NEW DATA TOWARDS THE DEVELOPMENT OF A COMPREHENSIVE TAPHONOMIC FRAMEWORK FOR THE CLEVELAND-LLOYD DINOSAUR QUARRY

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ABSTRACT

The Cleveland-Lloyd Dinosaur Quarry (CLDQ) is the densest deposit of Jurassic theropod dinosaurs discovered to date. Unlike typical Jurassic bone deposits, it is dominated by the presence of *Allosaurus fragilis*. Since excavation began in the 1920's numerous hypotheses have been put forward to explain the taphonomy of CLDQ, including a predator trap, a drought assemblage, and a poison spring. In an effort to reconcile the various interpretations of the quarry and reach a consensus on the depositional history of CLDQ, new data is required to develop a robust taphonomic framework congruent with all available data. Here we present two new data sets which aid in the development of such a robust taphonomic framework for CLDQ. First, x-ray fluorescence of CLDQ sediments indicate elevated barite and sulfide minerals relative to other sediments from the Morrison Formation, suggesting an ephemeral environment dominated by periods of hypereutrophic conditions during bone accumulation. Second, the degree of weathering and hydraulic equivalency of small bone fragments dispersed throughout the matrix were analyzed from CLDQ. Results of these analyses suggest that bone fragments are autochthonous or parautochthonous and are derived from bones deposited in the assemblage. The variability in abrasion exhibited by the fragments is most parsimoniously explained by periodic reworking and redeposition during seasonal fluctuations throughout the duration of the quarry assemblage. Collectively, these data support some previous interpretations that the CLDQ represents an attritional assemblage in a poorly-drained overbank deposit where vertebrate remains were introduced post-mortem to an ephemeral pond during flood conditions. Furthermore, elevated heavy metals and rare earth elements detected at the quarry are likely a

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diagenetic signal, potentially produced in part from an abundance of vertebrate remains, and not the primary driver for the accumulation of carcasses. These new data help to explain the specific depositional environment of the quarry, and represent a significant step in understanding the taphonomy of the bone bed and late Jurassic paleoecology.

INTRODUCTION

The Cleveland-Lloyd Dinosaur Quarry (CLDQ) of central Utah is located in the Brushy Basin Member of the Upper Jurassic Morrison Formation at the northern end of the San Rafael Swell (Figure 1A, B). The quarry is world-famous for its unusually high concentration of dinosaur bones, including at least 70 individuals representing a minimum of nine genera (Madsen, 1976; Gates, 2005). Of these, over 60% (MNI: 46, based on a count of left femora) are attributable to a single taxon – *Allosaurus fragilis*, yielding a predator-prey ratio of 3:1, which is unusual compared to other herbivore-dominated Morrison bonebeds (Madsen, 1976; Miller et al, 1996; Gates, 2005) (Figure 2). As such, the quarry represents a potential wealth of Jurassic paleoecological data.

Since the initial discovery of the site in 1927, nearly 10,000 bones have been collected by at least seven institutions. The first formal excavations were carried out by the University of Utah, collecting nearly 1,000 bones from 1929 to 1931 (Miller et al., 1996). Excavations resumed again in 1939 through 1941 by W. L. Stokes and Princeton University, which excavated and collected approximately 450 bones during the three-year period. During the early 1960s, the University of Utah resumed excavations and collected nearly 7,000 bones from 1960-1964 (Miller et al., 1996). Excavations resumed again in the late 1970s by the Utah Division of State History, and continued intermittently through the 1980s by Brigham Young University, collecting nearly 1,100 bones (Miller et al., 1996). The quarry was once again worked from 2001-2003 through the Natural History Museum of Utah, yielding nearly 400 bones (Gates, 2005). In 2012, a coordinated effort between the University of Wisconsin Oshkosh and Indiana

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University of Pennsylvania began surveying the quarry and began excavations in the south Butler Building, collecting nearly 50 bones to date.

While nearly all prior research conducted at the CLDQ has focused on macrovertebrate taphonomy (e.g. Dodson et al., 1980; Stokes, 1985; Hunt, 1986; Richmond and Morris, 1996; Gates, 2005; Hunt et al., 2006), geochemical considerations have received considerably less attention (i.e. Bilbey, 1999). Furthermore, other data types (such as microfossils) are available to aid in interpreting the depositional environment, yet have received only passing attention. Charophytes and ostracods have been recovered from the quarry matrix and utilized for general depositional interpretations (Suarez, 2003; Gates, 2005; Hunt et al., 2006). While specimens of turtle shell and shed crocodilian teeth have been reported in the quarry, their abundances are considerably low (i.e. two shed crocodilian teeth and a few fragments of turtle shell) in contrast with other sedimentologically similar deposits, suggesting that the depositional environment may not have been permanently inundated (Madsen, 1976; Gates, 2005). However, the quarry does contain abundant bone fragments within the matrix (clasts <10 mm) (Gates, 2005). While these fragments are far too small for taxonomic diagnosis, they can be characterized as transportable sedimentary particles ("bioclasts"); the fragments are widely dispersed throughout the matrix of the quarry and are relatively uniform in size, suggesting syndepositional incorporation of the fragments with the larger remains in the quarry assemblage and hydraulic sorting. As such, their taphonomic characteristics and patterns such as hydraulic equivalence and abrasion can be utilized to further interpret depositional histories (Peterson et al., 2011).

In addition to the microfossils and microvertebrate remains at the quarry, still more data is available to consider when interpreting the taphonomy of the CLDQ. Feeding traces and syndepositionally crushed bone are nearly absent from the quarry (Hunt et al., 2006).

Furthermore, concretions of calcite with trace amounts of barite form as nodules (calcite/barite nodules hereafter) around many of the bones from the CLDQ (Bilbey 1999). Finally, the bones in the quarry are found isolated or associated, and only rarely articulated (Gates, 2005).

While recent researchers agree that the deposit was formed in a small, likely ephemeral, pond (e.g. Richmond and Morris, 1996; Gates, 2005; Hunt et al., 2006), the above evidence has led to a suite of highly variable explanations of the specific taphonomy and depositional environment preserved at the CLDQ. Initial interpretations classified the quarry as a drought-induced death assemblage (Stokes 1945; Gates, 2005). One hypothesis suggest that the quarry represents a predator trap where sauropods mired in the mud, in an effort to explain the high numbers of *Allosaurus* (Richmond and Morris, 1996). Bilbey (1999) posited that the quarry represents a lethal spring-fed pond or seep where dinosaurs died after drinking the water. Hunt et al. (2006) suggests that the dinosaur remains at the quarry represent a single population which died and were subsequently transported into a shallow pond.

Each of the above taphonomic hypotheses is insightful, however each hypothesis conflicts with the existing taphonomic data to some degree. For example, bones in a predator trap should be heavily tooth-marked, as are over 50% of the bones recovered from the Rancho La Brea tar pits (Spencer et al., 2003). However, only 4% of bones recovered from the CLDQ show evidence of feeding traces (Gates, 2005). Furthermore, bones from a predator trap would show a higher frequency of taphonomic modification, such as bones crushed by larger animals, such as sauropods, attempting to escape the miring mud, and pit wear from remains wearing against each other during early diagenesis (i.e. Friscia et al., 2008), both of which are conspicuously rare or absent at the CLDQ (Gates, 2005).

Bilbey's (1999) lethal spring fed pond hypothesis is powerful in that it can explain the lack of microvertebrate remains found at the CLDQ; a toxic pond would not support the fish, turtles, and crocodilians typical of pond deposits. The spatial distribution of bones in the quarry also fits well with Bilbey's (1999) hypothesis, however the 'dinoturbation' hypothesized to contribute to the disarticulation of remains would result in bone crushing. Furthermore, organisms would likely move away from the pond after drinking the water, rather than remaining until death to be buried in place. Additionally, Bilbey (1999) does not explain the potential source of the toxicity of the pond.

Given the complicated taphonomy of the CLDQ and the problems with existing taphonomic hypotheses, new data is required to create a new or hybrid taphonomic hypothesis for the CLDQ which can address the complications of the available data. Here we present new taphonomic and geochemical data in the forms of x-ray diffraction (XRD) and x-ray fluorescence (XRF) data from a stratigraphic column spanning the Salt Wash and Brushy Basin members of the Morrison formation which crops out in the Cow Flats Quadrangle, including XRF data from sediment and bone fragments from the CLDQ (Figure 1A, B). These data are contrasted with geochemical data from a lithologically similar Brushy Basin bonebed, the Mygatt-Moore Quarry (MMQ). We further provide characteristics of the intramatrix bone fragments (IBFs) of the CLDQ and a new locality (UWO-12-001, "Johnsonville") in attempt to formulate depositional and taphonomic inferences among sites with different taphofacies. The geochemical and micropaleontological data presented here are meaningful in terms of contributing to existing data available to interpret the CLDQ taphonomy. The following questions are addressed:

1. What are the geochemical signatures of the CLDQ, and how do they compare to the regional Morrison Formation outcrops and bone beds?
2. What are the abrasion patterns of recovered IBFs from the CLDQ?
3. What do the hydraulic equivalences of IBFs suggest about depositional history of the CLDQ?

GEOLOGIC SETTING

The CLDQ and Johnsonville localities are located on the northern end of the San Rafael swell, southwest of Price, Utah, and stratigraphically located in the Brushy Basin Member of the Upper Jurassic Morrison Formation (~147 Ma) (Bilbey, 1998). The Brushy Basin Member is composed of floodplain-deposited mudstones with freshwater limestone and some channel sandstones, and is the youngest of three laterally extensive members of the Morrison Formation (Gates, 2005). In the immediate vicinity of the CLDQ and Johnsonville sites are the distal alluvial fan complex of the Salt Wash Member, which underlies the Brushy Basin Member, and the Middle Jurassic Summerville Formation, which underlies the Morrison Formation (Peterson and Turner-Peterson, 1987). Previous reconstructions of late Jurassic climate patterns in Utah indicate strong seasonality, subject to variably arid to monsoonal conditions (e.g. Hallam, 1993; Dodson et al., 1980; Rees et al., 2000; Parrish et al., 2004; Sellwood and Valdes, 2008; Tanner et al., 2014). This interpretation is supported by scarce plant material and coal deposits (Dodson et al., 1980) and the distribution of authigenic minerals such as barite, present throughout the Morrison Formation that are strongly associated with periodic aridity (Turner and Fishman, 1991).

Cleveland-Lloyd Dinosaur Quarry (CLDQ) - The Cleveland-Lloyd Dinosaur Quarry (CLDQ) is located approximately 38 meters above the basal contact of the Brushy Basin Member (Bilbey, 1992) (Figure 1A, B). The bone-bearing unit is composed of a calcareous mudstone that varies in thickness from a few centimeters to one-meter, and also includes abundant diagenetic limestone nodules and clay clasts. The mudstone underlies a bone-bearing micritic limestone unit that varies in thickness from 0.3-1.0 m, and overlies a massive silty mudstone approximately 20 meters in thickness (Gates, 2005; Bilbey, 1992). Based on limited exposures, the mudstone unit is laterally continuous for 50-75 meters before pinching out to the south (Gates, 2005). The mudstone contains calcite/barite nodules, typically as overgrowths on bone, interpreted as resulting from soft tissue decay (Bilbey, 1998; Gates, 2005). The evaporative nature of the deposit would help to form these nodules, as evaporation would induce increased saturation of the relevant ions, however the nodules would have to form when the pond still contained water. While various depositional models have been proposed for the CLDQ, the lithologies, abundant vertebrate macrofossils, and rare microvertebrate and invertebrate remains suggest an ephemeral pond or similar overbank deposit with a fluctuating water table (calcareous mudstone facies) that became a more permanent basin in the form of a shallow lacustrine setting (limestone facies) (Bilbey, 1999; Gates, 2005). The presence of freshwater ostracods, gastropods and charophytes in the limestone cap over the bone-bearing mudstone suggests that the environment supported a freshwater ecosystem during the last stages of sediment filling the pond (Bilbey, 1992). The deposit has been dated to 147.2 ± 1 Ma to 146.8 ± 1 Ma via K/Ar dating of an ash bed approximately 1 m above the limestone cap (Bilbey 1998).

Johnsonville (UWO-12-001 "JONS") - The Johnsonville quarry (University of Wisconsin Oshkosh locality UWO-12-001) is located 470 meters southeast of the CLDQ locality and is stratigraphically positioned approximately 11 meters below the CLDQ in the lower portion of the Brushy Basin Member (Figure 1A, B). The site was discovered by the University of Wisconsin Oshkosh field crew in the summer of 2012. This site is composed of a 15-meter-thick yellowish/gray silty mudstone. Vertebrate microfossils, such as turtle shell fragments, shed crocodilian and theropod dinosaur teeth are common, and the site also includes larger macrovertebrate remains such as sauropod caudal vertebrae and other large vertebrate bone fragments (Figure 3A, B). Fossil material is present in the upper six meters of the silty mudstone. The Johnsonville unit is laterally extensive over ~10 meters and overlies a one-meter tan sandstone. Based on interpretations of similar lithologies in the Morrison Formation, the Johnsonville site is interpreted as an overbank deposit such as a wet floodplain or crevasse splay with a relatively high water table (Bilbey, 1999). While the JONS site is a microvertebrate locality and not a large bonebed like the CLDQ, it serves as a robust comparison to the CLDQ as a depositionally distinct site for taphofacies comparisons.

MATERIALS AND METHODS

Collection localities for this study are managed by the Bureau of Land Management (BLM) and all fossil material was collected under survey and excavation permits. Exact coordinates for these collection sites are on file with the BLM and the Natural History Museum of Utah, where all collected materials are maintained. All materials were collected under BLM Permit #UT12-003E.

Stratigraphy and Geochemistry - Utilizing a Jacob's staff and Brunton compass-clinometer, a bed-by-bed stratigraphic column was generated for the Brushy Basin and Salt Wash Members of the Morrison Formation from its lower contact with the Middle Jurassic

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Summerville Formation to the uppermost horizon of the Morrison Formation preserved at the upper limit of the butte above and to the west of the CLDQ (Figure 1A, B). Beds were identified in the field on the basis of color and lithological change. Some beds were divided into subunits based on changes in grain size and surface weathering. A hand sample of rock from beneath the upper weathered horizon was collected from the center of each bed or subunit. Hand samples were also collected from the center of the fossiliferous mudstone horizon of the North and South Butler Buildings at the CLDQ.

As a comparison to CLDQ, three samples of siltstone and one bone fragment from the Mygatt-Moore Quarry (MMQ) were included in this analysis. The MMQ is located approximately 2.5 km east of the Colorado-Utah state line in western Mesa County, Colorado and stratigraphically positioned in the middle to lower Brushy Basin member (Trujillo et al., 2014). MMQ is composed of a 1 meter-thick smectitic mudstone with interbedded silt-sized grains and clay balls. The mudstone is rich in carbonized plant and wood fragments (Trujillo et al., 2014). Since 1981, the quarry has yielded nearly 2,400 bones of at least six different taxa of Jurassic dinosaurs, with sauropods, such as *Apatosaurus*, *Camarasaurus*, and diplodocines (cf. *Diplodocus* or *Barosaurus*) which constitute 50% of the total assemblage, and 30% represented by theropods such as *Allosaurus* and *Ceratosaurus* (Foster, 2007). Due to the similar lithology and rich abundance of dinosaur remains of the MMQ, samples of sediment and bone fragments were included in this analysis for comparisons with CLDQ.

All rock samples were hand ground via mortar and pestle for XRD and XRF analysis. Bone chips from the CLDQ and MMQ were also analyzed via XRF and petrographic thin section, however they were not ground prior to analysis. XRD was carried out at the University of Wisconsin - Oshkosh Department of Geology utilizing a Rigaku D/Max-2000T X-ray diffractometer operating at 40 kV and 40 mA and utilizing a Cu Ka target to determine sample mineralogy. XRD data was subsequently analyzed using the Jade (v9.3; Materials Data, Inc., Livermore, CA) software package. XRF for all stratigraphic samples and CLDQ samples was conducted at Beloit College in Beloit, Wisconsin with a Niton XL3t GOLDD+ handheld XRF analyzer in Test All Geo mode. This mode analyzes the full suite of elements which the unit is capable of detecting. XRF of material from MMQ was conducted at Indiana University of Pennsylvania using an Innov X Delta Professional handheld XRF analyzer in soil mode. Similarly, this mode of operation analyzes the full suite of elements the unit is capable of detecting.

Intramatrix Bone Fragments - To better understand the various taphonomic processes that influence the deposition, preservation, and recovery of IBFs, it was important to choose sites for these experiments from different facies that represent typical Brushy Basin member lithologies. The two sites in this analysis were chosen based on their lithological differences (e.g. Wilson, 2008; Peterson et al., 2011) and the presence of IBFs. The data collected at each site included local thickness of the sedimentary subunits and their lateral extent where possible.

In order to quantify intramatrix bone fragment abundance, approximately 60 kg of bulk sediment was quarried from each of two localities; the CLDQ, and UWO-12-001 (Johnsonville). Samples were taken from below the weathering zone to avoid biases caused by ongoing erosion of fossil samples and disaggregated under controlled laboratory conditions (following Peterson et al., 2011).

All collected fossil fragments were obtained by a method of submerged screen washing with gentle air agitation similar to previously utilized methods (e.g. McKenna, 1962; Ward, 1981; Peterson et al, 2011). Two mesh baskets 23 x 33 cm (23 cm deep) were constructed of 1 cm hardware cloth and internally lined with 1.0 mm plastic window screen. The mesh baskets were placed in 23 x 43 cm (28 cm deep) plastic basins. Below the mesh baskets, 1 meter of flexible perforated airline tubing was coiled at the bottom of the basins and connected to a double-output aquarium air pump (3.5 watt, 1200cc air per minute output) placed outside of the basins. The resulting system produced gentle air-powered agitation in the basins to promote sediment disaggregation (Figure 4). Unweathered sediment samples were physically broken down to roughly 5 cm pieces, placed in the agitation basins, and submerged until disaggregation was complete, which took roughly two days. Following disaggregation, baskets were removed from the basins and left to air dry.

All fossil bone fragments were collected regardless of taxonomic identification. Subsequently, bone fragments were measured along three perpendicular axes to determine volume and hydraulic equivalence (Behrensmeyer, 1975). The equation for hydraulic equivalence is:

$$dq = (pb - 1)*db/1.65$$

$$db = \text{Nominal diameter of bone} = \sqrt[3]{(1.91 \times \text{Volume})}$$

$$pb = \text{Bone density}$$

Fragment were also classified by degree of abrasion as a signal of relative transport. Abrasion was measured on a 0-3 scale (Wilson, 2008), with 0 representing no apparent abrasion, and 3 representing nearly complete rounding of the specimen (Figure 5).

Chi-Square Tests were used to determine whether a statistically significant relationship existed between two categorical variables. A nominal level of significance (type I error rate) of $\alpha = 0.05$ was used in all tests, i.e., an observed significance level (p-value) of <0.05 was required in all tests to reject the null hypothesis that the variables were not related. Specifically, Chi-Square tests were used to determine if the degree of abrasion of the intramatrix bone fragments significantly differed between the two sites.

RESULTS

Geochemistry - XRD data are presented on Table 1A, B. Excluding the CLDQ, the Morrison Formation is overwhelmingly composed of quartz and calcite. Two strata also contained dolomite and ankerite ($CaMg_{0.27}Fe_{0.63}(CO_3)_2$) (Table 1A: Units 1b and 25). The quarry itself is composed primarily of quartz and calcite, with smaller amounts of barite, chalcopyrite, fluorapatite, covellite (CuS) and litharge (PbO). XRD analysis of sediments from the JONS site detected only quartz.

The total XRF data are presented on Table S1. Comparisons of the concentrations of selected metals in CLDQ bone and sediment, MMQ bone and sediment, as well as regional Morrison Formation sediment is presented on Figure 6. The XRF unit utilized to analyze MMQ samples does not detect Si. Si concentrations, available for all non-MMQ samples, ranged between 24,646.01 ± 581.59 ppm to 522,405.2 ± 4166.98 ppm throughout the sampled units of the Salt Wash and Brushy Basin members in the vicinity of the CLDQ, with samples from the quarry having values of 24,646.01 ± 581.59 ppm and 30,643.28 ± 1,309.51 ppm. The 'balance' measured by the XRF, i.e., the summed concentration of all elements lighter than Mg (i.e. those not detectable by the unit), and occasional instrument error due to air space in the ground samples, ranged from 282,284.22 ± 4,650.26 ppm to 712,203.63 ± 2,258.34 ppm. The quarry samples yielded balance values of 412,387.59 ± 4,891.71 ppm and 436,363.78 ± 3,107.65 ppm. Sediment samples from CLDQ had higher values than those of the rest of the stratigraphic column for Mo, Sr, As, U, Cu, Ni, Nb, P, and S. The CLDQ sediment had higher concentrations than most other samples from the stratigraphic column for Pb, Mn and Cr. The quarry sediment fell within the range the rest of the stratigraphic column for Zr, Rb, Th, Zn, W, Si, V, Ti, Ca, K, Al, Cl, Sc, Mg and Fe. Any elements not specifically listed above were either not present or undetectable via the XRF gun in all analyzed samples. Sediments from Mygatt-Moore Quarry contained more Cu, Ni and Bi than the stratigraphic column samples. MMQ sediment contained more Rb, Pb, As, Zn, Cl and V than most stratigraphic samples. Finally, MMQ samples were within the range of concentrations of Mo, Zr, Fe, Mn, Ti, Ca, K, Cl, Sr, W, Cr, and P seen within the stratigraphic samples. In contrast to the CLDQ and MMQ, the sediments of JONS resemble those of local Morrison Formation outcrops. None of the metals detected via XRF at JONS were found at elevated levels compared to all other samples analyzed, including those of the CLDQ and MMQ.

CLDQ bone revealed a similar pattern of heavy metal enrichment as CLDQ sediments (Figure 6). Exceptions include As and Cr, for which the bone samples have similar concentrations to Morrison Formation sediment as opposed to CLDQ sediment, i.e. CLDQ sediments contain more abundant As and Cr than both Morrison Formation sediment and CLDQ bone. CLDQ bone is more enriched in Ni, Cu and W with respect to Morrison sediment than CLDQ sediment. For all other detected elements, the bone samples and sediment samples from the CLDQ show similar elemental concentrations. Thin section analysis of bone fragments encased in quarry matrix from CLDQ indicate permineralization in the form of phosphate crystallites filling void spaces within the bone fragments (Figure 7).

In regards to MMQ, the bone sample generally had a similar heavy metal content to that of the sediment samples. Exceptions include Sr, W, Cr, V and P which were in higher

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concentrations in the bone than the sediments and K which was in higher concentration in the sediment than in the bone.

Intramatrix Bone Fragments - The IBFs collected from CLDQ and JONS were compared according to their physical characteristics and taphonomic differences to investigate whether these differences were statistically significant (raw data available in Tables S2, S3). Analyses suggest different patterns of abrasion variability between the two localities, and these patterns were found to be significantly different ($p < 0.001$; Table 2A-D, Figure 8).

The CLDQ IBFs display a wide range of degrees of abrasion; recovered fragments fall between 15-30% of each abrasion category (Figure 8). However, the JONS IBFs possess higher degrees of abrasion; JONS bone fragments show a strong trend towards more mature levels of abrasion with only 5% of IBFs scoring as angular.

Following Behrensmeyer (1975), hydraulic equivalents (E_{HY}) were calculated based on specimen volume, relative density, and size for each assemblage of bone fragments. Hydraulic equivalences and relative densities were compared between assemblages (Table 2E). Although shape is a significant factor for settling velocities, this feature has been omitted simply to gain a general view of hydraulic equivalences to a quartz sphere (Behrensmeyer, 1975; Peterson et al., 2011). Results of hydraulic equivalence analysis indicate that bone fragments obtained from both localities have similar hydraulic equivalences (fine sand) despite differences in lithology.

DISCUSSION

Geochemistry - X-ray diffraction data largely agree with those presented by Bilbey (1999), in that the Brushy Basin and Salt Wash Members of the Morrison Formation are primarily composed of quartz and calcite. The mineralogy of the CLDQ itself is distinguished from the surrounding Brushy Basin and nearby Salt Wash Members, as well as the mudstones at the same stratigraphic level as the quarry, by the presence of metal oxides (primarily litharge) and sulfides (chalcopyrite, and covellite) as well as barite. This suite of minerals implies that the environment represented by the quarry was very likely reducing (Eby, 2004). High levels of decaying organic matter, due at least in part to the abundance of decaying dinosaurs utilizing the available dissolved oxygen, would contribute to a reducing environment, especially given the ephemeral nature of the CLDQ pond.

The presence of calcite/barite nodules on the bones further supports the hypothesis that the dinosaur remains were decaying in the CLDQ pond. Ligament and cartilage would be among the last of the organic matter to decay, and the highest concentration of dissolved organic matter would occur there (Madsen, 1976; Bilbey, 1999). The position of the calcite/barite nodules, most commonly found where ligaments and cartilage attached to bone (Madsen, 1976), supports the hypothesis that they formed during decay. Furthermore, in subaqueous settings barite formation is associated with supersaturation of chemical microenvironments surrounding decaying organic matter (Paytan and Griffith, 2007).

Despite suggestions of an abundance of available organic matter at the CLDQ, evidence of scavenging is conspicuously rare, as previous authors have noted (e.g. Berner 1968; Bilbey 1998; Gates 2005). However, hypereutrophic conditions resulting from decaying dinosaur carcasses, as evidenced by the presence and position of the calcite/barite nodules, is one possible explanation of the lack of scavengers.

X-ray fluorescence and x-ray diffraction data show the quarry as enriched in heavy metals, e.g. Mo, As, U, Pb, relative to the rest of the local outcropping of the Morrison Formation. Some of these metals, Sr, Zn, Na and Mg, are known to easily replace Ca in biogenic

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apatite during diagenesis (Trueman and Tuross, 2002; Goodwin et al., 2007). Furthermore, Morrison formation bone is known to be enriched in U as a result of diagenesis, therefore elevated levels of U detected in CLDQ sediment and bone is not anomalous (Hubert et al., 1996). However, Gillette (1994) notes that U enrichment in dinosaur bone is most common in bones buried within the local water table. High U concentrations seen here help to support the hypothesis that the bones of CLDQ were deposited into a shallow pond which was in hydrological contact with groundwater during deposition.

Unfortunately, while studies of the geochemical compositions of fossil remains from bone beds are common (e.g. Trueman and Benton 1997; Trueman and Tuross 2002; Rogers et al., 2010), similar studies focusing on the sediments from bone beds are lacking in the literature. One possible origin for the heavy metals at CLDQ is accumulation through diagenetic processes. The high abundance of buried bone undergoing diagenetic dissolution may be responsible for the elevated levels of As; elevated levels of As have been noted in *Dilophosaurus* bones from the lower Jurassic Kayenta Formation (Goodwin et al., 2007). It is worth noting, however, that while Goodwin et al (2007) found higher concentrations of As in bone than in the surrounding sediment (200-500 ppm in bone, 10-20 ppm in sediment), the opposite was seen at CLDQ (18-28 ppm in bone, 50 ppm in sediment). Two of the three sediment samples from MMQ contained more As than the bone from MMQ, following the pattern observed by Goodwin et al (2007). Strong negative pairwise elemental correlations were observed for As and Fe in the CLDQ sediment samples, similar to what has been observed in material from the Kayenta Formation (Goodwin et al., 2007). This may reflect As desorption from iron oxides, given that [Fe] is low at the CLDQ and higher elsewhere in the Morrison Formation; the negative correlation between Fe and As at the CLDQ may be the result of desorption and absorption reactions during the dissolution and weathering of the large accumulation of bones. Bone dissolution would produce a high concentration of P, as observed via XRF, which can promote desorption of As (Goodwin et al, 2007). It is possible that similar processes resulted in the high concentrations of other metals in the sediments of CLDQ relative to concentrations seen in the rest of the Morrison Formation analyzed here, however these elements were not considered by Goodwin et al (2007). Elevated concentrations of metals seen in MMQ support the conclusion that diagenetic processes contributed to the heavy metal signature observed at CLDQ.

A second possibility for the origin of the elevated heavy metals at the CLDQ is bioaccumulation. Studies of modern grave soils suggest one potential source of heavy metals detected in bone and sediment of the CLDQ which are not necessarily explained by apatite diagenesis, i.e. Ni, Cu, Mo, As, Pb and W: the dinosaur carcasses themselves. Modern grave soils have long been seen as potential ecological hazards and sources of organic and inorganic pollutants (Aruomero and Afolabi 2014). While many studies of necrosols focus on burials with caskets which are not relevant to a Mesozoic bone bed (e.g. Üçisik and Rushbrook 1998), some studies have focused on geochemistry of mass graves and primitive burials lacking caskets and burial goods (Kemerich et al. 2012; Amuno 2013). Kemerich et al. (2012) utilized XRF to find elevated levels of Ba, Cu, Cr and Zn in the soil and groundwater associated with a mass grave in Brazil. Amuno (2013) found elevated levels of As, Cu, Cr, Pb and Zn in necrosols within and near to a mass grave site in Rwanda. While full soil development is not evident at the CLDQ, the deposit is an analogous accumulation of quickly buried vertebrate remains in fine grained sediment.

While it is highly unlikely that high concentrations of As, Cu, and Pb seen in CLDQ sediments indicate these metals occurred at toxic concentrations in the bodies of the dinosaurs which accumulated there (Goodwin et al, 2007), large numbers of carnivores decaying could lead to the accumulation of these metals in the CLDQ pond. Carnivores are especially likely to contribute heavy metals via trophic focusing of toxins as they are high level predators (e.g. Vijver et al., 2004; Gall et al., 2015). During diagenesis these metals would then be held within the sediments and bones of the deposit (Goodwin et al., 2007). While more extensive work is required to interpret the geochemical signal of the bones recovered from the CLDQ, the similarity of CLDQ sediment and preliminary bone geochemistry data, taken with the strong contrast between geochemistry of sediments from the CLDQ and from surrounding Morrison sediments, implies a unique setting for the CLDQ assemblage.

The MMQ samples provide a significant comparison when considering bioaccumulation as a source of the metals observed at the CLDQ. Some elements found in CLDQ sediments and bone, specifically W, Cu, Ni and Cl, are found in higher concentrations in CLDQ materials than MMQ materials. However, Zr, Rb, V and K are found in higher concentrations at MMQ than at CLDQ. These differences could have arisen due to diagenetic differences, however bioaccumulation and taphonomic differences may also explain the disparity in heavy metal content between the CLDQ and MMQ. Further experimentation and sediment collection will be required to determine the extent to which bioaccumulation and dinosaur decay contributed to the metals present in CLDQ sediment and bone.

One further possibility for the elevated presence of heavy metals found at the CLDQ is the dissolution of volcanic ash, which may have concentrated in the pond as it washed in during flood periods. Hubert et al (1996) analyzed the chemical composition of “a large data base for silicic obsidians that proxies for the unknown composition of the altered silicic ashes in the Brushy Basin Member.” The compositional data presented by Hubert et al (1996) contrast

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significantly with the sediments of the CLDQ (Table 3). Given that the CLDQ sediment geochemistry does not match well with that of the proxy obsidians (Hubert et al., 1996), the metals present in the CLDQ are not likely sourced from local volcanic ashes emplaced during bone burial.

Both XRD and XRF analyses, taken together, support the hypothesis that the CLDQ represents an ephemeral pond that became hypereutrophic as dinosaur carcasses decayed. The source the calcite/barite nodules on the bones and sulfide minerals present in the quarry but not found in other Morrison sediments, is likely the decay and dissolution of the dinosaurs themselves. Dinosaur decay could potentially have contributed to the heavy metal signature of CLDQ sediments as well.

Hypereutrophy can explain the near total lack of microvertebrate remains, e.g. turtle, fish and crocodilian fossils typically associated with pond deposits, and near total lack of scavenging marks on CLDQ dinosaur bones. The typical freshwater fauna which would create microvertebrate remains and also scavenge on the carcasses, e.g. fish, turtles and crocodilians, would not have been able to tolerate the water column. Furthermore, as the carcasses rotted the formation of calcareous soaps would have inhibited scavenging before leading to the formation of calcite/barite nodules on bones. While both diagenetic processes and hypereutrophy are possible sources of the heavy metals found at the CLDQ, given the evidence in support of hypereutrophy of the CLDQ pond, diagenetic processes are not likely the primary cause of elevated concentrations for all of the metals seen here.

Geochemical analysis of the JONS site strengthen the interpretation of the CLDQ as a unique bone-bearing site. Typical indicators of eutrophy, e.g. elevated levels of metals, sulfide minerals and calcite/barite nodules, are not present at JONS. Furthermore, a typical freshwater microvertebrate assemblage of turtle and crocodilian remains are found at JONS. This data helps to support the hypothesis that diagenesis is not the sole contributor to heavy metals at the CLDQ. While JONS also contains large vertebrate bones, the heavy metal signatures seen at the CLDQ are absent here. Metal concentrations would not be expected to be as high at JONS as at the CLDQ, given the disparity in number of fossils found at each site. However, if diagenetic processes were the dominant source of heavy metals in the sediments of the CLDQ, some elevation in these metals would be expected at JONS.

Finally, analysis of MMQ sediment and bone provides meaningful contrast to that found at CLDQ and again highlights the uniqueness of CLDQ. The bones of MMQ show extensive evidence of biostratinomic alteration, implying the presence of scavengers. Aquatic vertebrate remains are rare at MMQ, as at CLDQ, owing to the ephemeral nature of the pond (Trujillo et al 2014), however they are more numerous at MMQ. Furthermore, the sediments of MMQ contain abundant carbonized plant fragments where CLDQ contains none. This is potentially due to differences in local vegetation during the time of deposition, but could also be a taphonomic effect. Bones recovered from MMQ are not associated with calcite/barite nodules. Rates of organic matter decay at MMQ must not have been high enough to form the calcareous soaps necessary for calcite formation. Taken together, these data imply that the MMQ pond was not hypereutrophic, where the CLDQ pond was. The differences in preservation of bone and plant material, the respective presence and absence of calcite/barite nodules, as well as differences in biostratinomy and microvertebrate fossil abundance between the two sites are best explained by variations in water chemistry: periodic hypereutrophic conditions at CLDQ, and an oligotrophic pond at MMQ.

Intramatrix Bone Fragments - Previous studies have discussed distinct taphonomic characteristics among microvertebrate fossils from localities with dissimilar facies (e.g., Behrensmeyer, 1975; Brinkman, 1990; Eberth, 1990; Blob and Fiorillo, 1996; Wilson, 2008; Peterson et al, 2011). Peterson et al. (2011) reported on taphonomic variability of microvertebrate assemblages collected from crevasse-splay and flood basin deposits from the Late Cretaceous Hell Creek Formation of Carter County, Montana. The results suggested a strong correlation between taphonomic processes such as transport, sorting, and weathering, sedimentary facies, and physical characteristics of recovered fossils (Peterson et al., 2011). A similar trend is observed in the collected intramatrix bone fragments from the CLDQ and the JONS site in the upper Morrison Formation. While both localities possess abundant bone fragments that share a suite of physical characteristics (i.e. sizes < 0.5mm and comparable relative densities), the variation in abrasion between the two sites is significant.

The average hydraulic equivalence for both localities corresponded with fine sand (Table 2E). This similarity may be due to the specific measurement method utilized; minor differences in volume between angular and non-angular fragments may have been missed by standard angular measurements. However, given the small sizes and homogeneous densities of the fragments, the hydraulic equivalences of the assemblages are not expected to vary considerably with alternative measuring methods.

The matrices of both localities are dominated by sediments much finer than the respective hydraulic equivalence of bone fragments recovered from each site; the CLDQ is composed of a calcareous mudstone whereas the JONS site is dominated by a silty mudstone, while the bone fragments from both sites are hydraulically equivalent to fine sand. This particular disparity between the hydraulic equivalence of bone fragments and the dominant lithologies suggest that the intramatrix bone fragments at both localities are a mixture of locally-crushed, autochthonous or parautochthonous fragments from locally-crushed larger bones and washed-in allochthonous fragments, all of which accumulated on the flood basin or in a crevasse-splay (Behrensmeyer, 1975; Wilson, 2008; Peterson et al., 2011).

The significant variability in the extent of abrasion between the sites is explained by the highly dynamic depositional conditions of the two localities. The JONS assemblage includes IBFs that are more rounded than the fragments found in the CLDQ assemblage. This suggests that the Johnsonville locality was subjected to relatively higher and more consistent energy. While the sedimentological evidence does not indicate an in-channel depositional subsystem, the silty mudstone lithology and the presence of abundant freshwater microvertebrate fossils (i.e. crocodilian, turtle, and fish) support the interpretation of wet floodplain or crevasse-splay with a generally higher water table (Bilbey, 1998).

Conversely, the CLDQ assemblage exhibits considerably greater diversity in the degree of abrasion with a mixture of angular and rounded fragments. The matrix at the CLDQ is a fine calcareous mudstone, representing a normally low-energy system that likely was ephemeral. However, the fragments possess a hydraulic equivalence of fine sand, suggesting that some of the fragments are autochthonous or parautochthonous remains of crushed local bones while others allochthonous and washed in from upstream (sensu Fernandez-Jalvo and Andrews, 2003). The physical characteristics of the bone fragments of CLDQ suggest variable taphonomic histories among the fragments; angular fragments suggest a pulverization followed immediately by burial while rounded fragments suggest prolonged exposure and local transport (Fernandez-Jalvo and Andrews, 2003).

Considering the majority of macrovertebrate remains at CLDQ had an approximate subaerial exposure time of two years or less (Gates, 2005), with rapid burial or submersion in water halting the progression of weathering and abrasion (Gifford, 1985), these results indicate that some fragments were exposed longer than others. Similarly, thin section analyses of IBFs within the CLDQ matrix show the presence of phosphate crystallites within the void spaces of bone fragments (Figure 7). The morphology of the crystallites is globular, indicative of microbially-mediated phosphate infilling of bone pore space from the dissolution and re-precipitation of organic phosphates (i.e. bone) (Hirschler et al., 1990), implying that the bone fragments were pedogenically reworked following initial permineralization (Jennings and Hasiotis, 2006). This suggests that the total CLDQ assemblage, both intramatrix fragments and the well-documented macrovertebrate fauna, formed from multiple depositional events - perhaps seasonal - and not from a single catastrophic episode (sensu Gates, 2005). If the CLDQ had formed from a single event, multiple abrasion and weathering signatures on bone fragments would not be expected. This interpretation is further supported by the apparent lack of abundant identifiable freshwater microvertebrate remains; the lack of permanent water would reduce the abundance of freshwater taxa such as fish, turtles, and crocodilians. Meanwhile, seasonal fluctuations in the local water table related to the monsoonal climate patterns of the late Jurassic (e.g. Hallam, 1993; Rees et al., 2000; Sellwood and Valdes, 2008) would have rejuvenated mobilization of fragments that otherwise remained at the surface.

Paleoecological Inferences - While geochemical and sedimentological data can assist in reconstructing the depositional environment and taphonomic history of the CLDQ, the question remains - Why is there a dominating abundance of *Allosaurus* remains at the Cleveland-Lloyd Dinosaur Quarry?

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Most multi-taxa bone beds in the Morrison formation are dominated by large herbivorous dinosaurs (Dodson et al., 1980), though many Morrison bone beds also include remains of theropods, commonly *Allosaurus* (Dodsen et al., 1980). However, predator-dominant localities are known from other units in the Mesozoic system, such as the Upper Chinle *Coelophysis* quarry from Ghost Ranch, New Mexico (Schwartz and Gillette, 1994) and the Upper Horseshoe Canyon *Albertosaurus* bonebed from southern Alberta (Eberth and Currie, 2010). The nature of these accumulations are both interpreted to be the result seasonally-influenced events; a drought-induced death assemblage of *Coelophysis* carcasses that were transported post-mortem by subsequent fluvial current (Schwartz and Gillette, 1994), and a storm-induced flooding event either directly or indirectly resulting in the death of a population of *Albertosaurus* (Eberth and Currie, 2010). Similarly, the CLDQ taphonomic data presented here also supports an interpretation of a post-mortem attritional accumulation due to season fluctuations.

Previously studies on Morrison climate and ecosystems suggest strong seasonality with periods of aridity during weak monsoons to sub-humid conditions during stronger monsoons similar to climates seen in modern savannahs (Turner and Peterson, 2004; Parrish et al., 2004; Tanner et al., 2014). While such climate interpretations generally agree with taphonomic reconstructions of various Morrison bone beds, including the CLDQ, they can also offer insight into paleoecological interpretations that may have contributed to the quarry assemblage.

Fossil accumulations of multiple individuals of a single species are not necessarily indicative of complex familial or social behaviors. In modern savannahs, seasonal aridity brings grazing animals that are typically solitary together into larger groups near evaporating bodies of water (Western, 1975). Extant archosaurs, such as the Common Ostrich (*Struthio camelus*) and the Spectacled Caiman (*Caiman crocodilus crocodilus*) congregate in increased numbers during extreme seasonal changes, either for breeding or following food sources, leading to increased mortality during times of increased aridity or drought (e.g. Staton and Dixon, 1975; Knight, 1995). Furthermore, the reproductive cycles of many of these animals are tied to environmental and seasonal fluctuations, where fecundity, ovulation, and birth occur near an oncoming wet season (Hanks, 1979).

Breeding or nesting sites are relatively rare in the Morrison; only nine such localities have been described to date (Bray and Hirsch, 1998). While there is no direct evidence of the CLDQ being a breeding site for *Allosaurus*, a single fossilized egg was collected from the quarry (Hirsch et al., 1989), and has been attributed to *Allosaurus* due to the high frequency of the taxon in the quarry (Madsen, 1991). However, the CLDQ egg possesses an abnormally thick shell layer (Hirsch et al., 1989), which is frequently caused by environmental or seasonal stress (Mills et al., 1987; Hirsch, 2001). Though a single egg does not directly suggest that the CLDQ was a breeding site for *Allosaurus;* eggs could potentially have survived short distance transport in a fluvial system (e.g. Jackson et al 2013).

Given the extreme seasonal variability in the late Jurassic and the evidence described here for an attritional accumulation for the CLDQ, *Allosaurus* may have been congregating seasonally in the vicinity for a number of reasons, such as breeding, food, or water. With increased aridity, mortality rates may have been higher, producing carcasses that would mobilize during subsequent wet seasons similar to what is observed with extant archosaur carcasses during strong seasonality (Weigelt, 1989; Knight, 1995; Staton and Dixon, 1975). Further geochemical and isotopic analysis of the *Allosaurus* remains recovered from CLDQ will help to evaluate whether the *Allosaurus* were congregating before death and deposition or, alternatively, were transported in from across a landscape post-mortem.

CONCLUSIONS

The Cleveland-Lloyd Dinosaur Quarry is a potentially significant source of data for understanding Jurassic dinosaur paleoecology. However, interpretation is constrained by the taphonomic and environmental framework the quarry represents. Two new lines of evidence, sediment geochemistry and intramatrix bone fragment abrasion and weathering patterns, support previous conclusions that the CLDQ represents and ephemeral, seasonally dry pond. Furthermore, both data sets support the interpretation that the CLDQ was formed from multiple depositional events. In addition, each data set can add to the current understanding of CLDQ taphonomy.

New geochemical data show the quarry is enriched in heavy metals and sulfide minerals in stark contrast to the surrounding Morrison Formation strata, including mudstones at the same stratigraphic level surrounding the quarry deposit. While diagenetic processes certainly contributed to the heavy metal composition of CLDQ materials, the presence of sulfides and calcite/barite nodules in the CLDQ sediments suggest a hypereutrophic environment resulting from the decay of many dinosaurs in a small depression. Significant numbers of rotting dinosaurs in a body of standing water would potentially have contributed to the heavy metals composition of the water column via bioaccumulation. High rates of organic matter decay would have led to hypoxia or anoxia and the subsequent formation of sulfide minerals and the calcareous soaps required to form calcite nodules.

Finally, hypereutrophy can help explain the near total lack of gnawing and other biostratinomic effects seen in a typical freshwater ecosystem. While these new geochemical data do not inform where the dinosaurs found at the CLDQ died, hypereutrophy related to dinosaur carcass decay is one possible explanation for the lack of typical freshwater faunal remains and feeding traces at the CLDQ. Initial geochemical data presented here suggest this taphonomic framework, however a more extensive analysis of bone geochemistry is needed to support this hypothesis. Analysis of sediment and bone from the Mygatt-Moore Quarry support these conclusions by providing strong contrast. While heavy metals are present in MMQ, as expected from bone bed diagenesis, the other geochemical indicators of hypereutrophy are not present. The unique preservation of bone found at CLDQ is a result of chemical conditions not present in the more common depositional setting represented by MMQ.

Furthermore, quantitative and qualitative assessment of intramatrix bone fragments at the CLDQ and the new Johnsonville site indicate subtle but important differences in the depositional systems that produced the respective assemblages. While the bone fragments at both localities suggests a comparable hydraulic equivalence, the differences in the local lithologies and average abrasion profiles for bone fragments at each locality suggest considerable disparity in the genesis of each site. In particular, the taphonomic characteristics of the IBFs of the CLDQ assemblage, coupled with the quarry lithology, support the interpretation that the quarry assemblage was produced by a series of separate depositional events punctuated by periodic aridity. The IBF data presented here contribute to former taphonomic assessments of the CLDQ by providing previously uninvestigated sedimentological and micro-taphonomic insight into the origins of the quarry assemblage. Unidentifiable fossil fragments are often overlooked. While small, the utilization of IBF data in conjunction with associated macro-taphonomic and sedimentologic data, has the potential to improve the resolution of complex and perplexing taphonomic questions.

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FIGURES

1. Regional stratigraphy of the CLDQ vicinity. A) Stratigraphic column of the Morrison Formation in the area around the Cleveland-Lloyd Dinosaur Quarry (CLDQ) and the Johnsonville (JONS) sites, shown in meters above the basal contact of the Salt Wash Member of the Morrison Formation with the upper Summerville Formation. Standard USGS symbols of rock units are used in the diagram. B) Map showing sites, stratigraphic section line, and regional stratigraphy in context of the San Rafael Swell.

2. Vertebrate fauna of the Cleveland-Lloyd Dinosaur Quarry, illustrating the 3:1 ratio of predators to prey and minimum number of individuals for each taxa, based on left femoral count. Modified from Gates, 2005.

3. Fossils of the Johnsonville site. A) Sauropod caudal vertebra; B) Shed theropod teeth (left), crocodilian vertebra (center), and turtle shell (right). Scale bar equals 5 cm.

4. Schematic diagram of the sediment processing tanks. Sediment was placed into the meshed boxes and submerged with gentle air agitation for approximately 48-72 hours.

5. Examples of fragment abrasion stages, based on Wilson, 2008. Stage 0 – angular fragments; Stage 1 – subangular fragments; Stage 2 – subrounded fragments; Stage 3 – rounded fragments. Scale bar equals 5mm.

6. X-ray Fluorescence results. The concentrations of selected metals detected in sediment and bone collected from the CLDQ are compared with those of sediments local Morrison Formation strata, labeled “Strat” and sediment and bone from MMQ. CLDQ sediments and bone stand out in contrast to most other elements, yet are similar to those found at MMQ. All values are given in ppm, and abbreviations are as follows: min - minimum; avg - average; max - maximum.

7. Intramatrix bone fragment in petrographic thin section. Arrows annotating the location of phosphate crystallites in porous cavities within the fragment. Scale bar equals 10 µm.

8. Distribution of abrasion stages of intramatrix bone fragments at the CLDQ (gray) and JONS (white) localities. Error bars represent standard error.

TABLES

1. XRD data. All minerals identified in every sample analyzed from the stratigraphic column are presented. A) XRD data from stratigraphic column; B) XRD data for CLDQ samples. CLDQ stands out given the presence of barite and sulfide minerals.

2. Taphonomic characteristics and comparisons of intramatrix bone fragments of the CLDQ and JONS sites. Characteristics include A) dominant lithology, B) depositional interpretation, C) percentages of 60kg matrix sample represented by fossil fragments, D)

abrasion stages (based on Wilson, 2008), and E) hydraulic equivalence calculation results.

3. Obsidian chemistry vs CLDQ chemistry. This table shows the contrasting geochemistry of metals detected in CLDQ sediments with that of obsidians which act as proxies for ashes emplaced locally during the Jurassic (Hubert et al., 1996). The contrasting elemental profiles suggest that volcanic ashes are not the source of metals detected at the CLDQ.

SUPPLEMENTARY DOCUMENT AND TABLES

Supplementary tables are posted on Figshare and can be accessed via: https://figshare.com/articles/Peterson_et_al_CLDQ_Taphonomy_Supplemental_Tables/4238906

1. Table S1: XRF data. The chemical composition of all samples analyzed via XRF is given in ppm. Missing values represent metals not detectable by the pXRF located at Indiana University of Pennsylvania

2. Table S2: CLDQ IBF Measurements and data.

3. Table S3: JONS IBF Measurements and data.

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Figure 1

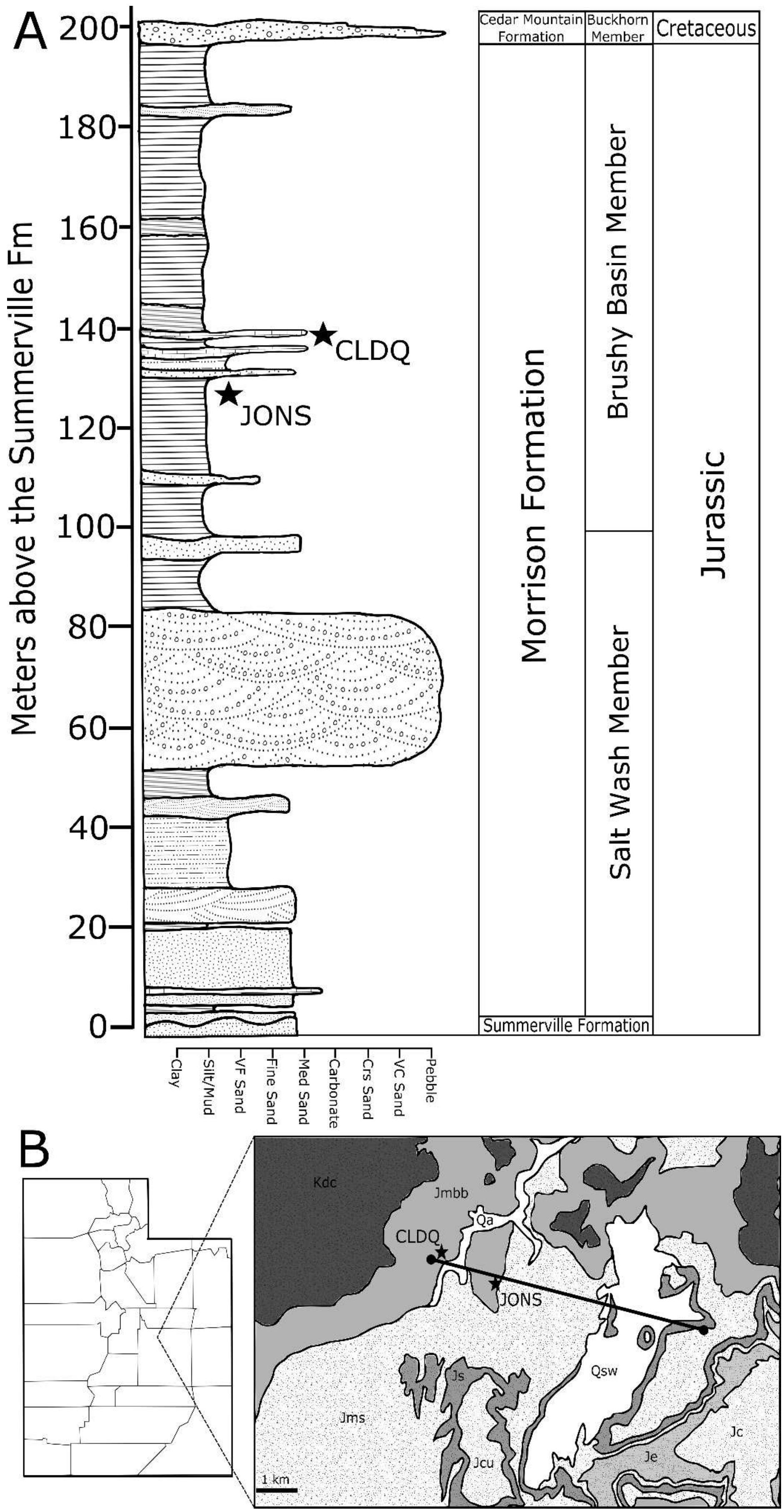
A
Meters above the Summerville Fm
200
180
160
140
120
100
80
60
40
20
0
CLDQ
JONS
Clay
Silt/Mud
VF Sand
Fine Sand
Med Sand
Carbonate
Crs Sand
VC Sand
Pebble
Cedar Mountain Formation
Buckhorn Member
Cretaceous
Morrison Formation
Brushy Basin Member
Salt Wash Member
Jurassic
Summerville Formation
B
Kdc
Jmbb
Qa
CLDQ
JONS
Qsw
Js
Jms
Jcu
Je
Jc
1 km

Figure 2

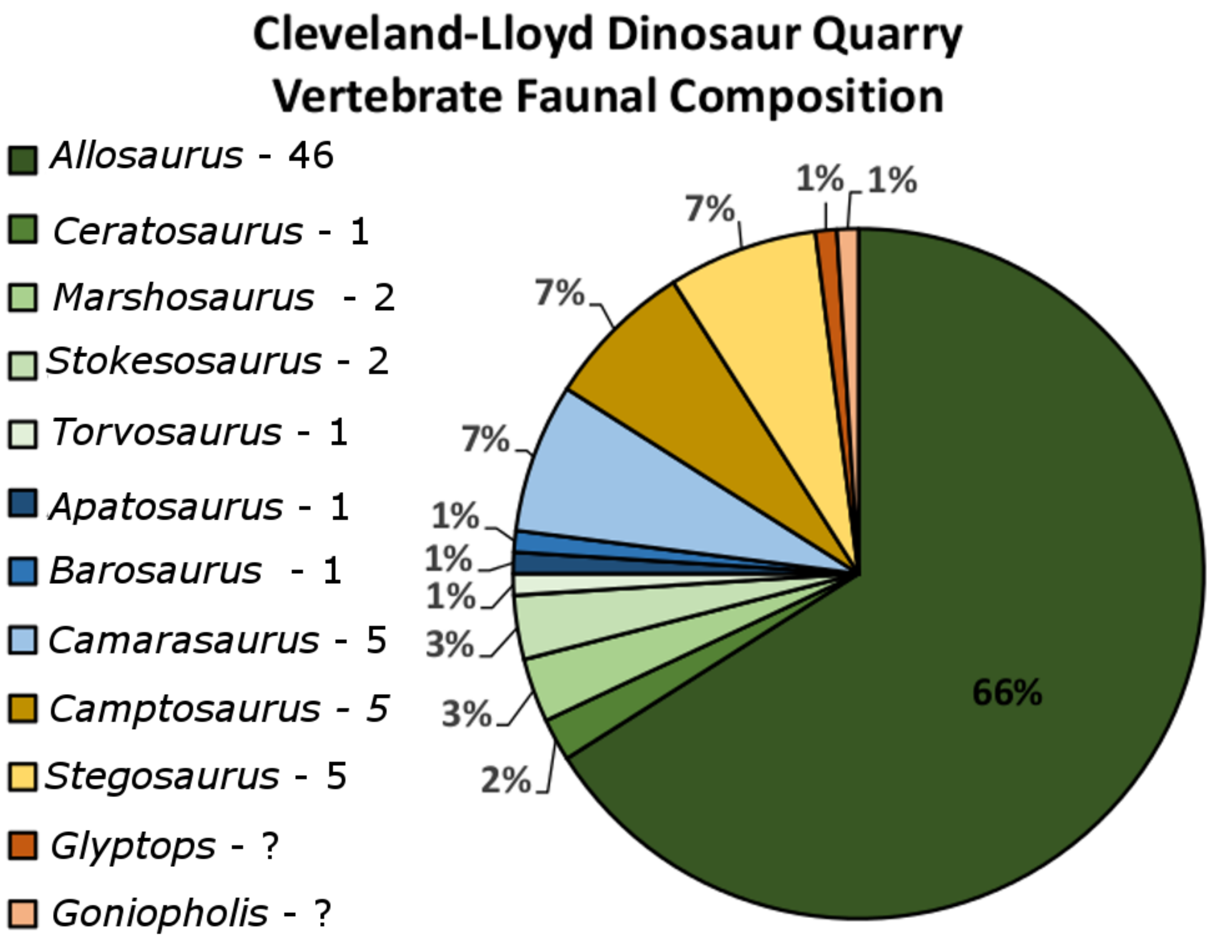
Cleveland-Lloyd Dinosaur Quarry
Vertebrate Faunal Composition
Allosaurus - 46
Ceratosaurus - 1
Marshosaurus - 2
Stokesosaurus - 2
Torvosaurus - 1
Apatosaurus - 1
Barosaurus - 1
Camarasaurus - 5
Camptosaurus - 5
Stegosaurus - 5
Glyptops - ?
Goniopholis - ?
66%
2%
3%
3%
1%
1%
1%
7%
7%
7%
1%
1%

Figure 3

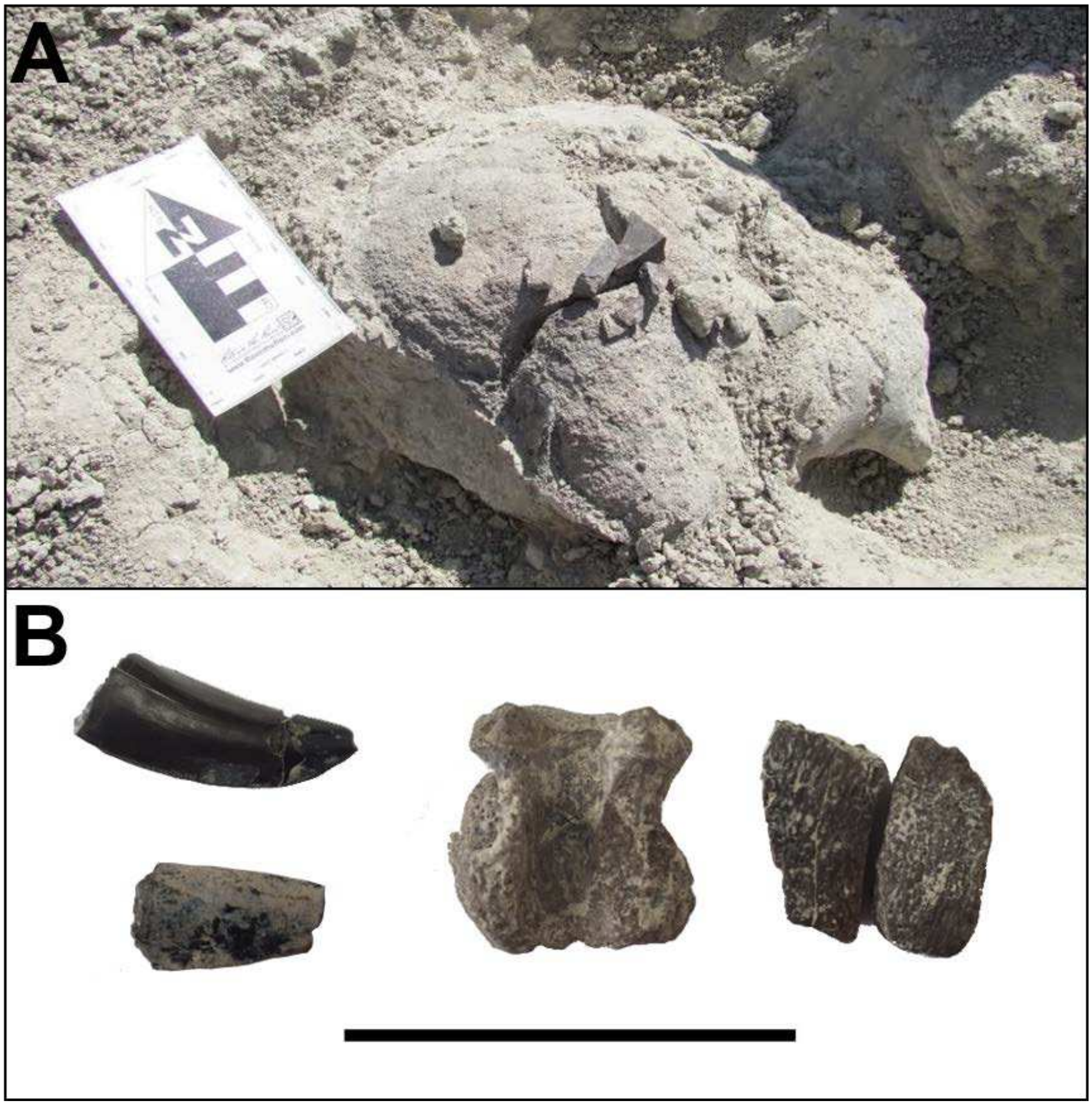

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Figure 4

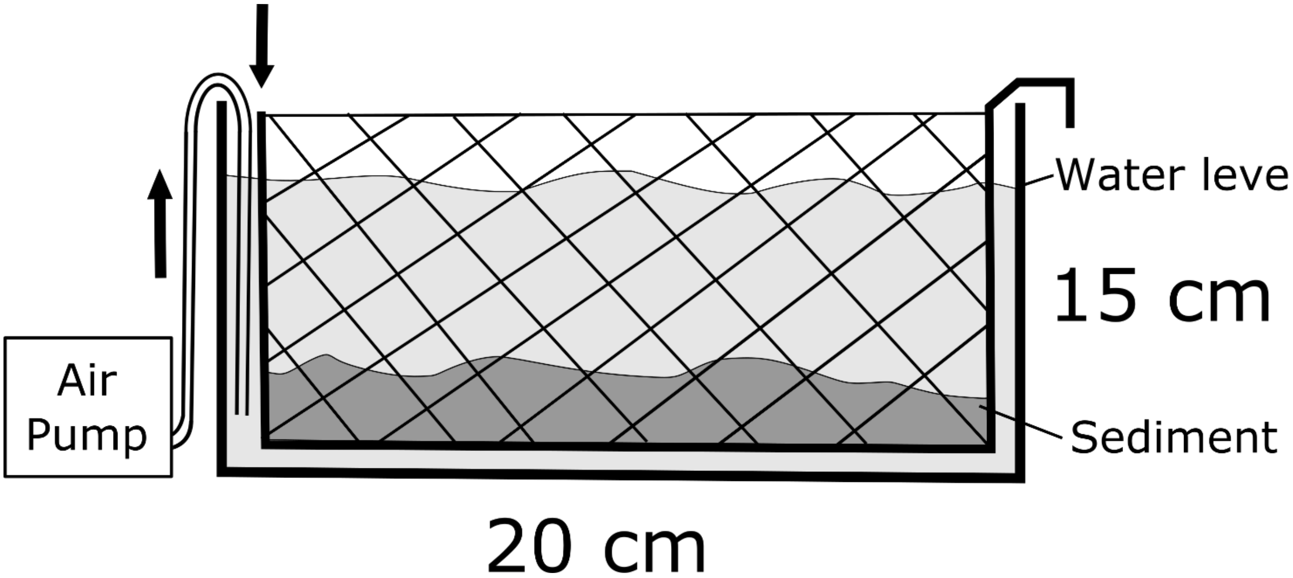

Figure 5

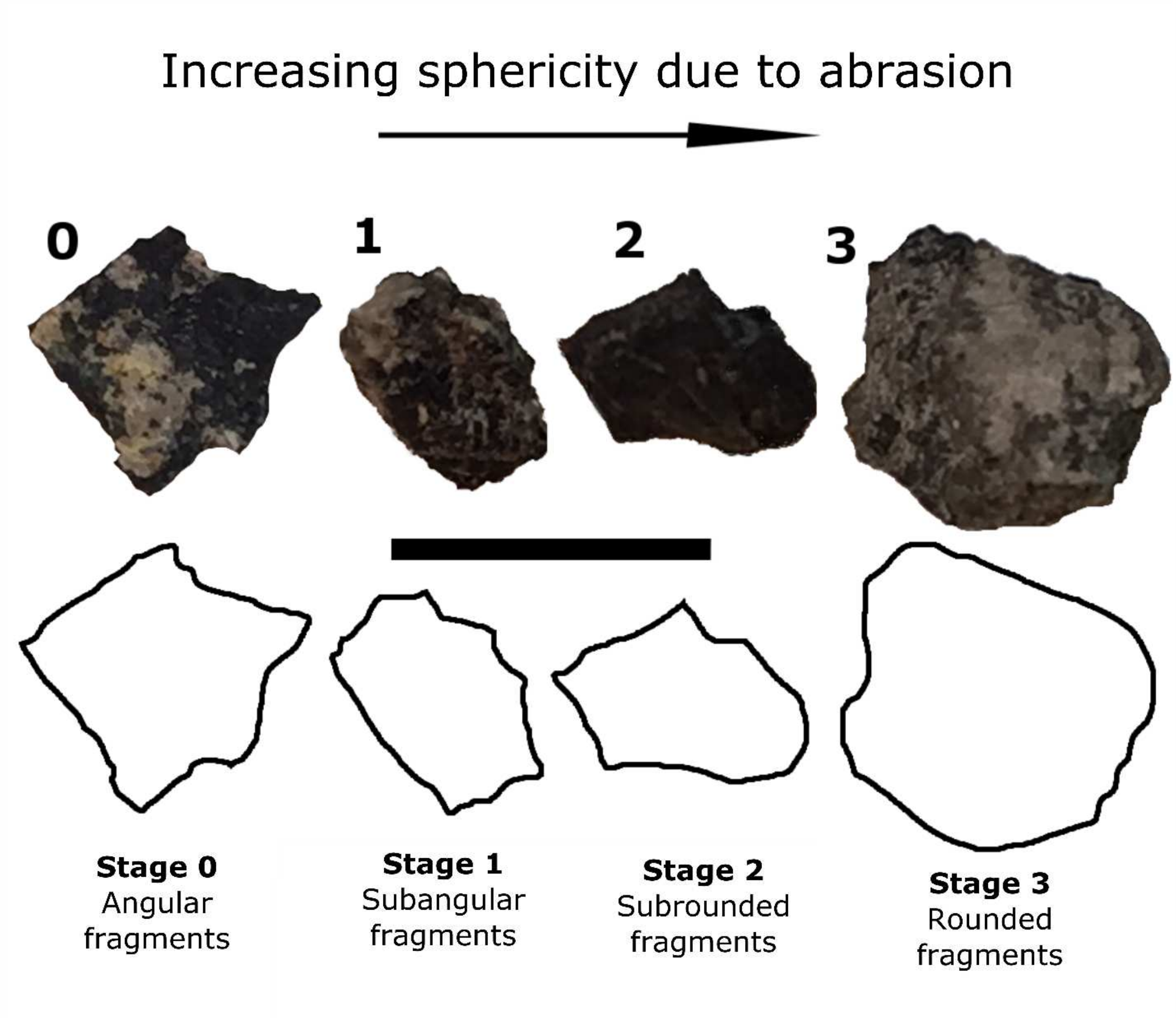
Increasing sphericity due to abrasion
0
1
2
3
Stage 0
Angular
fragments
Stage 1
Subangular
fragments
Stage 2
Subrounded
fragments
Stage 3
Rounded
fragments

Figure 6

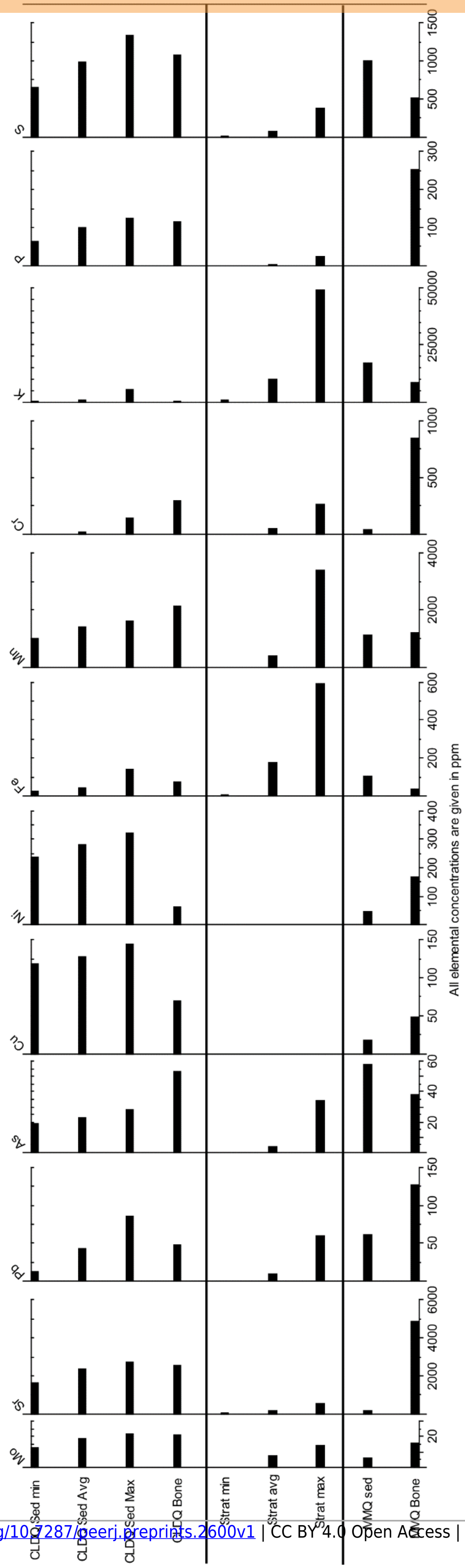
S
P
K
Cr
Mn
Fe
Ni
Cu
As
Pb
Sr
Mo
CLDQ Sed min
CLDQ Sed Avg
CLDQ Sed Max
CLDQ Bone
Strat min
Strat avg
Strat max
MMQ sed
MMQ Bone
All elemental concentrations are given in ppm

Figure 7

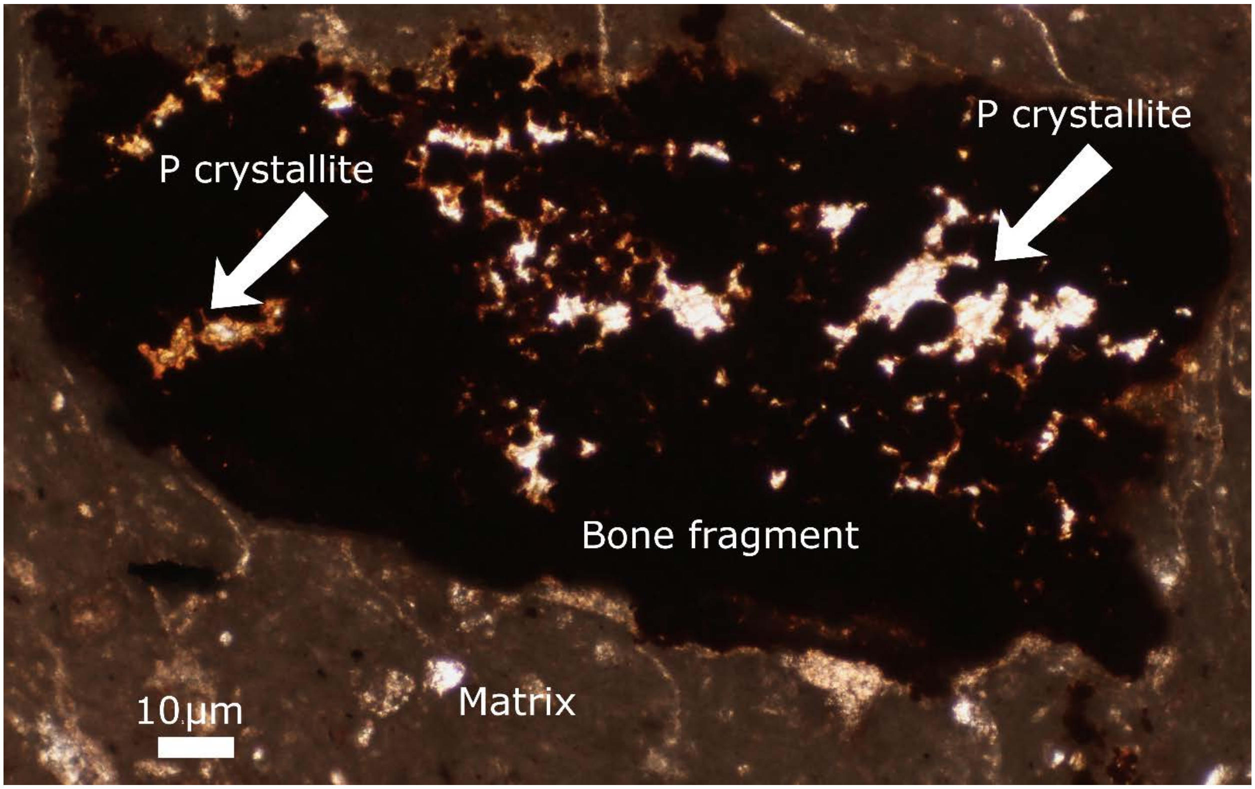

Figure 8

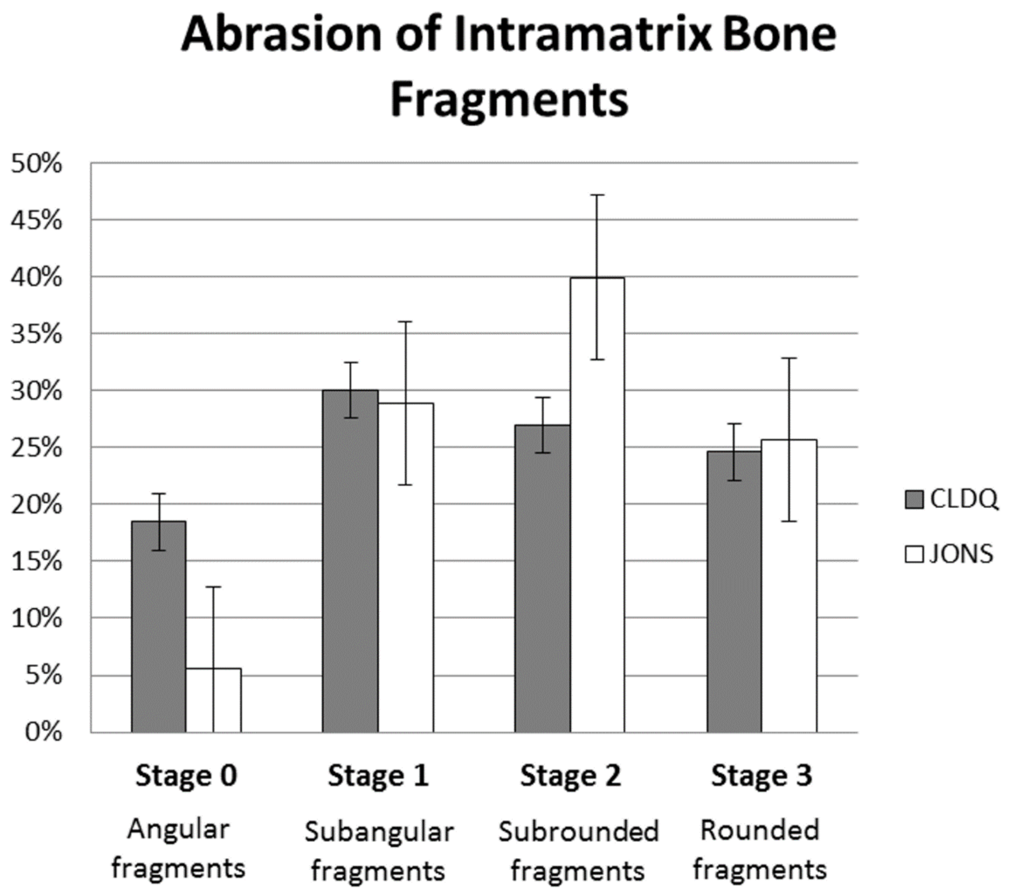

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Table 1

A.

CLDQ Regional Strat Samples	Identified peaks
Unit 01 sub1	calcite
Unit 01 sub2	graphite; quartz; dolomite; ankerite
Unit 02	calcite
Unit 03	calcite
Unit 04	quartz
Unit 05	calcite
Unit 06	quartz
Unit 07	quartz
Unit 08	quartz
Unit 09	quartz
Unit 10	quartz
Unit 11	quartz
Unit 12	quartz
Unit 13	calcite; quartz
Unit 14	quartz; calcite
Unit 15	quartz; calcite
Unit 16	quartz
Unit 16 sub1	quartz; calcite
Unit 17a	quartz; calcite
Unit 17b	quartz
Unit 18a	quartz
Unit 18b	quartz; calcite
Unit 19	Quartz
Unit 20	calcite; quartz
Unit 21a	quartz
Unit 22 - Johnsonville	quartz
Unit 23	quartz
Unit 24	quartz
Unit 25	dolomite; ankerite; quartz; graphite
Unit 26	calcite; quartz
Unit 27	quartz
Unit 28	quartz
Unit 29	quartz
Unit 30	quartz
Unit 31	quartz
Unit 32	quartz
Unit 33	quartz
Unit 34	quartz
Unit 34 sub1a	quartz
Unit 34 sub1b	quartz
Unit 35	quartz
Unit 36	quartz; graphite
Unit 37	quartz
Unit 37 sub1	calcite; quartz

Table 1

B.

CLDQ Quarry Samples	Identified peaks
Sample 1	quartz; qalcite
Sample 2	quartz
Sample 3	quartz; calcite
Sample 4	quartz; calcite
Sample 5	calcite; quartz
Sample 6	calcite; quartz; barite; chalcopyrite; fluorapatite; litharge
Sample 7	fluorapatite; calcite
CLN BF1	calcite; fluorapatite; chalcopyrite; covellite
SBF1	fluorapatite; calcite

Table 2.

		CLDQ (n=1155)	JONS (n=616)
A	**Dominant Lithology**	Calcareous mudstone	Silty mudstone
B	**Interpretation**	Ephemeral pond (Gates, 2005)	Wet floodplain/crevasse splay
C	**% Fossil Fragments per 60 kg Sample**	0.08%	0.04%
D	**Abrasion**		
	Stage 0	213	34
	Stage 1	347	178
	Stage 2	311	246
	Stage 3	284	158
	Significance Level	$p < 0.001$	
E	**Hydraulic Equivalence**		
	Average Relative Densities	0.124	0.133
	Average Hydraulic Equivalent	0.08	0.09
	Equivalent Grain Size	Fine sand	Fine sand

Table 3.

Element	CLDQ	Obsidian
Cr	258-332	1-25
Ni	60-63	1-35
Pb	31-62	10-44
V	0	15-38
Rb	7-9	23-300

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