm. F) Horizontal thin section of boxwork fabric of fibrous calcite nodules from Trench 4.

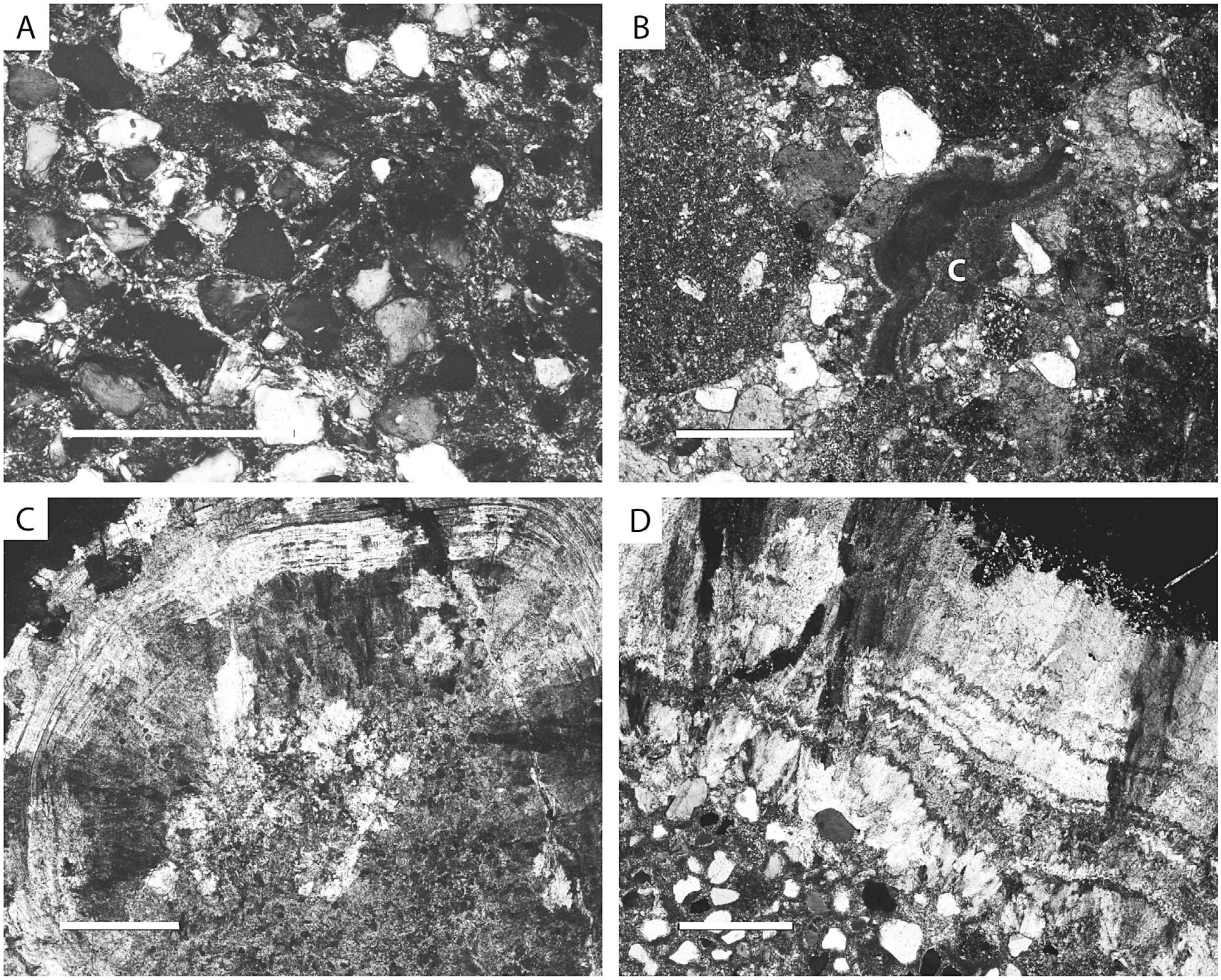


FIGURE 8—Photomicrographs of the Trench 5 and the East Hill Trench, cross-polarized light. All scales = 500 μm. A) Vertical thin section of sandstone at Trench 5 containing translocated birefringent clays and vermiform kaolinite. B) Vertical thin section of a travertine clast (c) within a sandy carbonate concretion at the East-Hill Trench. C) Horizontal thin section of a knobby structure composed of concentric laminar chalcedony. D) Vertical thin section of the knobby structure in Fig. 8C composed of fan-shaped, fibrous chalcedony.

To the southeast (East-Hill Trench), root traces are filled with quartz sand and moderately birefringent clays. Carbonate nodules consist of matrix-supported quartz sand grains and have circular calcite veins filled with sparry calcite in the center. The overlying pale-green mudstone contains relict-bedded clays and lenses of sandy micritic carbonate. These lenses also contain travertine clasts (Fig. 8B).

At both locations, the caprock consists of micrite-cemented quartz sandstone fining upward to a sandy micritic limestone. The interbedded micritic nodules in the caprock at Trench 4 have patches of iron staining and stringers of quartz sand throughout a micritic matrix. The upper parts of the caprock have veins of radial chalcedony filling cracks or spaces between bedding planes. The knobby structures, which are also composed of chalcedony, are concentric and laminar in horizontal view (Fig. 8C) and fan radially in the vertical section (Fig. 8D).

INTERPRETATION

The caprock, bone-bearing beds, and basal carbonate can be confidently correlated between the measured sections. The variation in thickness of the units between the top of the Morrison Formation and the caprock was controlled by the paleotopography of the unconformity on the Morrison. Throughout the depositional history of CGDQ, the accumulation of colluvium and fluvial deposits resulted in the gradual filling of the paleotopography produced by the erosion of the Morrison Formation. The typical subaerial alteration of the Morrison during the hiatus between Morrison and Cedar Mountain Formation deposition (Aubrey, 1998; Currie, 1998; Stikes, 2003; Demko et al., 2004; S. Madsen, personal communication, 2004) is only preserved in the form of drab-haloed root traces at the East-Hill Trench.

Potential origins of carbonates in terrestrial settings include precipitation within lacustrine, pedogenic, spring-water, or groundwater settings. The presence of pisolites and the nature of other calcite textures (e.g., radial fibrous and dendritic calcite, travertine clasts, and clotted clasts) in the basal carbonates suggests that these carbonate features were precipitated in association with springs. Calcite morphologies from the CGDQ closely resemble those documented from spring deposits (Risacher and Eugster, 1979; Jones and Renaut, 1995; Evans and Welzenbach, 1998; Fouke et al., 2000). Pisolites similar to those in Quarry Profile 2 (Fig. 4B) and Trench 4 (Fig. 5B) have been described from modern spring-fed pools in Pastos Grandes, Bolivia (Risacher and Eugster, 1979; Jones and Renaut, 1994). Spring deposits similar to the CGDQ deposits containing pisolites, travertine and tufa clasts, clotted micrite clasts, and ray crystals (i.e., radial fibrous crystals) have been described by Evans and Welzenbach (1998) and Evans (1999) from the upper Eocene Chadron Formation of South Dakota. The scandulitic dendrite fabrics, as seen in the basal carbonates (Fig. 6C), have been described from modern springs in Kenya by Jones and Renaut (1995). In general, the CGDQ basal carbonate deposits resemble the distal slope travertine deposits described by Fouke et al. (2000) from the Angel Terrace Spring at Mammoth Springs, Yellowstone National Park, where much of the travertine and other carbonates are not in place and have been transported down slope from the spring's central vent (Fouke et al., 2000).

For further comparison to the CGDQ textures and fabrics, we analyzed deposits of the Crystal Geyser, a modern CO_2-rich spring along the banks of the Green River, and from which the CGDQ name is derived (Fig. 9). Conglomeratic travertine is found in the distal portions of the deposit along the banks of the Green River. These conglomeratic travertines are very similar to those of the CGDQ basal carbonates (Fig. 9A). In thin section, Crystal Geyser deposits display fabrics and textures similar to those found in quarry rocks, including radial fibrous calcite, calcite crystal clusters, clotted micrite clasts, and iron oxide banding within radial fibrous calcites (Figs. 9B–E).

Collectively, the calcite fabrics from CGDQ basal carbonates, travertine clasts, pisolites, and clotted micrite clasts with fibrous calcites suggest that most of the carbonates were not precipitated in place but were transported across the land surface, perhaps by episodic overland flow during intense storms. During these episodes, spring-produced materials were mixed with other colluvial materials, including dinosaur bones, claystone clasts, and chert pebbles, which had settled in topographic lows. Because of the delicate nature of the radial fibrous calcite fabrics, scandulitic dendrites, calcite-feathered crystals, and travertine clasts, the source area for these materials must have been very close.

Micritic cements in the basal carbonate appear to be of mixed origin and display characteristics indicative of both groundwater and pedogenic carbonates. The cement is finely crystalline and has in situ fibrous calcite indicative of near-surface vadose conditions (Pimentel et al., 1996). The brecciated claystones, dinosaur bones, and floating pebble texture are similar to described textures of both pedogenic (Gile et al., 1966) and groundwater carbonates (Pimentel et al., 1996). The basal carbonate is relatively thin and similar to many pedogenic carbonates, whereas groundwater carbonates are commonly tens of meters thick. The basal carbonate is mostly restricted to areas of coarse grains (pebbles, dinosaur bones, and travertine fragments), which is more indicative of groundwater carbonates (Pimentel et al., 1996), though in some places it is a relatively pure micrite without coarse grains. Also, there are no rhizoliths or laminar crusts indicative of pedogenic carbonates.

The strata above the basal carbonate suggest different environmental conditions. As a whole, the channel-filling, cross-bedded sandstone in the southeasternmost sections, laminated fine-grained sandstone with pedogenic modifications (Trench 5 section), and the abundance of sandy mudstones suggest a fluvial dominated environment. The sections to the south and southeast dominated by sandstone are consistent with river channels (east hill) and adjacent crevasse splays (t5). The quarry and sections to the north dominated by sandy mudstones represent distal overbank facies.

Subtle pedogenic processes were continuously operating on the overbank sandstones and mudstones. In the fine-to-medium-grained sandstones interpreted as crevasse splays (Trench 5), pedogenesis is manifested by the presence of drab-haloed root traces and clay films, with the resulting obliteration of original bedding. In the more distal portions, pedogenesis is indicated by sparse carbonate-filled root traces at the top of the bone-bearing horizon, calcite pendant cements, carbonate encrustation of bones, and nodular carbonate development. Pedogenic carbonate accumulation is consistent with stage II of Gile et al. (1966).

The presence of small pisolite clusters, calcite crystal clusters, and clasts of fragmented tufa, travertine, and isolated pisoids throughout the measured sections indicates that spring activity continued during the fluvially dominated part of deposition. As with the spring materials in the lower part of the sections, the preservation of delicate calcite fabrics in the upper part requires that the source of the materials be close to the site of deposition. The spring materials could have been sourced from nearby springs along the banks of the river and transported during flooding events. Alternatively, some of the materials could be colluvium, derived from springs in nearby topographic highs.

The deposits above the basal carbonate and below the greenish gray mudstone below the caprock at Trench 4 are quite different from equivalent strata in other sections. Trench 4 is the only section with abundant carbonate-filled (calcite and siderite) fractures producing a boxwork fabric (Fig. 5C). This section resembles recent inactive spring deposits along the Little Grand Wash Fault (Fig. 9F). The presence of sphaerosiderites in a calcite matrix (Figs. 7D–E) indicates the redox state varied through time, resulting in periods of reduced conditions that favored sphaerosiderite precipitation (Ludvigson et al., 1998, 2002; Ufnar et al., 2004) and less reduced conditions that favored calcite precipitation.

The greenish gray horizon below the caprock is present in all of the measured sections. The green color of these sediments in the Cedar Mountain Formation is most likely the result of gleization under water-saturated conditions (Stikes, 2003). The gleyed horizons are variable in thickness—thickest in Quarry Profile 2 and thinnest at Trench 2. Overall, the presence of the gleyed units indicates that conditions were wetter. In the majority of sections, the gleyed horizons are most likely due to elevated water tables.

Based on the lithology, aerial extent, and lenticular geometry, the limestone at the top of the caprock appears to have been deposited in a shallow lake or pond. This body of water was influenced by fluvial and overland flow input, as suggested by abundance of sand grains and various carbonate clasts. Clotted micrite and pisoid clasts indicate some spring input. Circumgranular cracks and veins present in the caprock suggest occasional drying (Pimentel et al., 1996). The knobby structures at the top of the caprock at the East-Hill Trench closely resemble the calcified ''ice sheets'' and bubbles of Fouke et al. (2000) from Mammoth Hot Springs, though the structures at the East-Hill Trench are siliceous (Figs. 5C, 8C–D). Silicification of the caprock suggests either a change in spring-water chemistry or later diagenesis.

DISCUSSION

Development of the Crystal Geyser Dinosaur Quarry Strata

The lower Cedar Mountain Formation at the CGDQ has a complex multistaged history. To account for the macroscopic and microscopic features described, we propose three general stages of the development of the quarry: (1) a bone-bed-deposition stage, (2) a post-bone-bed-deposition stage, and (3) deposition of the caprock stage.

Bone-Bed-Deposition Stage.—The contact between the Morrison and Cedar Mountain Formations represents a complex erosional surface. The earliest bone accumulation within the quarry was associated with materials transported from nearby springs (Fig. 10, Time 1). Most of these materials (spring-derived carbonates, bones, and other clasts) were likely rain-washed colluvium deposited in the topographic lows on the erosional surface. Some bones, especially those not cemented by the limestone at the base of the quarry, though generally well preserved, have an east-west orientation, and some have small parallel scratch marks that collectively indicate short transport by flowing water (possibly rain washed; see Suarez et al., 2007, for taphonomic data). Some prefossilization spiral fractures may have been produced during fluvial transport (Behrensmeyer, 1991). Brecciation of claystone fragments and some dinosaur bones was caused by precipitating micritic cements. Preliminary isotopic data indicate a strong evaporative component to these cements (G.A. Ludvigson, personal communication, 2005).

Bone accumulation continued during evolution into a fluvial-dominated overbank system. Bones deposited during this time include numerous fragments and flakes, suggesting transport from relatively short-distant

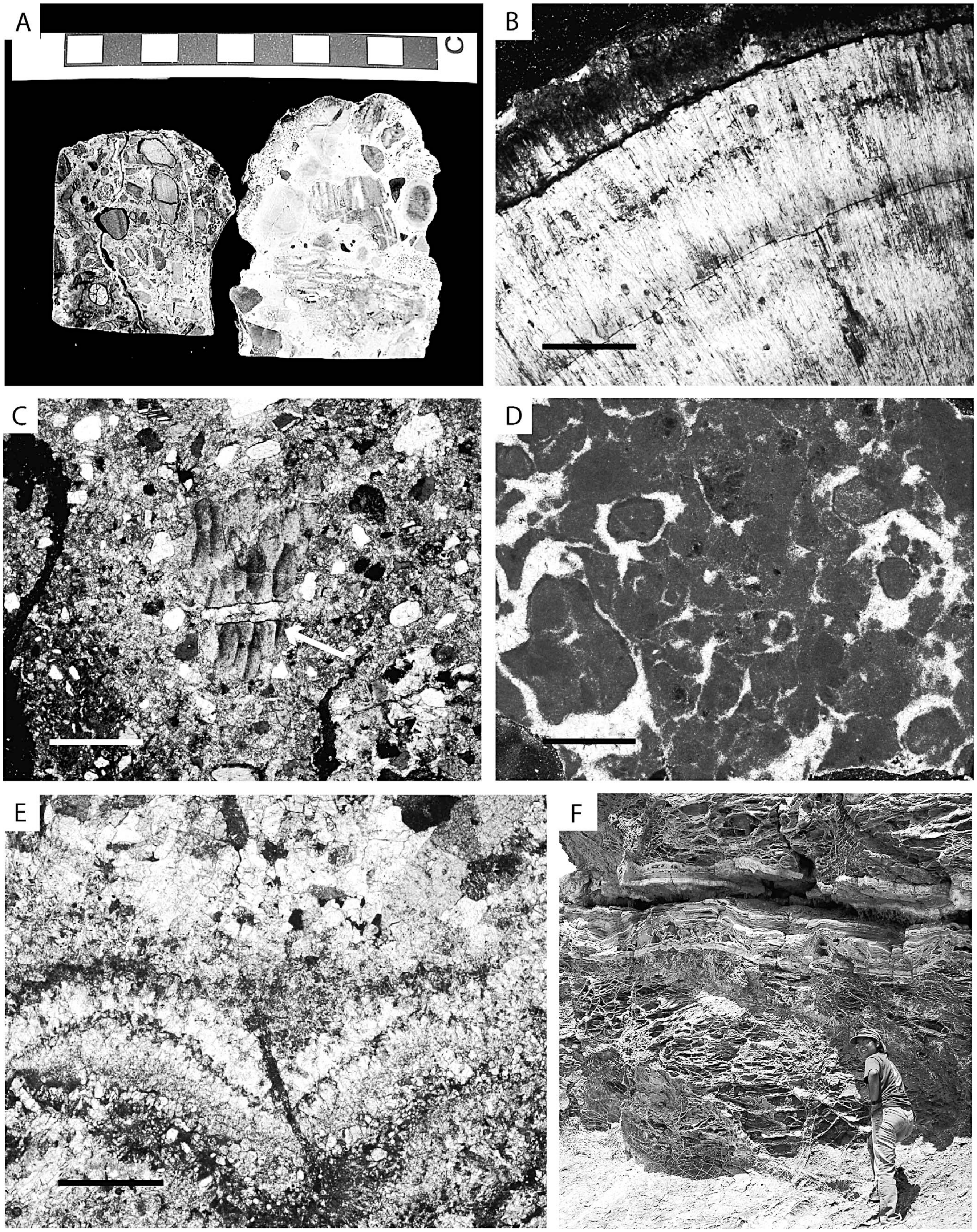
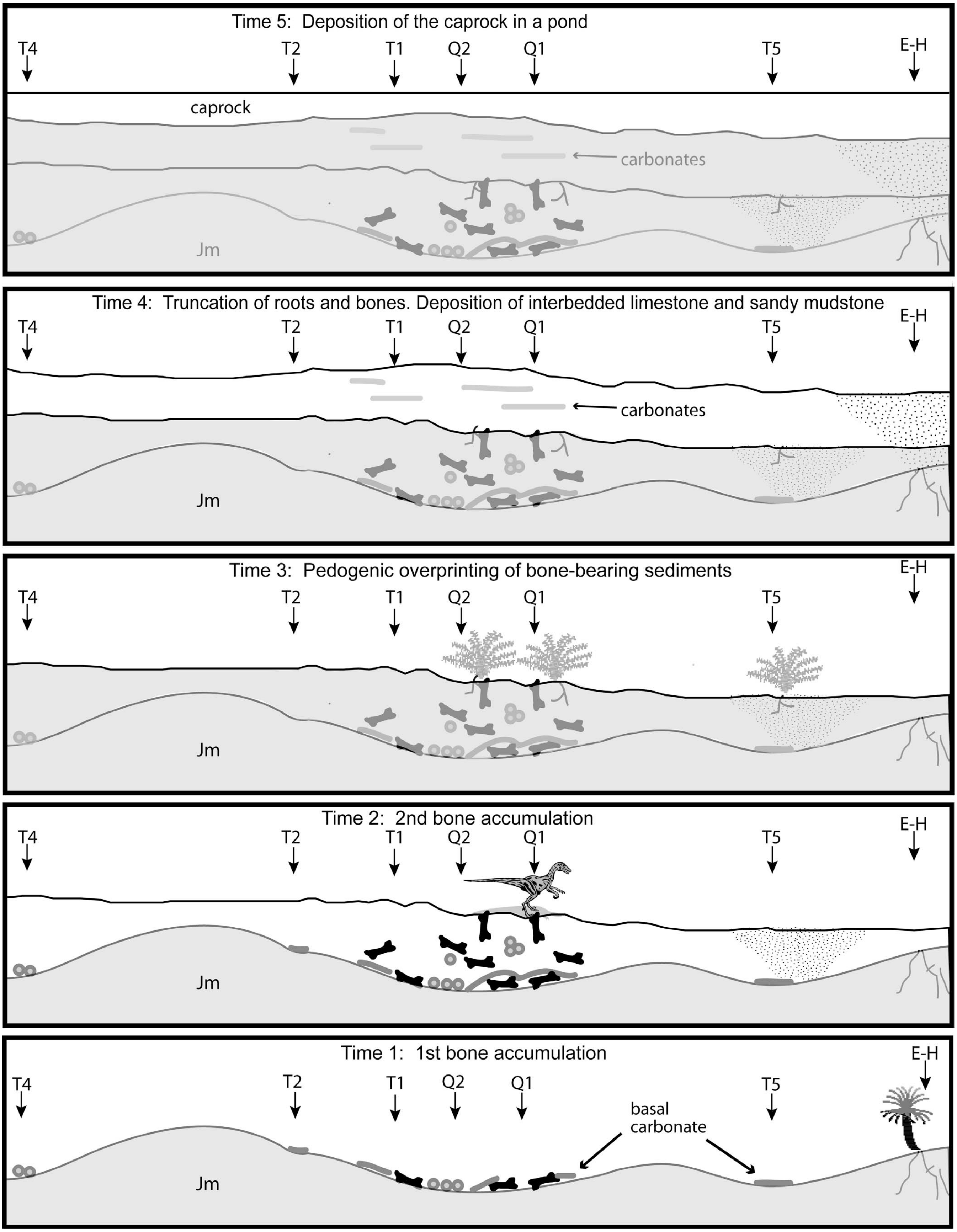


FIGURE 9—Carbonates from the modern Crystal Geyser. All scales except A = 500 μm. A) Comparison of conglomeratic travertine from Crystal Geyser (left) and basal carbonate from Quarry Profile 1 (right). Scale in centimeters. B) Unoriented photomicrograph of radial calcite crystals from travertine at the modern Crystal Geyser; outer portion is encrusted with micrite. C) Unoriented thin section from modern conglomeratic travertine in A showing sandy micritic matrix and large calcite crystal cluster (arrow). D) Unoriented photomicrograph of clotted micrite from modern conglomeratic travertine in Fig. 9A. E) Unoriented photomicrograph of a travertine fragment from modern conglomeratic travertine in Fig. 9A. F) Boxwork structures from recent travertine deposits along the Little Grand Wash Fault. Compare the boxwork structures, especially at the base of the mound, with the fractured silty mudstone in Fig. 5C.


Time 5: Deposition of the caprock in a pond
T4
T2
T1
Q2
Q1
T5
E-H
caprock
carbonates
Jm
Time 4: Truncation of roots and bones. Deposition of interbedded limestone and sandy mudstone
carbonates
Time 3: Pedogenic overprinting of bone-bearing sediments
Time 2: 2nd bone accumulation
Time 1: 1st bone accumulation
basal carbonate

sources. Some bones, however, are in good condition, and require in situ or nearby remains transported as partial skeletons. At the top of the bone-bearing section, many isolated limb bones are found at near-vertical positions, suggesting that the bones were pushed into these high angles by trampling of carcasses by other animals (Behrensmeyer, 1991). Other bones, however, are small pneumatic bones, such as cervical and dorsal vertebrae, and could not have been trampled given their relatively good condition. The presence of pisolite and tufa fragments suggests that spring deposition continued nearby and that spring material was transported by colluvial or fluvial processes to this location (Fig. 10, Time 2).

Post-Bone-Bed-Deposition Stage.—Pedogenesis occurred throughout the development of the overbank facies but is most obvious at the top of the bone-bearing horizon, as indicated by the carbonate-filled root traces at the top of the horizon in Quarry Profile 1 (Fig. 4F). In addition, bones are more heavily encrusted with carbonate than bones lower in the quarry, and pendant carbonate cements commonly form on bone fragments (Fig. 10, Time 3).

Vertical bones and paleosols are truncated by an erosional surface (Fig. 10, Time 4). Sediments deposited above this level are coarser than those below and are in places cross-bedded with interbedded limestone. These light greenish gray beds are consistently present in all measured sections, represent more extensive flooding events, and are consistent with gleying associated with high water tables or lacustrine settings. Typical lacustrine fossils (charophytes, ostracodes, and gastropods), however, are so far absent from localities in and around the quarry.

Deposition of the Caprock.—As the area became more extensively flooded and the topographic lows filled, a small lake or pond developed (Fig. 10, Time 5). Based on the presence of abundant siliciclastics and springlike structures, this body of water received input from streams, overland flow, and springs. Microstructures, such as circumgranular cracking, indicate the pond was shallow and dried periodically. Deposition of the caprock was probably critical to the preservation of the quarry interval since, without it, the soft rocks composing most of the quarry would have easily been eroded.

Implications for the Crystal Geyser Dinosaur Quarry

The CGDQ represents a very unusual deposit. Few dinosaur bone beds have been described from spring settings. One large, nearly monospecific bone bed that has been attributed to a spring deposit is the Cleveland-Lloyd Dinosaur Quarry, within the lower Brushy Basin Member of the Morrison Formation (Bilbey, 1999). This quarry is dominated by numerous individuals of *Allosaurus fragilis*. Bilbey stated that the dinosaur bones were probably reworked by upwelling water that allowed settling of the larger bones toward the base of the quarry with smaller bones toward the top. Despite Bilbey's detailed observations, the strata at the Cleveland-Lloyd quarry do not strongly suggest spring conditions, since there are no calcite morphologies that would suggest a spring deposit. Bilbey's descriptions are, however, consistent with the interpretation that the Cleveland-Lloyd quarry was deposited in a wetland-lacustrine setting on a poorly drained floodplain (Dunagan and Turner, 2004; Gates, 2005). In addition, Gates (2005) suggested that the dinosaurs at the Cleveland-Lloyd quarry were not mired but died as a result of drought conditions. This is supported by the lack of vertical-to-high-angle bone orientation.

Another association of dinosaur bones with spring deposits also comes from the Morrison Formation. Spring-fed pond deposits that contain scattered dinosaur bones and teeth were mentioned by Kirkland et al. (2005a) from the Fruita Paleontological Area. In addition, those deposits contain freshwater fish skeletons, mollusks, and plant fossils.

Therizinosauroids from Asia represent isolated individuals and not large bone beds (Clark et al., 2004). In contrast, the CGDQ represents either one episode of bone accumulation that has been reworked or two or more episodes of accumulation: one at the level of the basal carbonate, and at least one above. Regardless of the number of events, such a large, monospecific accumulation suggests that *Falcarius utahensis* was gregarious and may have been attracted to the area due to local springs.

Spring deposits described by Evans (1999) and Ashley et al. (2004) have associated freshwater floras and faunas, such as ostracodes, bivalves, and charophytes. It is striking that no invertebrates were found at any location in or around the quarry, but this may be due to the limited amount of time over which the quarry has been excavated. In addition, the quarry sediments may have accumulated far enough from the spring source that floras and faunas did not thrive in the CGDQ location. The lack of any invertebrate fossils (with the possible exception of algae) also suggests that spring-water chemistry or temperature may have been incapable of sustaining creatures other than algae. The death and accumulation of such great numbers of *F. utahensis* may also be related to such spring dynamics.

Implications for the Morrison-Cedar Mountain Formation Boundary

The Morrison-Cedar Mountain Formation boundary is characterized in this area by a calcrete. Most authors attributed this deposit to pedogenic or groundwater precipitation of calcium carbonate during the hiatus between deposition of the Tithonian Brushy Basin Member of the Morrison Formation and the Barremian Yellow Cat Member of the Cedar Mountain Formation (Kirkland et al., 1997; Aubrey, 1998; Currie, 1998; Demko, 2004). Aubrey (1998) described the unit as either a hardpan, nodular, or pedotubule calcrete, suggesting a pedogenic origin for the deposit. Currie (1998) described the calcrete as nodular, laminar, or structureless and suggested a pedogenic or groundwater origin for the calcrete that formed as a result of a stable landscape with little to no deposition. Currie (1998) noted that the calcrete contains pisolites but did not describe them in detail.

The present interpretation of the quarry strata is consistent with these works but adds another perspective on the origin of carbonates at the Morrison-Cedar Mountain Formation contact. This is the first interpretation of carbonate features as spring deposits for the Cedar Mountain Formation. Pisolites have been recognized in some parts of the Ruby Ranch Member on the western side of the San Rafael Swell. Those in the area of the CGDQ appear to be concentrated along the boundary between the Morrison Formation and Cedar Mountain Formation. The genesis of these spring deposits is somewhat uncertain. The modern Crystal Geyser is associated with multiple thick, mound-shaped, ancient travertine deposits that cap some of the hills along the Little Grand Wash Fault (Fig. 9F). The spring deposits are sourced from CO_2-rich waters originating in the Late Triassic–Early Jurassic Wingate and Navajo Sandstones and are released through the fault (Baer and Rigby, 1978; Waltham, 2001). No such fault system appears to have been present in the study area during the Early Cretaceous and deposition of the CGDQ strata. Active thrust faulting did occur farther to the west in association with the Sevier Orogeny during the Late Jurassic and Early Cretaceous

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FIGURE 10—Diagrams showing the development and accumulation of dinosaur bones in the Crystal Geyser Dinosaur Quarry. Approximate relative locations of measured sections described in text are indicated by abbreviations: T1 = Trench 1, T2 = Trench 2, T4 = Trench 4, T5 = Trench 5, Q1 = Quarry Profile 1, Q2 = Quarry Profile 2, E-H = East-Hill Trench. Sketches not to scale. Time 1: Deposition of dinosaur bones, pebbles, claystone fragments, and spring carbonate fragments, cemented by micrite. Time 2: Increased fluvial activity deposits a second and possibly third bone accumulation, along with silty to sandy mudstones in the quarry and sandstones (stippled pattern) at Trench 5 (T5). Time 3: More significant pedogenesis occurs. Time 4: Truncation of paleosols and increase of fluvial deposition and overbank facies represented by sandstones at the East Hill Trench (E-H) and coarser sandy mudstone and limestone in the quarry area. Time 5: Deposition of the caprock in a pond or small lake fed by springs or streams.

(Currie, 1998, 2002). Reactivation of faults in pre-Mesozoic basement structure had some effect on depozones according Currie (2002) and may have provided conduits for CO_2-rich water that were responsible for spring deposits at or near the CGDQ.

Future study at the CGDQ is critical to the understanding of this important bone bed and Early Cretaceous environments. A more detailed study of the paleosols in and around the quarry, including geochemical data, will contribute to a better understanding of the complex geomorphology of the area. A more detailed study of the calcretes at the Morrison-Cedar Mountain Formation boundary, including stable isotope geochemistry, will help constrain the origin(s) of these deposits.

CONCLUSIONS

The CGDQ represents fossil preservation within a spring-influenced overbank floodplain environment in an arid to semiarid climate. This conclusion is based on macroscopic features (travertine banding, pisolites, boxwork structures, and tufa and travertine fragments) and microscopic features (radial fibrous calcite) present in carbonates in and around the quarry. The base of the quarry preserves much of the spring carbonates that were transported along with dinosaur bones as colluvium on the erosion surface above the Morrison Formation. Variations in the sedimentology and stratigraphy reveal a complex geomorphic relationship between measured sections, in which the southern and southeastern sections represent proximal fluvial facies and the northern and northwestern sections represent distal overbank facies. The caprock likely represents a larger body of water that was fed by both springs and streams. Deposition of this caprock and its silicification was critical for the preservation of the soft sediments containing dinosaur bones at the CGDQ.

Based on differences in taphonomic features (Suarez et al., 2007) and stratigraphic and lithologic relationships, the bone deposits within the CGDQ probably represent more than one period of accumulation. In a related study (Suarez et al., 2007), geochemical analyses suggest that there are three different bone accumulations. Currently, the stratigraphic evidence supports at least two periods of accumulation.

Since the initiation of this study, three more bone beds have been discovered nearby, suggesting the potential for well-preserved fossils is high for this stratigraphic interval and area. The CGDQ and associated paleontological sites preserve a wealth of paleobiological and paleoenvironmental data that will help to better characterize the Early Cretaceous in North America.

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