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RARE EARTH ELEMENT GEOCHEMISTRY AND TAPHONOMY OF THE EARLY CRETACEOUS CRYSTAL GEYSER DINOSAUR QUARRY, EAST-CENTRAL UTAH

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ABSTRACT

The Crystal Geyser Dinosaur Quarry contains a large monospecific accumulation of bones from a basal therizinosaur, *Falcarius utahensis*. The quarry is located approximately 16 km south of Green River, Utah, at the base of the early Cretaceous (Barremian) Yellow Cat Member of the Cedar Mountain Formation. Fossil bones in the quarry occur in three units that have distinct taphonomic, lithologic, and geochemical characteristics. Rare earth element compositions of fossils suggest that bones from each unit were drawn from different reservoirs or sources having distinctly different compositions, and fossils were not reworked between units. Compositions of bones differ greatly within Units 1 and 2, even within the same 1-m^2 quarry grid. These chemical differences and taphonomic characteristics, such as current orientation, hydraulic sorting, and occasional extensive abrasion, suggest that bones from these two units are allochthonous and were fossilized at other localities, possibly over an area of several kilometers, and were then eroded, transported, and concentrated in a spring-influenced fluvial environment. Bones in Unit 3 have very similar rare earth element signatures, suggesting that they were probably fossilized in situ at a separate time from bones in Units 1 and 2. At least two mass mortality events were responsible for the monospecific assemblage of bones at the quarry. Because bones may have been concentrated from a wide area, causes of mass mortality must have been regionally extensive, possibly owing to seasonal drought, sudden changes in weather, or disease.

INTRODUCTION

The Crystal Geyser Dinosaur Quarry (CGDQ) is located in Grand County, ~16 km south of Green River, in east-central Utah (Fig. 1) on lands managed by the U.S. Bureau of Land Management and has been excavated by the Utah Geological Survey and the Utah Museum of Natural History at the University of Utah since 2001. The CGDQ is at the base of the early Cretaceous (Barremian) Yellow Cat Member of the Cedar Mountain Formation, which unconformably overlies the Jurassic Morrison Formation (Kirkland et al., 1999, 2005a, 2005b; Suarez et al., 2007). It represents one of the earliest Cretaceous dinosaur localities in North America. The quarry contains nearly monospecific bone beds composed of the remains of tens to possibly thousands of individuals of a new basal therizinosauroid, *Falcarius utahensis* (Kirkland et al., 2005b). *Falcarius* is interpreted as shifting its dietary habit from predation to herbivory (Kirkland et al., 2005b); therefore, study of the taphonomy and paleoenvironment of this site is important to our understanding of the evolution and ecology of these transitional dinosaurs. This study presents initial geochemical and taphonomic data for the CGDQ.

A variety of methods have been developed to study vertebrate bone beds, including analysis of bone articulation, transport, and dispersion; weathering; abrasion; bone-surface features; fracturing; hydraulic sorting; and sedimentary facies analysis (e.g.,Weigelt, 1989; Voorhies, 1969; Dodson, 1973; Behrensmeyer, 1975, 1978, 1982, 1991; Dodson et al., 1980; Shipman, 1981; Kidwell, 1986; Fiorillo, 1988; Behrensmeyer et al., 1992; Lyman, 1994; Aslan and Behrensmeyer, 1996; Martin, 1999; Rogers and Kidwell, 2000; Ryan et al., 2001; Brinkman et al., 2004; and Gates, 2005). Such classical techniques, however, cannot always decipher some aspects of bone-bed formation. For example, in her discussion of fluvially influenced bone accumulations, Behrensmeyer (1982) suggested that bones derived from various taphonomic pathways might eventually be distinguished based on differences in chemical characteristics. Since that time, researchers have developed methods using lanthanide, or rare earth elements (REE), in fossil bones to determine their stratigraphic associations, provenance, taphonomic history, paleoenvironment, and degree of reworking (Wright et al., 1987; Trueman and Benton, 1997; Reynard et al., 1999; Trueman, 1999; Staron et al., 2001; Trueman et al., 2003, 2005, 2006; Metzger et al., 2004; Patrick et al., 2004; Martin et al., 2005). Rare earth element analyses of fossil bones, coupled with traditional methods of taphonomic analysis, allow researchers to more fully distinguish bones affected by various taphonomic processes and from multiple stratigraphic sources. Both classical sedimentologic (Suarez et al., 2007) and taphonomic methods and REE geochemistry are used in this study to constrain the depositional environment and taphonomic processes that affected the bone assemblages at the CGDQ.

BACKGROUND

The basis for, and use of, REE in vertebrate fossils has been extensively discussed in a number of publications (Elderfield and Pagett, 1986; Picard et al., 2002; Trueman and Tuross, 2002; Trueman et al., 2003, 2005, 2006; Martin et al., 2005; and references cited therein and above). Bones of living organisms contain low REE concentrations; after death REE are adsorbed from early diagenetic waters onto apatite surfaces and incorporated into the growing crystals during fossilization, where they are retained unless the apatite is dissolved or highly metamorphosed (Trueman, 1999; Armstrong et al., 2001). The REE pattern or signature in the bone reflects that of the average pore-water chemistry during fossilization (Koeppenkastrop and DeCarlo, 1992; Trueman and Benton, 1997; Trueman and Tuross, 2002; Lécuyer et al., 2004; Martin et al., 2005), which is influenced, in part, by environmental factors, including fluid pH, redox, concentrations of complexing ligands (including organic ligands), and reactions with colloids (Erel and Stolper, 1993; Johannesson and Zhou, 1997; Dia et al., 2000; Johannesson et al., 2000; Gruau et al., 2004). Fossilization and REE incorporation is often accomplished within a few thousand years after death (Trueman, 1999; Patrick et al., 2001; Trueman and Tuross, 2002; Martin et al., 2005, Trueman et al., 2005), and bones from successive stratigraphic units may contain significantly different REE patterns (Staron et al., 2001; Patrick et al., 2004; Martin et al., 2005; Trueman et al., 2005). Bones fossilized in a limited or chemically uniform area have essentially identical signatures, whereas bones fossilized over wider areas having REE compositional gradients and fractionation may incorporate a variety of REE signatures. Erosion and mixing of fossilized materials from different localities may produce allochthonous assemblag-

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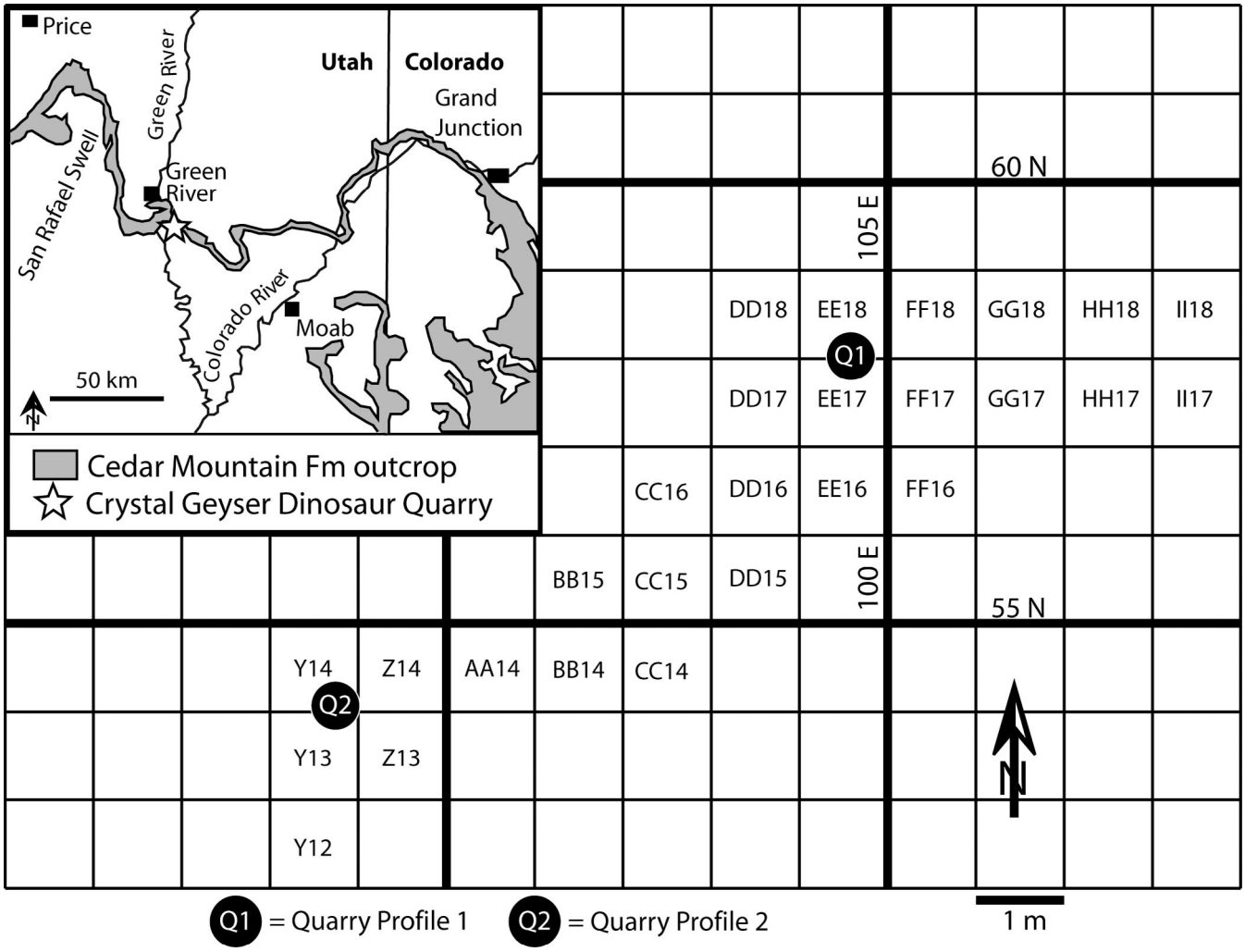

FIGURE 1—Location of the Crystal Geyser Dinosaur Quarry and quarry grids as of summer 2004. The site is located approximately 16 km south of Green River, Utah. Individual grids are 1 m^2. The current total excavated area is about 27 m^2.

es of fossils having different REE signatures. The degree of difference in signatures may indicate the relative extent of reworking in various stratigraphic units (Trueman et al., 2003; Metzger et al., 2004).

METHODS

We used a total station to set up a precise quarry excavation grid (Fig. 1) and vertical datum by Utah Geological Survey excavators at the start of excavation in 2001. The arbitrary vertical datum is relative to the top of an extensive limestone unit that caps the mesa containing the quarry. Positions of stratigraphic sections, sedimentary and taphonomic units, and bones in the quarry were measured relative to the x-y grid and the elevation datum. The orientation and dip of bones were measured using a Brunton® pocket transit. Many bones were prepared at the Utah Geological Survey before final repository at the Utah Museum of Natural History. Prepared bones housed at the Utah Geological Survey were examined for taphonomic features such as fractures, Behrensmeyer (1978) weathering stages, tooth and scratch marks, and abrasion. Behrensmeyer weathering stages represent the relative degree of exposure, ranging from unweathered bones (Stage 0), to cracked and flaked bones (Stages 1–3), to completely weathered shards of bone (Stages 4–5).

Unfortunately, many of the bones currently in collections were illegally collected materials returned to the Utah Geological Survey by fossil poachers after illegal excavation and collection were revealed. Therefore, stratigraphic and lateral locations of these bones within the quarry are not known, and no specific taphonomic conclusions for various units can be made. Where possible, taphonomic analyses were made on bones in the field. We compared these results with those from the illegally collected material and, where possible, reassociated the poached materials with the correct unit. We determined Voorhies Groups (transportability) from field catalogs for the 2002–2004 field seasons, assuming that elements of *Falcarius* were transported in a manner similar to coyote and sheep bones (Voorhies, 1969; Martin, 1999). Chevrons were placed in Group I (flotation transport); claws and ankylosaur scutes in Group II (saltation and flotation), and *Falcarius* brain cases and skull elements in Group III (lag), based on their size, shape, and density.

Bones sampled for chemical analysis were collected and documented in the field during the 2004 excavation period. Sample preparation methods followed those of Staron et al. (2001), Patrick et al. (2004), Metzger et al. (2004), and Martin et al. (2005). Cortical bone was separated from the specimens. Matrix was mechanically removed from the bone by probes, picks, and ultrasonic agitation. A few bones containing consolidants were soaked in acetone. Staron et al. (2001) have shown that consolidants contain only negligible REE and that acetone treatment has no effect on bone REE signatures. Bones were crushed into small fragments and cleaned of carbonate using 10% acetic acid. Cortical samples were powdered using a mortar and pestle. Bone powder (0.1 g) was placed in 100 mL flasks and dissolved in trace-metal-grade nitric acid with heating, where necessary, and diluted to 100 mL with dionized-distilled water. For

analysis, 0.5 mL of the stock solutions were added to 9.5 mL of 2% nitric acid with indium as an internal standard. Samples were analyzed for REE, U, Th, and other trace elements using an inductively coupled plasma mass spectrometer (ICP-MS). Trace-element abundances were determined at the University of Maryland using a ThermoFinnigan Element 2 single collector High Resolution Sector ICP-MS. Samples were introduced through a nominally 100 μL min^{-1} capillary tube and aspirated into a Cetac Aridus desolvating chamber run at 70°C. Sensitivity was ~10^6 counts per second (cps) per ppb for ^{115}In. Additional samples were analyzed in the Department of Geology at Temple University using a VG PlasmaQuad 3 quadrapole ICP-MS (Martin et al., 2005). NBS phosphate rock 120 was used as a reference standard. Samples have an analytical error of $<\pm 5\%$ based on triplicate analyses. The REE were normalized to the North American Shale Composite (NASC; see Gromet et al., 1984) and plotted on spider and ternary diagrams. Rare earth element concentrations may vary among individual bones from a given unit, depending on bone material type, rates of burial, the amount of recrystallization during fossilization, or sampling depth in the bone (Henderson et al., 1983; Elderfield and Pagett, 1986; Wright et al., 1987; Patrick et al., 2001; Trueman and Tuross, 2002); however, taphonomic conclusions are drawn from the shapes of the REE signatures or REE ratios (Trueman and Benton, 1997; Staron et al., 2001; Trueman and Tuross, 2002; Patrick et al., 2004; Martin et al., 2005). Ternary (triangular) diagrams with NASC-normalized Yb, Gd, and Nd (representative heavy, medium, and light REE) at the vertices allow the basic shape of the REE pattern to be represented (Patrick et al., 2002). Statistical analyses of data were accomplished using NCSS software (Hintze, 1997).

CGDQ STRATIGRAPHY

Details of the regional stratigraphy, sedimentology, and paleoenvironmental interpretations are given in Stokes (1986), Aubry (1998), B. Currie (1998), and Kirkland et al. (1999, 2005a), and quarry stratigraphy, sedimentology, and paleoenvironment are given in Suarez et al. (2007). Two representative stratigraphic sections from the quarry are shown in Figure 2. Locations of the sections are in Figure 1. The quarry stratigraphy is laterally variable, consistent with a spring-influenced environment in a semiarid or monsoonal climate (Kirkland et al., 1999) having at least intermittent fluvial inputs (Suarez et al., 2007). The CGDQ bone-bearing unit, which is generally less than 1 m thick, unconformably overlies the Jurassic (Tithonian) Morrison Formation; an unconformity of ~20–25 myr. The CGDQ currently covers an area of approximately 27 m^2 (Fig. 1). Several trenches located 5–10 m from the current quarry boundaries contain bone, however, indicating that the bone bed is much more extensive, possibly covering an area of as much as 100 m^2.

The CGDQ bone bed occurs within a lenticular-nodular limestone and is overlain by purple, carbonate-rich, silty-sandy mudstone with green mottles. The contact between the Cedar Mountain and the Morrison Formations at the CGDQ is marked by a discontinuous basal carbonate, as much as 13–15 cm thick, which contains abundant chert pebbles, carbonate (pisoids and travertine) clasts, many fragmented bones, and ripped-up claystone chips derived from the Morrison Formation (Suarez et al., 2007). Many clasts and bones are brecciated owing to the formation of this carbonate (Suarez et al., 2007). Carbonate pisoids and travertine fragments are composed of radial and fibrous calcite. The characteristics of these pisoliths are very similar to those in spring-formed carbonates (Suarez et al., 2007), such as those found in the modern CO_2 cold-water Crystal Geyser spring and other springs (Risacher and Eugster, 1979). The basal carbonate is laterally discontinuous in the southwestern part of the quarry (Fig. 1, grids Z14, Y13, AA14, BB14), and there is a mudstone-mudstone contact between the Morrison Formation, which is usually a very dark purple or dark red mudstone, and the Cedar Mountain Formation, which is usually light purple or light green, with dinosaur bones and isolated pisoids lying directly on top of the Morrison Formation (Fig. 2).

Above the carbonate is a purple, silty-to-gravelly mudstone that contains green mottles. The silty mudstone is about 50 cm thick in the southwest part of the quarry (Fig. 2, Profile 2) and thickens to about 70 cm in the northeastern part of the quarry (Fig. 2, Profile 1). Within this mudstone are extremely poorly sorted, floating coarse clasts composed of abundant bones and bone fragments, chert pebbles, and clay chips from the Morrison Formation. Bones are highly fractured in and immediately above the carbonate. The bones are often encrusted with micritic carbonate. There are also occasional carbonate nodules and pisolith clasts that may also be related to spring or pedogenic processes. About 60 cm above the Morrison Formation is a discontinuous carbonate layer that is relatively unfossiliferous. Larger carbonate nodules (>20 cm in diameter) occur in the southwestern part of the quarry. Green silty mudstone is found above the discontinuous carbonate. It contains small pebbles, pisoids, sparse carbonate-filled root traces, and bones with pendant cements.

The top of the bone deposit is marked by an erosional surface that truncates the bones and root traces. In Quarry Profile 2, the green mudstone occurs lower and has an irregular contact with the purple mudstone (Fig. 2). The thickness of bone-bearing strata varies from ~80 cm to 90 cm, indicating that the exposure surface that developed on top of the Morrison Formation during the Cretaceous was not flat but had some topographical variability. Several discontinuous limestones and muddy sandstones occur above the bone-bearing unit. The entire mesa is capped by a very dense, gray, sandy-to-gravelly carbonate that weathers to dark brown. This unit is laterally extensive and in some locations consists of a channel sandstone fining upward to a sandy limestone. Near the top of this unit are unusual silicified stromatolitic and travertine-like structures (Suarez et al., 2007).

RESULTS

Geochemical Analysis

Results of chemical analyses of bones from the CGDQ are given in the Supplementary Data[1]. Total REE concentrations range from ~320 ppm to >25,000 ppm. Various ratios of different REE were plotted against stratigraphic location to determine any trends or groupings. Figure 3 shows the most significant relationship, Nd_N/Gd_N versus elevation above the Morrison Formation. Bones become increasingly enriched in Nd and other light rare earth elements (LREE) with increasing elevation. Rather than a continuous change with elevation, however, bones separate into three distinct groups or units that lie within distinct lithologic units (Fig. 2). Bones from the first unit, 0 to ~13 cm above the contact (183–210 cm below the quarry datum set by the Utah Geological Survey), are contained in the basal carbonate and laterally equivalent mudstone. Unit 2 bones, from ~13 cm to 55 cm above the contact, are found directly above the basal layer in a gray-purple gravelly mudstone that sometimes contains green mottling. Unit 3 bones are in a purple and green mottled silty mudstone above a discontinuous carbonate layer, 55–96 cm above the Morrison Formation, or 124–100 cm below the datum (Fig. 2). Near the top of the unit the mudstone is green, rather than purple. Within these units the Nd_N/Gd_N ratio of bones does not vary systematically with elevation.

Representative NASC-normalized REE signatures of bones from the three units are presented as spider diagrams in Figure 4. REE signatures in bones from Unit 1, the lowest unit, are middle rare earth element (MREE) enriched and have large positive Ce anomalies (Fig. 4). Signatures of Unit 1 bones differ from one another primarily in the degree of heavy rare earth element (HREE) enrichment. Rare earth element signatures in Unit 2 bones differ greatly both from Unit 1 and from each other. Some Unit 2 bones have signatures that are generally flat, with little relative enrichment, whereas others have patterns that are LREE or HREE enriched. Most Unit 2 bones have positive Ce anomalies.

[1] paleo.ku.edu/palaios.

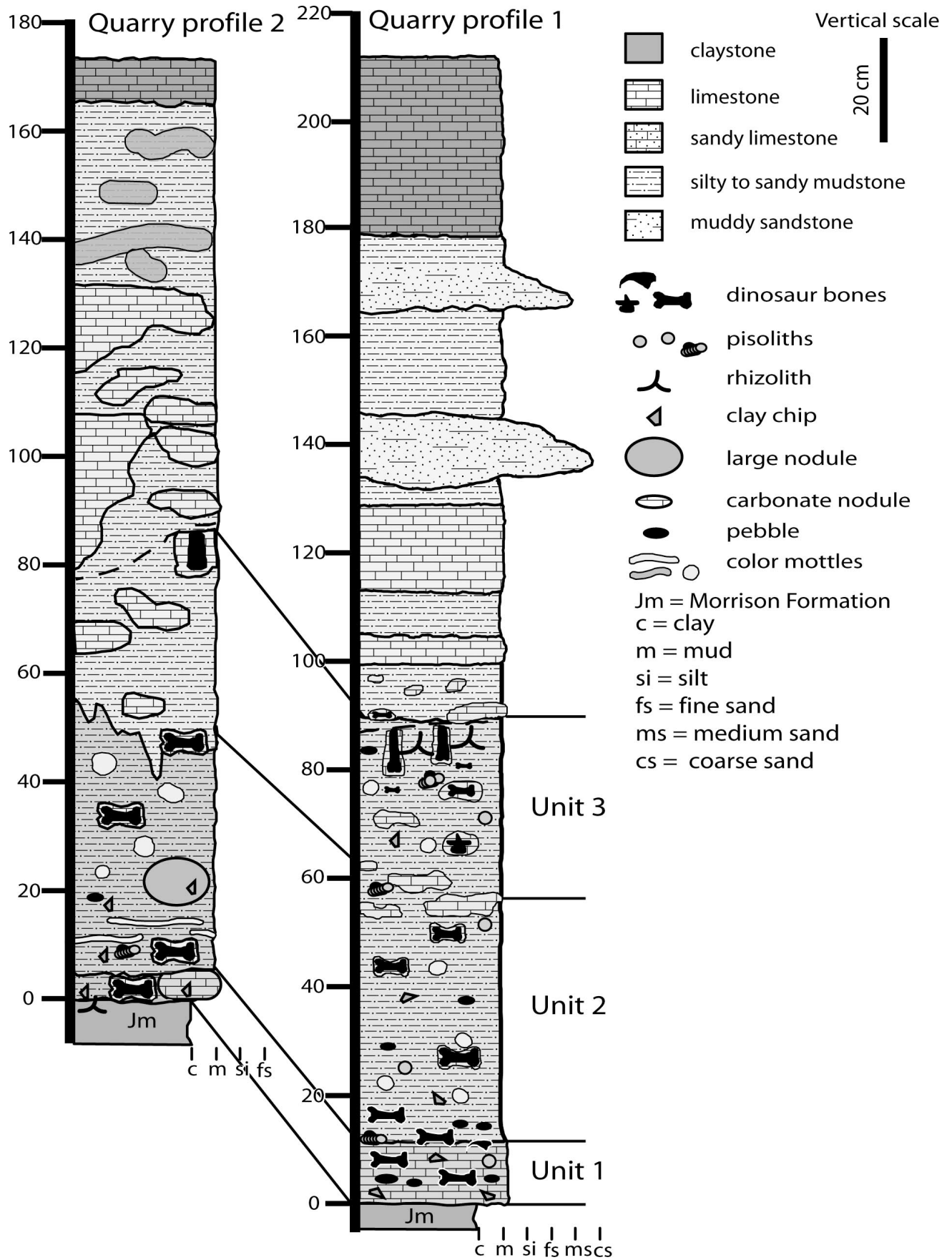

FIGURE 2—Two stratigraphic sections from the Crystal Geyser Dinosaur Quarry showing thicknesses of the bone-bearing lithologic units. Distances in centimeters above the Morrison Formation contact. Positions of the sections are shown in Figure 1. Bone-bearing strata are separated into three units based on differences in taphonomic, lithologic, and geochemical characteristics.

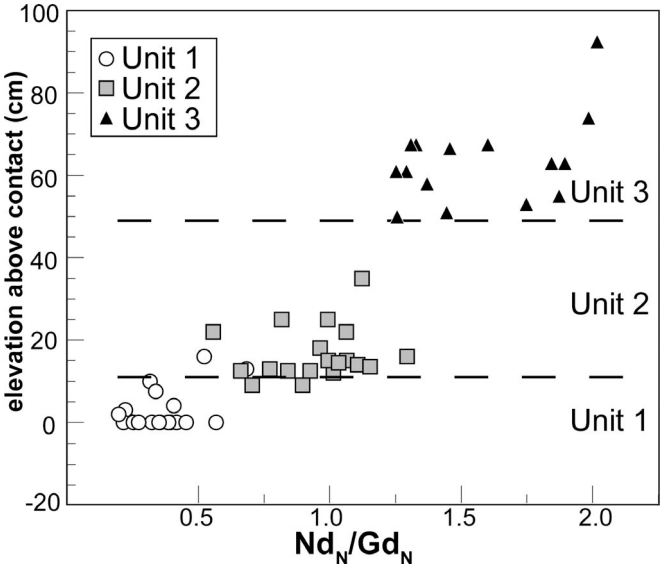

FIGURE 3—Nd_N/Gd_N in *Falcarius* bones from the Crystal Geyser Dinosaur Quarry versus elevation above the Jurassic Morrison Formation. The three groupings also correspond to the three lithologic units.

Bones from Unit 3, the upper unit, are more LREE enriched and do not significantly vary from bone to bone (Fig. 4). The exception to this is one vertically oriented long bone (Sample CGDQ 74) which seems taphonomically different from other Unit 3 bones (see discussion below in Taphonomic Analysis). This bone has been excluded from present considerations, pending further study.

Rare earth element signatures in bones from the three units are visibly different from each other (Fig. 4). The extent of these differences is also revealed in a ternary diagram (Fig. 5) and by various statistical tests. Data from the three units plot in different parts of the ternary diagram, with little overlap between units (Fig. 5). Most bones from Unit 1 plot near the Gd_N apex as a result of their highly MREE-enriched signatures (Figs. 4, 5). Unit 1 bones from the mudstone and carbonate have the same range of MREE-enriched signatures, bones from Unit 2 are intermediate, and those from Unit 3, the uppermost unit, are most Nd_N (LREE) enriched (Fig. 5). The differences of signatures in bones within Units 1 and 2 produce a spread of data points for those units, with data for some bones plotting toward the HREE apex as a result of greater HREE-enrichment (Fig. 5). The REE composition of bones from Unit 3, however, cluster tightly and plot generally within the 2σ analytical error (see legend on Fig. 5), indicating that these REE ratios in bones from Unit 3 are not significantly different from one another.

Taphonomic Analysis

Approximately 99% of the bones identified from the quarry are *Falcarius*. Based on the size variation of bone elements, young juveniles to full-sized adults are preserved. Insufficient bones have been examined, however, to allow a meaningful population census to be calculated. A few remains of other taxa have been found in the CGDQ, including one dorsal and one caudal vertebra, one proximal humerus, and three scutes from a very large, unidentified ankylosaur, a few possible crocodilian teeth, and one possible chelonian (turtle) claw. Most bones are disarticulated with some association. In the mudstone at the base of the quarry, a nearly articulated or associated pair of ischia were found along with associated tibia, fibula, radius, and ulna; just above the limestone there are associated forelimb elements. Results of preliminary taphonomic analyses are summarized in Table 1. Taphonomic data for bones from the three geochemical groups are presented below.

Spatial Variation.—Unit 1 bones are flat lying and have preferred orientation (Fig. 6). Bone orientations are somewhat variable from grid to grid but tend to be oriented either E-W or N-S. In grid BB14 (Fig. 7), long bones are oriented approximately NW-SE, and smaller bones, such as vertebrae, are imbricated on the SW side of these bones. Additionally, a few small bones, such as phalanges and caudal vertebrae, grade laterally to the NE.

Long bones in Unit 2, above the carbonate, are also commonly flat lying with variable orientation from N-S to E-W, depending on the location in the quarry (Fig. 8). In Unit 3, most bones are Voorhies Group 1, and therefore orientation cannot be easily determined. The few long bones found above 55 cm are vertically oriented limb bones. These are most notable in grid FF18. These bones may be taphonomically distinct from the underlying and surrounding Voorhies Group I bones in this unit and may form a separate taphonomic unit. Unfortunately, only a few such

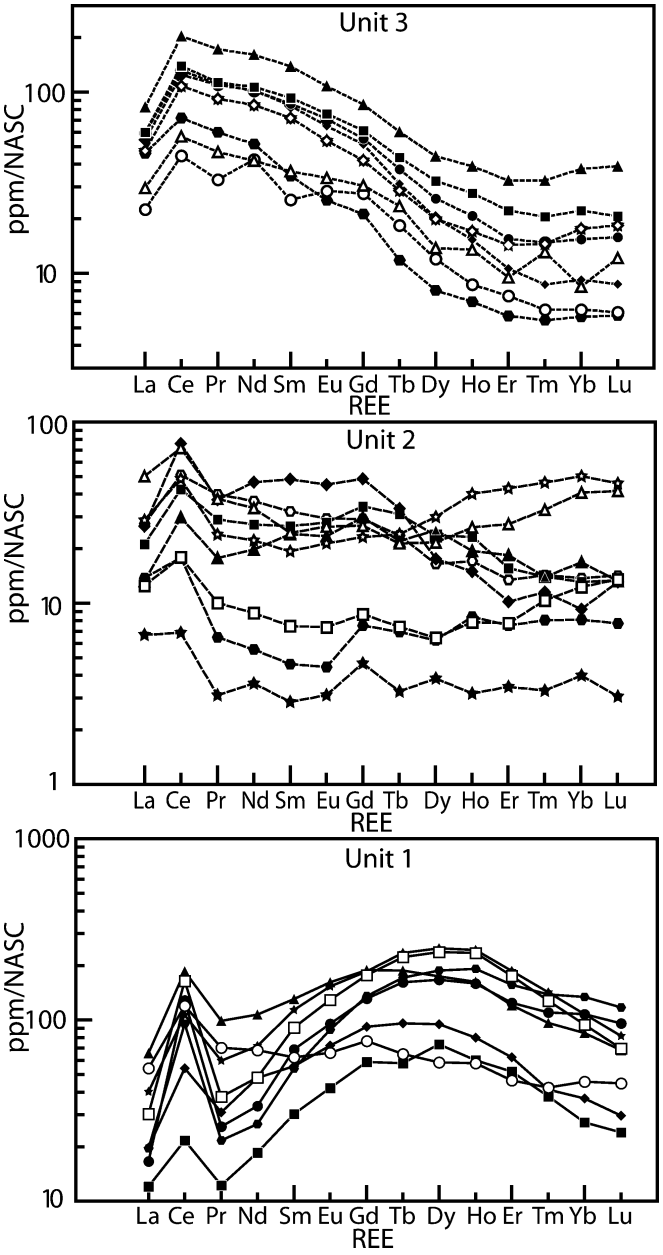

FIGURE 4—NASC-normalized spider diagrams of REE in bones from the three units in the Crystal Geyser Dinosaur Quarry. REE signatures of bones are different in each of the units. Signatures of bones also differ within Units 1 and 2, whereas bones from Unit 3 appear to have very similar REE signatures. NASC = North American Shale Composite; REE = rare earth elements.

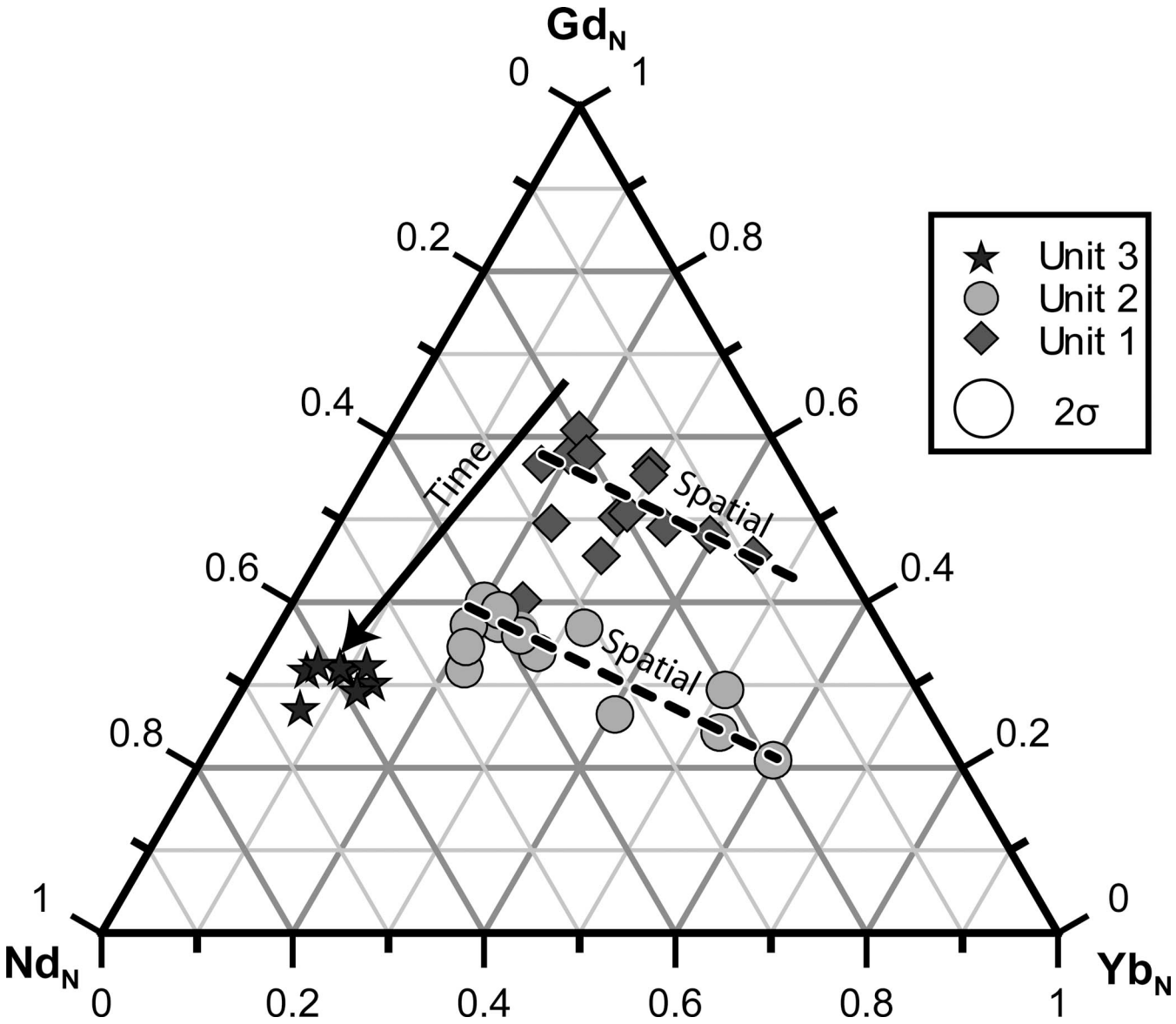

FIGURE 5—Ternary diagram of NASC-normalized REE in bones from Units 1, 2, and 3. Bones from the three units have distinctly different REE ratios, with little overlap, suggesting that bones were fossilized at different places or times and were not reworked between units or derived from a single reservoir of fossils. Bones from Units 1 and 2 have greater chemical variability than Unit 3. Chemical differences in bones from the two units may be due to spatial averaging (dotted-line) of bones fossilized along a geochemical gradient. Compositions of bones from Unit 3 cluster within a 2σ error circle (see legend in figure), indicating that they are essentially identical in composition and suggesting fossilization in situ. If bones in Units 1 and 2 fossilized at different times, the trend toward LREE enrichment is consistent with long-term changes in REE geochemistry over time (solid-lined arrow). Inductively coupled plasma mass spectrometer analyses at University of Maryland. The 2σ circle represents 2 standard deviations analytical error based on ±5% RSD (relative standard deviation). Ternary diagram apicies after Patrick et al. (2002). NASC = North American Shale Composite; REE = rare earth elements; LREE = light rare earth elements.

TABLE 1—Summary of preliminary taphonomic results from CGDQ.

	Behrensmeyer (1978) weathering stages	Abrasion	Fracture	Other Traces
Unit 3	Mosaic cracking	Few bone pebbles, abrasion near truncation surface	Transverse	None
Unit 2	0–2 (flaking)	On fractured surfaces	Spiral; articular ends missing	None
Unit 1	0 (unweathered)	On ends, scratches on shafts	Transverse and spiral in basal carbonate	Punctures and tooth gouges

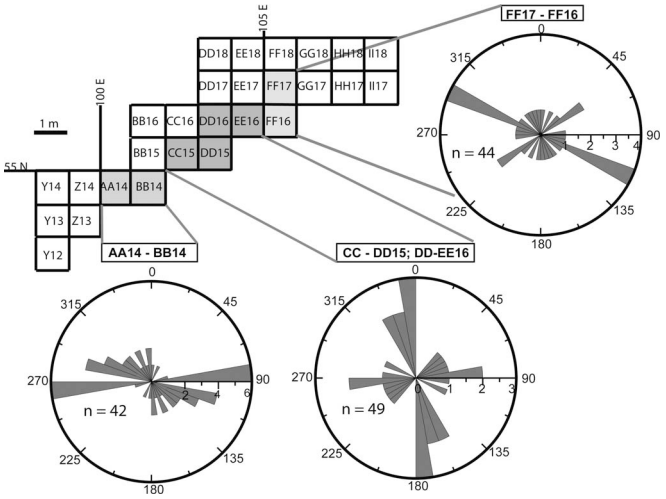

FIGURE 6—Bidirectional rose diagrams with 10° petals of orientation of long bones from different grids in Unit 1. Bone orientation changes from one grid to the next, suggesting laterally variable current direction or variable water depth.

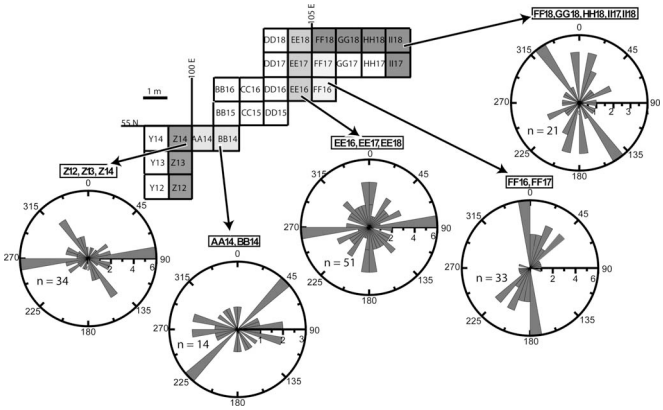

FIGURE 8—Bidirectional rose diagram with 10° petals of orientations of long bones in different grids from Unit 2. Bone orientations vary somewhat from grid to grid. If long bones are generally aligned parallel or perpendicular to transport direction, then bone orientations are consistent with either north-south or east-west currents.

bones have been collected, and their taphonomic associations remain unclear.

Figure 9 summarizes Voorhies Group distributions in the three geochemical units in a ternary diagram (n = 913). Bones in all of the units are hydraulically sorted, as evidenced by the virtual absence of Group III lag bones (most difficult to transport). Unit 1 contains the highest proportion of Voorhies Group II bones (saltation load) of intermediate transportability, and Units 2 and 3 contain progressively more Group I bones (easily transported).

Bones found higher in the quarry are smaller in size, with abundant, ~1-cm rib fragments and cortical flakes, and often represent Voorhies Group I. Less than 30% of these bones were collected, however, because, prior to this taphonomic study, the primary goal was to excavate material for morphologic description. Overall, there are a smaller proportion of Voorhies Group II bones in Unit 2 (Fig. 9). Most bones from Unit 3 are Voorhies Group I bones (Fig. 9) with the exception of the vertically oriented limb bones. The top of this unit is an erosional surface marked by truncated bones and fossil root traces.

Bone Modification.—Bones in the basal carbonate are often fragmentary, brecciated, or intensely fractured from growth of carbonate within and around the bone. In the mudstone they are usually complete, though small shards and rib fragments encased in micritic carbonate concretions are abundant. Both bones and bone fragments are often covered in a carbonate crust. Under the carbonate crust, bones are commonly coated with a very thin iron oxide or manganese oxide layer. Bones from Unit 1 are moderately abraded. On one bone the cortical layer on the articular ends has been completely removed and trabecular bone exposed. On unabraded bones, surfaces are unweathered (Behrensmeyer weathering stage 0).

The most common types of bone fractures are transverse and spiral. Most fractures are on bones in the basal carbonate, including transverse or postfossilization fractures and spiral fractures. Several limb bones from Unit 1 have circular puncture marks, about 0.5 cm wide and less than 0.5 cm deep with localized crushing. Parallel scratch marks are also found on bone surfaces.

Unit 2 bones are often well preserved and purple in color as a result

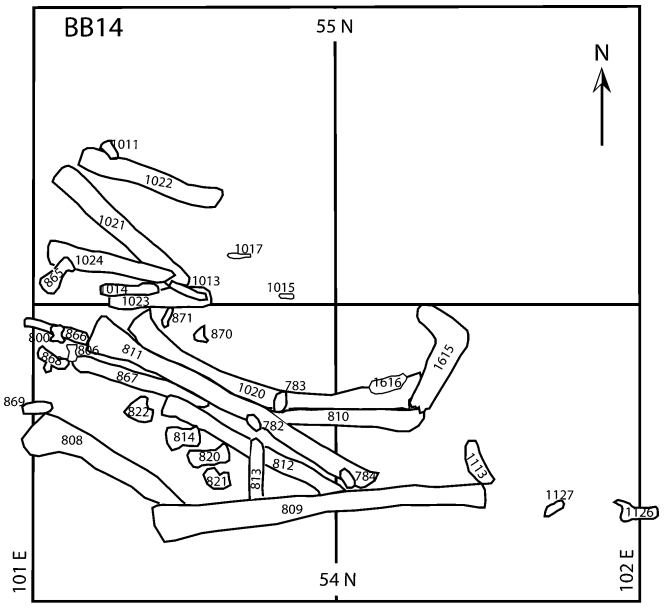

FIGURE 7—Orientation of bones from Unit 1 (>183 cm below the datum) in grid BB14. The orientation of long bones in a northwest-southeast direction, imbrication of smaller bones (vertebrae) on the southwest edge of the long bones, and lateral grading of bones to the northeast indicate that current directions in this grid were to the northeast. Grid is 1 m^2.

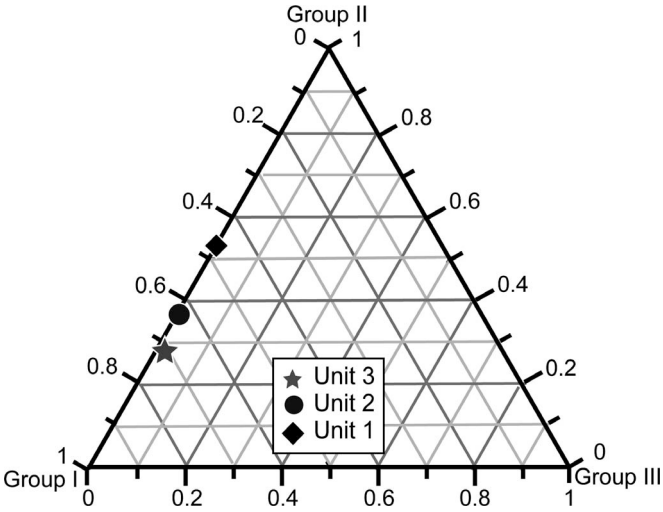

FIGURE 9—Ternary diagram of Voorhies Groups in the three bone-bearing units in the Crystal Geyser Dinosaur Quarry (n = 913). Group I = easily or first transported; Group II = transported by saltation; Group III = lag or bed load, most difficult to move. Bones in all of the units have been hydraulically sorted, with loss of Voorhies Group III bones. Ternary diagram after Fiorillo (1997).

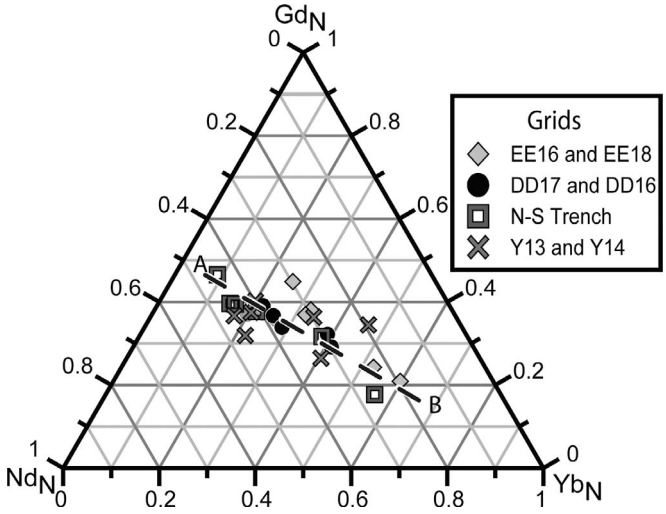

FIGURE 10—REE composition of bones from various grids in Unit 2. Bones plot along a mixing line from LREE-MREE enriched (A) to HREE enriched (B). Bone compositions differ greatly, even with a single 1 m^2 grid. There is no significant compositional trend with grid position. REE = rare earth elements; LREE, MREE, HREE = light, middle, and heavy rare earth elements.

of manganese oxide crusts on their surfaces. They are usually found in carbonate nodules and are intensely fractured, especially those directly above the basal carbonate. Bones occur either broken in half or with both articular ends missing or smashed, with the fractured ends sometimes showing signs of abrasion. They are slightly weathered, corresponding to Behrensmeyer weathering stages 1–2, consistent with short-term surface exposure.

Unit 3 bones are often in carbonate nodules or have pendant carbonates. Some near the top of the unit are moderately abraded, and a few bone pebbles were found, suggesting significant abrasion and fluvial transport. Several of the vertebrae and the braincases found in Unit 3 exhibit a weathering pattern described by Behrensmeyer (1978) as mosaic cracking or flaking. The specific cause of mosaic cracking is still unknown; however, the vertebrae and braincases of *Falcarius* are highly pneumatic, and the skulls are small and gracile, so this weathering pattern may be due to the fragile nature of these bones.

DISCUSSION

Geochemical Interpretations

Although they are stratigraphically adjacent, bones from Units 1 and 2 have drastically different REE signatures (Fig. 4). Bones in Units 1 and 2 have REE signatures that scatter along two different straight lines from LREE/MREE enriched (plotting toward the upper left part of the ternary diagram in Fig. 5) to HREE enriched (plotting toward the lower right of Fig. 5), suggesting mixing or evolutionary relationships within each unit. Such linear trends might have been produced by mixing of groundwaters or by adsorption or desorption of REE on colloids or mineral surfaces along a flow path (Erel and Stolper, 1993; Dia et al., 2000; Johannesson et al., 2000; Ojiambo et al., 2003; Gruau et al., 2004).

Mixing between LREE-enriched groundwater (Fig. 10, near point A) and HREE-enriched groundwater (near point B) could produce the range of signatures and trends seen in the ternary diagram of bones from Unit 2. The REE composition of groundwater is influenced by pH, redox, and composition of complex-forming ligands (Johannesson and Zhou, 1997; Dia et al., 2000; Johannesson et al., 2000; Ojiambo et al., 2003). Nearly neutral-pH natural waters may be LREE, MREE, or HREE enriched or have flat patterns showing no specific enrichment, whereas more basic and alkaline (carbonate-bearing) waters tend to be HREE enriched (Johannesson and Zhou, 1997). Thus, the observed differences could be produced by mixing of groundwaters having different pH values or compositions. For example, Johannesson et al. (1997) and Ojiambo et al. (2003) have shown that REE variations in groundwaters in Nevada and Kenya are consistent with groundwater mixing.

Light rare earth elements are often preferentially adsorbed onto or retained in weathering products such as hydrous ferric oxides, manganese oxides, clays, colloids, and organic matter, whereas HREE tend to remain in solution because they form stronger aqueous complexes with carbonate and other inorganic and organic ligands (Nesbitt, 1979; Wood, 1990; Erel and Stolper, 1993; Haas et al., 1995; Nesbitt and Markovics, 1997). Desorption or dissolution of such LREE-enriched materials could cause groundwaters to become LREE enriched, whereas precipitation or sorption would produce HREE enrichment. Therefore, REE may become fractionated along a flow path. For example, Johannesson et al. (2000) suggested that changes in concentration and fractionation of REE in a shallow southern Nevada aquifer were partially controlled by sorption. Byrne and Kim (1990), Piepgras and Jacobsen (1992), Erel and Stolper (1993), Möller and Bau (1993), and others have shown that REE concentrations and fractionation in the ocean can be explained by dissolution and adsorption-desorption on organics, hydrous ferric oxides, and other particles (see also Patrick et al., 2004).

Mixing and adsorption-desorption-dissolution of carrier phases can produce similar REE trends, and it may be difficult to distinguish between these mechanisms. Release of LREE into groundwaters by dissolution or desorption from hydrous ferric oxides, manganese oxides, organics, or other particles, however, may be the more likely mechanism for the bones from the CGDQ. Some bones are encrusted with calcite or have calcite in Haversian channels. Calcite precipitates under alkaline, neutral-to-basic pH conditions; such waters are usually HREE enriched (Johannesson and Zhou, 1997; Martin et al., 2005), for example, near B in Figure 10. Fossil preservation is favored by such conditions (e.g., Retallack, 1984). Desorption of REE, degradation, dissolution, or recrystallization of LREE-enriched carrier phases, such as organics, hydrous ferric oxides, or manganese oxides, would release an LREE-enriched component into solution causing the composition to migrate toward A (Fig. 10) (see also Patrick et al., 2004).

Manganese and iron oxides coat many of the CGDQ bones and are not removed by the acetic acid cleaning treatment. Concentrations of REE in such phases (e.g., Ohta and Kawabe, 2001; Dubinin, 2004), however, are generally less than concentrations in bones analyzed in this study (Supplementary Data[1]). Therefore, manganese oxide and iron oxide contaminants would greatly affect the total REE concentrations or signatures only if they constituted a large proportion of the specimen, which is not true in these samples. Therefore, there is no significant contamination from oxides.

Many CGDQ bones have positive cerium anomalies (Fig. 4). Cerium anomalies are often important components of REE signatures because they may be used to infer redox conditions. Negative Ce anomalies in marine and terrestrial waters usually indicate oxidizing conditions (Wright et al., 1987; German and Elderfield, 1990; Dia et al., 2000). Positive Ce anomalies are rare in terrestrial groundwaters (Johannesson and Zhou, 1997), but can be produced by reducing conditions or by highly saline, carbonate-rich waters (German and Elderfield, 1990; Möller and Bau, 1993; Martin et al., 2005). Highly reducing or highly saline environments, however, are not consistent with lithologic evidence or types of REE signatures in the CGDQ. Although sphaerosiderites have been found in some trenches lateral to the bone bed and abundant green mottles are found in and around the quarry (Suarez et al., 2007), no other significant minerals indicative of reducing conditions have been discovered at or near the quarry site, and it is likely that local environments were quite oxidizing. The presence of abundant carbonate nodules suggests alkaline conditions that normally produce highly HREE-enriched patterns (Möller and Bau, 1993; Johannesson et al., 1997; Johannesson and Zhou, 1997; Martin et al., 2005), which is inconsistent with the generally LREE- and MREE-enriched patterns in the CGDQ. Because geochemical variability

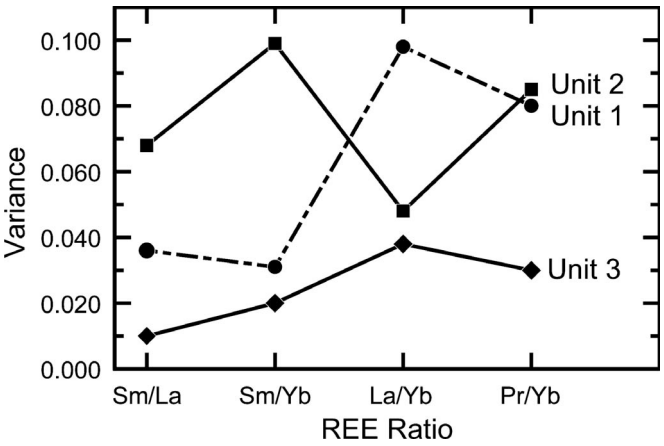

FIGURE 11—Values of statistical variance (s^2) for log Sm_N/La_N, Sm_N/Yb_N, La_N/Yb_N, and Pr_N/Yb_N ratios in bones from the three units. High variance values indicate greater differences in composition of bones within the unit, consistent with more extensive reworking or greater chemical gradients. Unit 3 has the lowest variance in all ratios. REE = rare earth elements.

and taphonomy suggest reworking of Units 1 and 2, which have the highest positive Ce anomalies, it is impossible to know the exact lithology in which the bones were originally fossilized.

Positive Ce anomalies might also result from the dissolution and weathering of source rocks and minerals with positive Ce anomalies. Positive Ce anomalies are found in manganese oxide nodules and crusts in oceanic sediments (e.g., Dubinin, 2004). Ce is oxidized to Ce^{4+} and strongly enriched in MnO_2 (Ohta and Kawabe, 2001); however, no such marine nodules exist in this area. It is most likely that dissolution of manganese oxides such as pyrolusite, found in the underlying terrestrial Jurassic Morrison Formation sediments, by neutral pH or suboxic waters flowing through those sediments, might produce a positive Ce anomaly, as well as LREE enrichment, in fluids in which the CGDQ bones were fossilized.

Trueman et al. (2003) proposed that the statistical variance (s^2) of the log Sm_N/La_N, log Sm_N/Yb_N, log La_N/Yb_N, and log Pr_N/Yb_N ratios in bones sampled from different units could be compared to quantitatively assess reworking and relative amounts of time or spatial averaging of bones between units. Variance values of the selected ratios in bones from each unit are plotted in Figure 11. Bones in Unit 3 have the smallest variances, consistent with the small difference in signatures from that unit (Figs. 4, 5). Bones from Unit 2 have the greatest variances for three of the ratios, and Unit 1 has the greatest variance for the other ratio (log La_N/Yb_N). The different values and patterns of variances in Units 1 and 2 reflect the different compositional trends of the two units (e.g., high variances of log La/Yb and log Pr/Yb for Unit 1 are due to changes in HREE concentrations for that unit; see Figs. 4, 5). Unit 2 has the greatest variance values for three of the four REE ratios and the largest spread of points in the ternary diagram; thus it appears that the bones in Unit 2 have the greatest difference in REE signatures.

We used an F-test to assess equality of variance of selected ratios for each of the units (Table 2). Variances of most ratios are significantly different between units. F-test results, coupled with differences in compositions and patterns of variances (Figs. 4, 5), indicate that bones from the three units are not drawn from the same population or reservoir of fossils.

Taphonomic Interpretations

Current-oriented bones, abrasion, and depletion of Voorhies Type III (lag) bones (Fig. 9) indicate that the bones have been transported and are hydraulically sorted. The presence of large proportions of Voorhies Group II (intermediate) bones, particularly in Units 1 and 2, suggests that strong currents oriented and sorted the bones. In Unit 1, bones are E-W or N-S oriented. Long bones tend to orient parallel or perpendicular to the current depending on water depth (Martin, 1999). Thus, these orientations could be consistent with either slightly variable E-W or N-S currents. The NE laterally graded bones in BB14 indicates that flow was to the NE in this location. A similar situation exists in Unit 2; however, no laterally grading bones have been documented, so specific flow direction is unknown. Significant differences in REE signatures (Figs. 4, 5), variances of selected REE ratios (Fig. 11, Table 2), Behrensmeyer (1978) weathering stages, abrasion, surface markings, and occurrence of fractures (Table 1) all suggest that the three CGDQ bone-bearing units are distinct from one another and that bones from one unit were not derived or reworked from the other units. Differences in REE signatures and variances of means and lack of overlap in compositions indicate that bones from the three units were fossilized at different times or places.

TABLE 2—Results of F-test calculations for significant differences in rare earth element composition between the three bone-bearing units; not sig. = not significant.

Ratio	log Sm_N/La_N	log Sm_N/Yb_N	log La_N/Yb_N	log Pr_N/Yb_N
Unit 1:Unit 2	5%	1%	1%	not sig.
Unit 1:Unit 3	1%	not sig.	1%	1%
Unit 2:Unit 3	1%	1%	not sig.	1%

The small puncture marks, interpreted as tooth marks, indicate some Unit 1 bones may have been processed by either scavengers or predators. These punctures are from blunt, conical teeth, such as those of crocodilians, rather than dinosaurs. The presence of large clasts such as gravel pebbles, clay chips, and bone in Unit 1 suggests this material was accumulated as a laglike deposit, but it still shows evidence of transportation and orientation. Parallel scratch marks are the result of trampling or transport along a coarse substrate. Secondary calcite formation brecciated both claystone clasts and bone.

Fracturing in Unit 2 may be the result of transport of weakened and dried bones, predator-scavenger activity, trampling, or transport onto an unyielding surface. The relative increase of smaller bones higher in the unit may be due to a fining-upward effect during the transportation of these bones (parautochthonous or allochthonous). The presence of oriented bones, fractured bones, and vertical sorting indicate that Unit 2 bones are an allochthonous accumulation.

Unit 3 bones are hydraulically sorted and were quickly winnowed from the site of death based on the dominance of Voorhies Group I bones (parautochthonous). Pendant cements and root traces suggest that soil formation may have occurred, although the degree of pedogenesis is very low because much of the quarry contains original bedding.

Overall, based on the statistical analysis of variance values for the log ratios, there is significant REE variability in both Units 1 and 2. Rare earth element compositions of bones are significantly different within both Units 1 and 2, even within the same 1 m^2 grid (Fig. 10). Such major compositional differences in such restricted areas could not occur in bones fossilized in situ. This suggests that bones that had acquired their REE signatures in other places were eroded, transported, and then deposited in the CGDQ, producing an allochthonous fossil assemblage with a mixture of different REE signatures for both Units 1 and 2 (Fig. 12). Bones may have acquired their original signatures at various places along a hydrologic flow path, in a groundwater mixing zone, or as a result of different degrees of reaction with REE carrier phases. The difference in composition between the two units suggests that fossilization of bones from the two units occurred in two different environments or at two different times and that there has been no subsequent sedimentary mixing of the fossils.

Conditions and distances needed for the fractionation in Units 1 and 2 are unknown. Rare earth element fractionations with depth can occur in thicker sedimentary profiles or weathered tills (Yan et al., 2001); however,

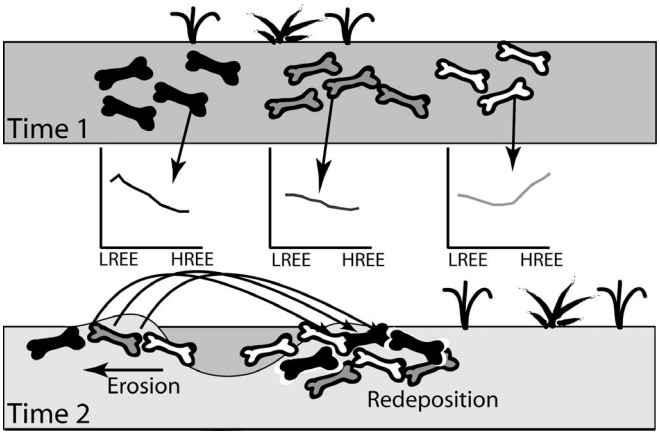

FIGURE 12—Illustration of reworking of bones fossilized along a geochemical gradient. The different signatures are represented by the different color bones (black, gray, and white). Reworking of bones fossilized along this gradient would result in significant differences in REE composition of bones within close lateral proximity. REE = rare earth elements; LREE, HREE = light and heavy rare earth elements.

in thinner, more poorly developed weathering profiles, such as those developed on the sediments that constitute the quarry and immediate area (Suarez et al., 2007), depth-related REE fractionations will probably be minor (Metzger et al., 2004). Therefore, REE fractionation must have occurred laterally. In studies by Johannesson et al. (1997), Dia et al. (2000), and Ojiambo et al. (2003), significant groundwater REE fractionations were observed over 1→10 km distances. Soils (Metzger et al., 2004; Trueman et al., 2006) and unique point sources, such as springs (Deocampo et al., 1998), however, may have a high degree of lateral chemical variability over a smaller area. The degree of variability within Units 1 and 2 is sufficient to suggest fossilization elsewhere and reworking into the quarry site. Therefore, bones in Units 1 and 2 may have been derived from source areas of several square kilometers, or perhaps less, if springs or soils contributed to a highly variable geochemical environment. If so, these bones have been spatially reworked and possibly temporally averaged, as often occurs with fossils in lag deposits (Rogers and Kidwell, 2000).

Based on the large spread of data points in the ternary diagram and the large variances of most selected REE ratios (Figs. 5, 11), the bones in Unit 2 have the greatest amount of variability. If REE fractionation gradients were similar in areas where bones from Units 1 and 2 were fossilized, then Unit 2 may have the greatest degree of spatial averaging. In contrast, bones from Unit 3 have very similar REE signatures and low variances. These bones may have fossilized in situ in the CGDQ or have been reworked from a limited or geochemically homogeneous area, which seems less likely. If they were fossilized in the CGDQ, they must have been transported and hydraulically sorted into the CGDQ area soon after death of the organisms but before fossilization. Fossilization and fixation of REE into bone occurred after this initial transport. This is consistent with the higher proportion of easily transported (Voorhies Group I) bones in Unit 3. Although transported fossils may occasionally have little wear, the relative lack of abrasion on the surfaces of Unit 3 bones suggests that they were not transported as far as those in Units 1 and 2.

Two scenarios are possible given the geochemical and taphonomic data. The near monospecific nature of the site suggests that the accumulations of bones resulted from one or more mass mortality events affecting packs or herds of communal dinosaurs (e.g., Currie and Dodson, 1984; Coria, 1994). In scenario I (Fig. 13A), the three distinct geochemical signatures represent fossilization events at three different times. In this scenario, Unit 1 was reworked from a previous mass mortality event. The carcasses were probably scavenged and buried; some were then fossilized and subsequently eroded, transported, and deposited in the location of the CGDQ along with coarse materials (pebbles, travertine fragments, etc.). Bones were oriented during deposition at this location. Bones that were cemented by carbonate were brecciated by the formation of surface

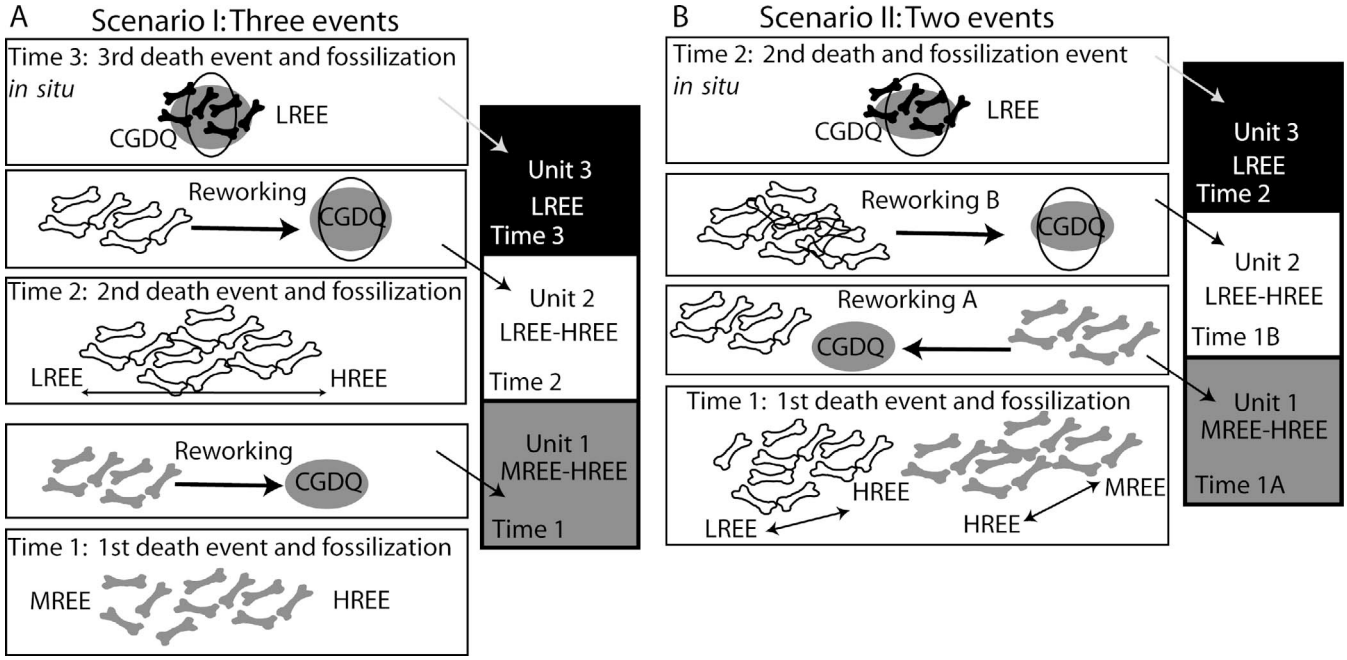

FIGURE 13—Scenarios that could result in the geochemical makeup of the CGDQ. A) Scenario I: Bones are fossilized in a MREE-HREE-enriched environment after a mass death event. These bones are subsequently reworked into the location of the CGDQ. A second mass death event at Time 2 results in the fossilization of bones in a LREE-HREE-enriched environment and is also reworked into the CGDQ. Finally, a third mass death event takes places (Time 3), and Voorhies Group I bones are quickly transported and fossilized in the CGDQ. B) Scenario II: Bones from a large mass death event are fossilized in an area that varies from LREE-HREE-MREE-enriched environments. Bones from the MREE-HREE-enriched environment are reworked into the location of the CGDQ, after which bones from the LREE-HREEE enriched are are reworked on top of the MREE enriched bones. A second fossilization event and in situ fossilization of Voorhies Group I bones results in the formation of Unit 3. CGDQ = Crystal Geyser Dinosaur Quarry; REE = rare earth elements; LREE, MREE, HREE = light, middle, and heavy rare earth elements.

calcite. Unit 2 was formed similarly from a later mass mortality event, possibly in the same source area. If bones from Units 1 and 2 were derived from the same general area, then several hundreds to thousands of years must have passed for the geochemical environment to change and REE to be incorporated in the fossils. The high degree of spiral fracturing of bone in Unit 2 is a result of transportation of fossilized bones along a hard surface, trampling of these bones, and scavenger or predator processing. Unit 3 bones were deposited and fossilized in situ (in the LREE-enriched environment). A soil then formed on the land surface as indicated by carbonate-filled root traces and pendant cements. Vertically oriented bones at the top of Unit 3, which have different REE signatures and are truncated by an erosional surface, may be evidence of a fourth fossil emplacement period.

Scenario II requires only two mass-mortality and fossilization events (Fig. 13B). Units 1 and 2 are the result of one fossilization event in two different areas. Carcasses distributed about a large area at one time were fossilized in two chemically different environments, one MREE-HREE enriched and the other LREE-HREE enriched. Subsequent reworking of previously fossilized bones from the MREE-enriched environment into the quarry area occurred first, followed by reworking of LREE- to HREE-enriched bones of Unit 2 on top of the reworked Unit 1 bones. Unit 3 was then formed as a separate mass-mortality event with in situ fossilization at some later time.

It is difficult to determine from present evidence which of these two scenarios is more likely. Scenario I requires three monospecific mass mortality events, which seems less probable considering the monospecific nature of the deposit. We currently favor Scenario I, however, because the composition of fossils in the three units is distinctly different (Figs. 4, 5) and there is no significant mixing of fossils between units. The availability of fossils having different REE compositions on or near a land surface, from which they might be eroded and transported, will produce a mixture of reworked bone compositions, such as those in the mixing lines for Units 1 and 2. If the *Falcarius* fossils resulted from a single mass mortality event and the bones were fossilized at the same time but in different places along different chemical or hydrologic flow paths, then the difference in composition of the units and lack of fossils of different composition range within each unit would require that the fossils be obtained sequentially from the different source areas with little or no mixing of samples from different chemical or hydrologic source areas. This seems unlikely. Meandering of a river or stream between bone source regions, for example, might produce a period in which bones from both regions were represented. Such mixing is not observed. Further, the progression from the highly MREE-enriched fossils in Unit 1 to the LREE-enriched fossils in Unit 3, with Unit 2 intermediate, could be consistent with a long-term variation in groundwater in that area. Further study is required to resolve these two possibilities.

The near-monospecific nature of this site suggests that the accumulation of bones represents several mass death assemblages (e.g., Currie and Dodson, 1984; Coria, 1994). The occurrence of multiple mass mortalities of a single therapod species (*Falcarius*) as suggested by this study is very unusual. Only a few occurrences, such as the *Allosaurus* bone bed at the Jurassic Cleveland-Lloyd Dinosaur Quarry, Utah (Stokes, 1986; Gates, 2005), the *Ceolophysis* bone bed in Ghost Ranch, New Mexico (Colbert, 1989; Schwartz and Gillette, 1994), and the *Albertosaurus* bone bed in Canada (P. Currie, 1998), are documented. If *Falcarius* were an omnivore or herbivore (as suggesting by Kirkland et al., 2005b), these individuals may have been gregarious. Rare earth element geochemistry suggests that the bones were derived from either a wide area or a depositional environment that had high geochemical gradients (i.e., springs). Regionally widespread causes of mortality, such as drought or flooding, rapid changes in weather conditions, or disease, may have been responsible for the deaths of these dinosaurs. The abundance of spring-formed carbonate suggests that a spring environment may have played a role in the congregation or death of these animals. Though this is speculative, it is an interesting point that should be investigated further.

CONCLUSIONS

The CGDQ bone bed consists of three chemically and taphonomically distinct, nearly monospecific units containing remains of many individuals of a basal therizinosaur, *Falcarius utahensis*. Hydraulic sorting, bone orientation, abrasion, surface markings, and sedimentary analysis all indicate that bones in the units are allochthonous or parautochthonous. Rare earth element signatures and variances indicate that bones from the units are distinct, not reworked from one another, and not derived from the same single reservoir of fossils. The variety of chemical compositions in Units 1 and 2, even within single meter-square grid areas, indicates that the fossilized bones, which acquired their REE compositions elsewhere, were eroded, transported, and redeposited as compositionally heterogeneous mixtures in the CGDQ. Large variances in compositions of bones from Units 1 and 2 suggest spatial averaging of bones from areas of perhaps more than one km^2 or from a highly geochemically variable area (such as soils or springs). Because bones in Units 1 and 2 were fossilized and transported from elsewhere, they are somewhat older than the surrounding sediments. Bones in Unit 3 have very low REE variances, suggesting fossilization in situ, at a later time than those from Units 1 and 2.

The nearly monospecific nature of the CGDQ, coupled with differences in REE compositions and variances for the three units, suggests bones are derived from at least two mass mortality events. The presence of springs may play a role in the death of the dinosaurs and preservation and geochemistry of the fossils in this location.

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