New data towards the development of a comprehensive taphonomic framework for the Cleveland-Lloyd Dinosaur Quarry (#15242)

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Graciela Piñeiro / 22 Jan 2017

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New data towards the development of a comprehensive taphonomic framework for the Cleveland-Lloyd Dinosaur Quarry

Joseph E Peterson [Corresp., 1] , Jonathan P Warnock [2] , Shawn L Eberhart [1] , Steven R Clawson [3] , Christopher R Noto [4]

[1] Department of Geology, University of Wisconsin-Oshkosh, Oshkosh, Wisconsin, United States
[2] Department of Geoscience, Indiana University of Pennsylvania, Indiana, Pennsylvania, United States
[3] Department of Entomology, University of Wisconsin-Madison, Madison, Wisconsin, United States
[4] Department of Biological Sciences, University of Wisconsin-Parkside, Kenosha, Wisconsin, United States

Corresponding Author: Joseph E Peterson
Email address: petersoj@uwosh.edu

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 poisoned 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 analysis 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 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.

1   **NEW DATA TOWARDS THE DEVELOPMENT OF A COMPREHENSIVE**
2   **TAPHONOMIC FRAMEWORK FOR THE CLEVELAND-LLOYD DINOSAUR**
3   **QUARRY**
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6   JOSEPH E. PETERSON[1]*, JONATHAN P. WARNOCK[2], SHAWN L. EBERHART[1], STEVEN
7   R. CLAWSON[3], AND CHRISTOPHER R. NOTO[4]
8
9   [1]*Department of Geology, University of Wisconsin Oshkosh, Oshkosh, WI 54901, USA;*
10   [2]*Department of Geoscience, Indiana University of Pennsylvania, Indiana, PA 15705, USA;*
11   [3]*Department of Entomology, University of Wisconsin-Madison, Madison WI 53706 USA;;*
12   [4]*Department of Biological Sciences, University of Wisconsin–Parkside, Kenosha, WI 53141*
13
14
15   *Corresponding author. *email: petersoj@uwosh.edu*
16   *RRH: PETERSON ET AL.*
17   *LRH: TAPHONOMY OF CLEVELAND-LLOYD*
18   Keywords: Geochemistry, Taphonomy, Paleoecology
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25   ABSTRACT

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27   theropod dinosaurs discovered to date. Unlike typical Jurassic bone deposits, it is dominated by

28   the presence of *Allosaurus fragilis*. Since excavation began in the 1920's numerous hypotheses

29   have been put forward to explain the taphonomy of CLDQ, including a predator trap, a drought

30   assemblage, and a poison spring. In an effort to reconcile the various interpretations of the quarry

31   and reach a consensus on the depositional history of CLDQ, new data is required to develop a

32   robust taphonomic framework congruent with all available data. Here we present two new data

33   sets which aid in the development of such a robust taphonomic framework for CLDQ. First, x-

34   ray fluorescence of CLDQ sediments indicate elevated barite and sulfide minerals relative to

35   other sediments from the Morrison Formation, suggesting an ephemeral environment dominated

36   by periods of hypereutrophic conditions during bone accumulation. Second, the degree of

37   weathering and hydraulic equivalency of small bone fragments dispersed throughout the matrix

38   were analyzed from CLDQ. Results of these analyses suggest that bone fragments are

39   autochthonous or parautochthonous and are derived from bones deposited in the assemblage. The

40   variability in abrasion exhibited by the fragments is most parsimoniously explained by periodic

41   reworking and redeposition during seasonal fluctuations throughout the duration of the quarry

42   assemblage. Collectively, these data support some previous interpretations that the CLDQ

43   represents an attritional assemblage in a poorly-drained overbank deposit where vertebrate

44   remains were introduced post-mortem to an ephemeral pond during flood conditions.

45   Furthermore, elevated heavy metals and rare earth elements detected at the quarry are likely a

46   diagenetic signal, potentially produced in part from an abundance of vertebrate remains, and not

47   the primary driver for the accumulation of carcasses. These new data help to explain the specific

48   depositional environment of the quarry, and represent a significant step in understanding the

49   taphonomy of the bone bed and Late Jurassic paleoecology.

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51

52   INTRODUCTION

53   The Cleveland-Lloyd Dinosaur Quarry (CLDQ) of central Utah is located in the Brushy

54   Basin Member of the Upper Jurassic Morrison Formation at the northern end of the San Rafael

55   Swell (Figure 1A, B). The quarry is world-famous for its unusually high concentration of

56   dinosaur bones, including at least 70 individuals representing a minimum of nine genera

57   (Madsen, 1976; Gates, 2005). Of these, over 60% (MNI: 46, based on a count of left femora) are

58   attributable to a single taxon – *Allosaurus fragilis*, yielding a predator-prey ratio of 3:1, which is

59   unusual compared to other herbivore-dominated Morrison bonebeds (Madsen, 1976; Miller et al,

60   1996; Gates, 2005) (Figure 2). As such, the quarry represents a potential wealth of Jurassic

61   paleoecological data.

62   Since the initial discovery of the site in 1927, nearly 10,000 bones have been collected by

63   at least seven institutions. The first formal excavations were carried out by the University of

64   Utah, collecting nearly 1,000 bones from 1929 to 1931 (Miller et al., 1996). Excavations

65   resumed again in 1939 through 1941 by W. L. Stokes and Princeton University, which excavated

66   and collected approximately 450 bones during the three-year period. During the early 1960s, the

67   University of Utah resumed excavations and collected nearly 7,000 bones from 1960-1964

68   (Miller et al., 1996). Excavations resumed again in the late 1970s by the Utah Division of State

69   History, and continued intermittently through the 1980s by Brigham Young University,

70   collecting nearly 1,100 bones (Miller et al., 1996). The quarry was once again worked from

71   2001-2003 through the Natural History Museum of Utah, yielding nearly 400 bones (Gates,

72   2005). In 2012, a coordinated effort between the University of Wisconsin-Oshkosh and Indiana

73   University of Pennsylvania began surveying the quarry and began excavations in the south

74   Butler Building, collecting nearly 50 bones to date.

75   While nearly all prior research conducted at the CLDQ has focused on macrovertebrate

76   taxonomy and taphonomy (e.g. Dodson et al., 1980; Stokes, 1985; Hunt, 1986; Richmond and

77   Morris, 1996; Gates, 2005; Hunt et al., 2006), geochemical considerations have received

78   considerably less attention (i.e. Bilbey, 1999). Furthermore, other data types (such as

79   microfossils) are available to aid in interpreting the depositional environment, yet have received

80   only passing attention. Charophytes and ostracods have been recovered from the quarry matrix

81   and utilized for general depositional interpretations (Suarez, 2003; Gates, 2005; Hunt et al.,

82   2006). Although specimens of turtle shell and shed crocodilian teeth have been reported in the

83   quarry, their abundance is low (i.e. two shed crocodilian teeth and a few fragments of turtle

84   shell). This contrasts with other sedimentologically similar deposits, suggesting that the

85   depositional environment at CLDQ may not have been permanently inundated (Madsen, 1976;

86   Gates, 2005). However, the quarry does contain abundant bone fragments within the matrix

87   (clasts <10 mm) (Gates, 2005). While far too small for taxonomic diagnosis, these intramatrix

88   bone fragments (IBFs) can be characterized as potentially transportable sedimentary particles

89   ("bioclasts"); the fragments are widely dispersed throughout the matrix of the quarry and are

90   relatively uniform in size, suggesting syndepositional incorporation of the fragments with the

91   larger remains in the quarry assemblage and hydraulic sorting. The bones from which these

92   fragments are derived would have been stripped of flesh prior to breakdown at the surface and

93   subsequent incorporation into CLDQ sediments. As such, their taphonomic characteristics and

94   patterns such as hydraulic equivalence and abrasion can be utilized to further interpret

95   depositional histories (Peterson et al., 2011).

96   In addition to the microfossils and microvertebrate remains at the quarry, more data is

97   available to consider when interpreting the taphonomy of the CLDQ. Feeding traces are nearly

98   absent from the quarry (Gates, 2005; Hunt et al., 2006). Furthermore, concretions of calcite with

99   trace amounts of barite form as nodules (calcite/barite nodules hereafter) around many of the

100   bones from the CLDQ (Bilbey 1999). Finally, the bones in the quarry are found isolated or

101   associated, and only rarely articulated (Gates, 2005).

102   Although recent researchers agree that the deposit was formed in a small, likely

103   ephemeral, pond (e.g. Richmond and Morris, 1996; Gates, 2005; Hunt et al., 2006), the above

104   evidence has led to a suite of highly variable explanations of the specific taphonomy and

105   depositional environment preserved at the CLDQ. Initial interpretations classified the quarry as a

106   drought-induced death assemblage (Stokes 1945, Gates, 2005). One hypothesis suggests that the

107   deposit represents a predator trap where sauropods mired in the mud, in an effort to explain the

108   high numbers of *Allosaurus* (Richmond and Morris, 1996). Bilbey (1999) posited that the deposit

109   represents a lethal spring-fed pond or seep where dinosaurs died after drinking the water. Hunt et

110   al. (2006) suggests that the dinosaur remains at the quarry represent a single population that died

111   from an unknown cause and were subsequently transported into a shallow pond.

112   Each of the above taphonomic hypotheses is insightful, however each hypothesis

113   conflicts with the existing taphonomic data to some degree. For example, bones in a predator

114   trap should be heavily tooth-marked, as are over 50% of the bones recovered from the Rancho

115   La Brea tar pits (Spencer et al., 2003). However, only 4% of bones recovered from the CLDQ

116   show evidence of feeding traces (Gates, 2005). Furthermore, bones from a predator trap would

117   show a higher frequency of taphonomic modification, such as bones crushed by larger animals,

118   such as sauropods, attempting to escape the miring mud, and pit wear from remains wearing

119   against each other during early diagenesis (i.e. Friscia et al., 2008), both of which are

120   conspicuously rare or absent at the CLDQ (Gates, 2005).

121   Bilbey's (1999) lethal spring fed pond hypothesis is powerful in that it can explain the

122   lack of microvertebrate remains found at the CLDQ; a toxic pond would not support the fish,

123   turtles, and crocodilians typical of pond deposits. The spatial distribution of bones in the quarry

124   also fits well with Bilbey's (1999) hypothesis, however the 'dinoturbation' hypothesized to

125   contribute to the disarticulation of remains would result in bone crushing. Furthermore,

126   organisms would likely move away from the pond after drinking the water, rather than remaining

127   until death to be buried in place. Additionally, Bilbey (1999) does not explain the potential

128   source of the toxicity of the pond.

129   Given the complicated taphonomy of the CLDQ and the problems with existing

130   taphonomic hypotheses, new data is required to create a new or hybrid taphonomic hypothesis

131   for the CLDQ that can address the complications of the available data. Here we present new

132   taphonomic and geochemical data in the forms of x-ray diffraction (XRD) and x-ray

133   fluorescence (XRF) data from a stratigraphic column spanning the Salt Wash and Brushy Basin

134   members of the Morrison Formation, which crops out in the Cow Flats Quadrangle, including

135   XRF data from sediment and bone fragments from the CLDQ (Figure 1A, B). These data are

136   contrasted with geochemical data from a lithologically similar Brushy Basin bonebed, the

137   Mygatt-Moore Quarry (MMQ). We further provide characteristics of the intramatrix bone

138   fragments (IBFs) of the CLDQ and a new locality (UWO-12-001, "Johnsonville") in attempt to

139   formulate depositional and taphonomic inferences among sites with different taphofacies. The

140   following questions are addressed:

141   1.   What are the geochemical signatures of the CLDQ, and how do they compare to

142   the regional Morrison Formation outcrops and bone beds?

143   2.   What are the abrasion patterns of recovered IBFs from the CLDQ?

144   3.   What do the hydraulic equivalences of IBFs suggest about depositional history

145   of the CLDQ?

146   The geochemical and micropaleontological data presented here are meaningful in terms

147   of contributing to existing data available to interpret the CLDQ taphonomy.

148

149   GEOLOGIC SETTING

150   The CLDQ and Johnsonville localities are located on the northern end of the San Rafael

151   swell, southwest of Price, Utah, and stratigraphically located in the Brushy Basin Member of the

152   Upper Jurassic Morrison Formation (~147 Ma) (Bilbey, 1998). The Brushy Basin Member is

153   composed of floodplain-deposited mudstones with freshwater limestone and some channel

154   sandstones, and is the youngest of three laterally extensive members of the Morrison Formation

155   (Gates, 2005). In the immediate vicinity of the CLDQ and Johnsonville sites are the distal

156   alluvial fan complex of the Salt Wash Member, which underlies the Brushy Basin Member, and

157   the Middle Jurassic Summerville Formation, which underlies the Morrison Formation (Peterson

158   and Turner-Peterson, 1987). Previous reconstructions of late Jurassic climate patterns in Utah

159   indicate strong seasonality, subject to variably arid to monsoonal conditions (e.g. Hallam, 1993;

160   Dodson et al., 1980; Rees et al., 2000; Parrish et al., 2004; Sellwood and Valdes, 2008; Tanner et

161   al., 2014). This interpretation is supported by scarce plant material and coal deposits (Dodson et

162   al., 1980) and the distribution of authigenic minerals such as barite, present throughout the

163   Morrison Formation that are strongly associated with periodic aridity (Turner and Fishman,

164   1991).

165   *Cleveland-Lloyd Dinosaur Quarry (CLDQ)* - The Cleveland-Lloyd Dinosaur Quarry

166   (CLDQ) is located approximately 38 meters above the basal contact of the Brushy Basin

167   Member (Bilbey, 1992) (Figure 1A, B). The bone-bearing unit is composed of a calcareous

168   mudstone that varies in thickness from a few centimeters to one-meter, and also includes

169   abundant diagenetic limestone nodules and clay clasts. The calcareous mudstone underlies a

170   bone-bearing micritic limestone unit that varies in thickness from 0.3-1.0 m, and overlies a

171   massive silty mudstone approximately 20 meters in thickness (Gates, 2005; Bilbey, 1992). Based

172   on limited exposures, the silty mudstone unit is laterally continuous for 50-75 meters before

173   pinching out to the south (Gates, 2005). The calcareous bone-bearing mudstone contains

174   calcite/barite nodules, typically as overgrowths on bone, interpreted as resulting from soft tissue

175   decay (Bilbey, 1998; Gates, 2005). The evaporative nature of the deposit would help to form

176   these nodules, as evaporation would induce increased saturation of the relevant ions, however the

177   nodules would have to form when the pond still contained water. While various depositional

178   models have been proposed for the CLDQ, the lithologies, abundant vertebrate macrofossils, and

179   rare microvertebrate and invertebrate remains suggest an ephemeral pond or similar overbank

180   deposit with a fluctuating water table (calcareous mudstone facies) that became a more

181   permanent basin in the form of a shallow lacustrine setting (limestone facies) (Bilbey, 1999;

182   Gates, 2005). The presence of freshwater ostracods, gastropods and charophytes in the limestone

183   cap over the bone-bearing mudstone suggests that the environment supported a freshwater

184   ecosystem during the last stages of sediment filling the pond (Bilbey, 1992). The deposit has

185   been dated to 147.2 ± 1 Ma to 146.8 ± 1 Ma via K/Ar dating of an ash bed approximately 1 m

186   above the limestone cap (Bilbey 1998).

187   *Johnsonville (UWO-12-001 "JONS")* - The Johnsonville quarry (University of

188   Wisconsin Oshkosh locality UWO-12-001) is located 470 meters southeast of the CLDQ locality

189   and is stratigraphically positioned approximately 11 meters below the CLDQ in the lower

190   portion of the Brushy Basin Member (Figure 1A, B). The site was discovered by the University

191   of Wisconsin Oshkosh field crew in the summer of 2012. This site is composed of a 15-meter-

192   thick yellowish/gray silty mudstone. Vertebrate microfossils, such as turtle shell fragments, shed

193   crocodilian and theropod dinosaur teeth are common, and the site also includes larger

194   macrovertebrate remains such as sauropod caudal vertebrae and other large vertebrate bone

195   fragments (Figure 3A, B). Fossil material is present in the upper six meters of the silty mudstone.

196   The Johnsonville unit is laterally extensive over ~10 meters and overlies a one-meter tan

197   sandstone. Based on interpretations of similar lithologies in the Morrison Formation, the

198   Johnsonville site is interpreted as an overbank deposit such as a wet floodplain or crevasse splay

199   with a relatively high water table (Bilbey, 1999). While the JONS site is a microvertebrate

200   locality and not a large bonebed like the CLDQ, it serves as a robust comparison to the CLDQ as

201   a depositionally distinct site for taphofacies comparisons.

202

203   MATERIALS AND METHODS

204   Collection localities for this study are managed by the Bureau of Land Management

205   (BLM) and all fossil material was collected under survey and excavation permits. Exact

206   coordinates for these collection sites are on file with the BLM and the Natural History Museum

207   of Utah, where all collected materials are maintained. Fieldwork for this study was conducted

208   under BLM Permit #UT12-003E.

209   *Stratigraphy and Geochemistry* - Utilizing a Jacob's staff and Brunton compass-

210   clinometer, a bed-by-bed stratigraphic column was generated for the Brushy Basin and Salt

211   Wash Members of the Morrison Formation from its lower contact with the Middle Jurassic

212   Summerville Formation to the uppermost horizon of the Morrison Formation preserved at the

213   upper limit of the butte above and to the west of the CLDQ (Figure 1A, B). Beds were identified

214   in the field on the basis of color and lithological change. Some beds were divided into subunits

215   based on changes in grain size and surface weathering. A hand sample of rock from beneath the

216   upper weathered horizon was collected from the center of each bed or subunit. Hand samples

217   were also collected from the center of the fossiliferous mudstone horizon of the North and South

218   Butler Buildings at the CLDQ.

219   As a comparison to CLDQ, three samples of siltstone and one bone fragment from the

220   Mygatt-Moore Quarry (MMQ) were included in this analysis. The MMQ is located

221   approximately 2.5 km east of the Colorado-Utah state line in western Mesa County, Colorado

222   and stratigraphically positioned in the middle to lower Brushy Basin member (Trujillo et al.,

223   2014). MMQ is composed of a 1 meter-thick smectitic mudstone with interbedded silt-sized

224   grains and clay balls. The mudstone is rich in carbonized plant and wood fragments (Trujillo et

225   al., 2014). Since 1981, the quarry has yielded nearly 2,400 bones of at least six different taxa of

226   Jurassic dinosaurs, with sauropods, such as *Apatosaurus*, *Camarasaurus*, and diplodocines (cf.

227   *Diplodocus* or *Barosaurus*) constituting 50% of the total assemblage, and 30% represented by

228   theropods such as *Allosaurus* and *Ceratosaurus* (Foster, 2007). Due to the similar lithology and

229   rich abundance of dinosaur remains of the MMQ, samples of sediment and bone fragments were

230   included in this analysis for comparisons with CLDQ.

231   All rock samples were hand ground via mortar and pestle for XRD and XRF analysis.

232   Bone chips from the CLDQ and MMQ were also analyzed via XRF and petrographic thin

233   section, however they were not ground prior to analysis. XRD was carried out at the University

234   of Wisconsin - Oshkosh Department of Geology utilizing a Rigaku D/Max-2000T X-ray

235   diffractometer operating at 40 kV and 40 mA and utilizing a Cu Ka target to determine sample

236   mineralogy. XRD data was subsequently analyzed using the Jade (v9.3; Materials Data, Inc.,

237   Livermore, CA) software package. XRF for all stratigraphic samples and CLDQ samples was

238   conducted at Beloit College in Beloit, Wisconsin with a Niton XL3t GOLDD+ handheld XRF

239   analyzer in Test All Geo mode. This mode analyzes the full suite of elements which the unit is

240   capable of detecting. XRF of material from MMQ was conducted at Indiana University of

241   Pennsylvania using an Innov X Delta Professional handheld XRF analyzer in soil mode.

242   Similarly, this mode of operation analyzes the full suite of elements the unit is capable of

243   detecting.

244   *Intramatrix Bone Fragments* - To better understand the various taphonomic processes

245   that influence the deposition, preservation, and recovery of IBFs, it was important to choose sites

246   for these experiments from different facies that represent typical Brushy Basin member

247   lithologies. The two sites in this analysis were chosen based on their lithological differences (e.g.

248   Wilson, 2008; Peterson et al., 2011) and the presence of IBFs. The data collected at each site

249   included local thickness of the sedimentary subunits and their lateral extent where possible.

250   In order to quantify intramatrix bone fragment abundance, approximately 60 kg of bulk

251   sediment was quarried from each of two localities; the CLDQ, and UWO-12-001 (Johnsonville).

252   Samples were taken from below the weathering zone to avoid biases caused by ongoing erosion

253   of fossil samples and disaggregated under controlled laboratory conditions (following Peterson et

254   al., 2011).

255   All collected fossil fragments were obtained by a method of submerged screen washing

256   with gentle air agitation similar to previously utilized methods (e.g. McKenna, 1962; Ward,

257   1981; Peterson et al, 2011). Two mesh baskets 23 x 33 cm (23 cm deep) were constructed of 1

258   cm hardware cloth and internally lined with 1.0 mm plastic window screen. The mesh baskets

259   were placed in 23 x 43 cm (28 cm deep) plastic basins. Below the mesh baskets, 1 meter of

260   flexible perforated airline tubing was coiled at the bottom of the basins and connected to a

261 double-output aquarium air pump (3.5 watt, 1200cc air per minute output) placed outside of the

262 basins. The resulting system produced gentle air-powered agitation in the basins to promote

263 sediment disaggregation (Figure 4). Unweathered sediment samples were physically broken

264 down to roughly 5 cm pieces, placed in the agitation basins, and submerged until disaggregation

265 was complete, which took roughly two days. Following disaggregation, baskets were removed

266 from the basins and left to air dry.

267   All fossil bone fragments were collected regardless of taxonomic identification.

268 Subsequently, bone fragments were measured along three perpendicular axes to determine

269 volume and hydraulic equivalence (Behrensmeyer, 1975). The equation for hydraulic

270 equivalence is:

271   `dq = (pb − 1)*db/1.65`

272   `db = Nominal diameter of bone = 3√(1.91 x Volume)`

273   `pb = Bone density`

274

275   Fragment were also classified by degree of abrasion as a signal of relative transport.

276 Abrasion was measured on a 0-3 scale (Wilson, 2008), with 0 representing no apparent abrasion,

277 and 3 representing nearly complete rounding of the specimen (Figure 5).

278   Chi-Square Tests were used to determine whether a statistically significant relationship

279 existed between two categorical variables. A nominal level of significance (type I error rate) of α

280 = 0.05 was used in all tests, i.e., an observed significance level (p-value) of <0.05 was required

281 in all tests to reject the null hypothesis that the variables were not related. Specifically, Chi-

282 Square tests were used to determine if the degree of abrasion of the intramatrix bone fragments

283 significantly differed between the two sites.

284

285 RESULTS

286   *Geochemistry* - XRD data are presented on Table 1A, B. Excluding the CLDQ, the

287 Morrison Formation is overwhelmingly composed of silicates and carbonates. Two strata also

288 contained dolomite and ankerite ($CaMg_{0.27}Fe_{0.63}(CO_3)_2$) (Table 1A: Units 1b and 25). The quarry

289 itself is composed primarily of silicates and carbonates, with smaller amounts of barite,

290 chalcopyrite, fluorapatite, covellite (CuS) and litharge (PbO). XRD analysis of sediments from

291 the JONS site detected only silicates.

292   The total XRF data are presented on Table S1. Comparisons of the concentrations of

293 selected metals in CLDQ bone and sediment, MMQ bone and sediment, as well as regional

294 Morrison Formation sediment is presented on Figure 6. The XRF unit utilized to analyze MMQ

295 samples does not detect Si. Si concentrations, available for all non-MMQ samples, ranged

296 between $24,646.01 \pm 581.59$ ppm to $522,405.2 \pm 4166.98$ ppm throughout the sampled units of

297 the Salt Wash and Brushy Basin members in the vicinity of the CLDQ, with samples from the

298 quarry having values of $24,646.01 \pm 581.59$ ppm and $30,643.28 \pm 1,309.51$ ppm. The 'balance'

299 measured by the XRF, i.e., the summed concentration of all elements lighter than Mg (i.e. those

300 not detectable by the unit), and occasional instrument error due to air space in the ground

301 samples, ranged from $282,284.22 \pm 4,650.26$ ppm to $712,203.63 \pm 2,258.34$ ppm. The quarry

302 samples yielded balance values of $412,387.59 \pm 4,891.71$ ppm and $436,363.78 \pm 3,107.65$ ppm.

303 Sediment samples from CLDQ had higher values than those of the rest of the stratigraphic

304 column for Mo, Sr, As, U, Cu, Ni, Nb, P, and S. The CLDQ sediment had higher concentrations

305 than most other samples from the stratigraphic column for Pb, Mn and Cr. The quarry sediment

306 fell within the range the rest of the stratigraphic column for Zr, Rb, Th, Zn, W, Si, V, Ti, Ca, K,

307 Al, Cl, Sc, Mg and Fe. Any elements not specifically listed above were either not present or

308   undetectable via the XRF gun in all analyzed samples. Sediments from Mygatt-Moore Quarry

309   contained more Cu, Ni and Bi than the stratigraphic column samples. MMQ sediment contained

310   more Rb, Pb, As, Zn, Cl and V than most stratigraphic samples. Finally, MMQ samples were

311   within the range of concentrations of Mo, Zr, Fe, Mn, Ti, Ca, K, Cl, Sr, W, Cr, and P seen within

312   the stratigraphic samples. In contrast to the CLDQ and MMQ, the sediments of JONS resemble

313   those of local Morrison Formation outcrops. None of the metals detected via XRF at JONS were

314   found at elevated levels compared to all other samples analyzed, including those of the CLDQ

315   and MMQ.

316   CLDQ bone revealed a similar pattern of heavy metal enrichment as CLDQ sediments

317   (Figure 6). Exceptions include As and Cr, for which the bone samples have similar

318   concentrations to Morrison Formation sediment as opposed to CLDQ sediment, i.e. CLDQ

319   sediments contain more abundant As and Cr than both Morrison Formation sediment and CLDQ

320   bone. CLDQ bone is more enriched in Ni, Cu and W with respect to Morrison sediment than

321   CLDQ sediment. For all other detected elements, the bone samples and sediment samples from

322   the CLDQ show similar elemental concentrations. Thin section analysis of bone fragments

323   encased in quarry matrix from CLDQ indicate permineralization in the form of phosphate

324   crystallites filling void spaces within the bone fragments (Figure 7

325   In regards to MMQ, the bone sample generally had a similar heavy metal content to that

326   of the sediment samples. Exceptions include Sr, W, Cr, V and P which were in higher

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

328   sediment than in the bone.

329   *Intramatrix Bone Fragments* - The IBFs collected from CLDQ and JONS were compared

330   according to their physical characteristics and taphonomic differences to investigate whether

331 these differences were statistically significant (raw data available in Tables S2, S3). Analyses

332 suggest different patterns of abrasion variability between the two localities, and these patterns

333 were found to be significantly different ($p < 0.001$; Table 2A-D, Figure 8).

334   The CLDQ IBFs display a wide range of degrees of abrasion; recovered fragments fall

335 between 15-30% of each abrasion category (Figure 8). However, the JONS IBFs possess higher

336 degrees of abrasion; JONS bone fragments show a strong trend towards more mature levels of

337 abrasion with only 5% of IBFs scoring as angular.

338   Following Behrensmeyer (1975), hydraulic equivalents (E_{HY}) were calculated based on

339 specimen volume, relative density, and size for each assemblage of bone fragments. Hydraulic

340 equivalences and relative densities were compared between assemblages (Table 2E). Although

341 shape is a significant factor for settling velocities, this feature has been omitted simply to gain a

342 general view of hydraulic equivalences to a quartz sphere (Behrensmeyer, 1975; Peterson et al.,

343 2011). Results of hydraulic equivalence analysis indicate that bone fragments obtained from

344 both localities have similar hydraulic equivalences (fine sand) despite differences in lithology.

345

346 DISCUSSION

347   *Geochemistry* - X-ray diffraction data largely agree with those presented by Bilbey

348 (1999), in that the Brushy Basin and Salt Wash Members of the Morrison Formation are

349 primarily composed of quartz and calcite. The mineralogy of the CLDQ itself is distinguished

350 from the surrounding Brushy Basin and nearby Salt Wash Members, as well as the mudstones at

351 the same stratigraphic level as the quarry, by the presence of metal oxides (primarily litharge)

352 and sulfides (chalcopyrite, and covellite) as well as barite. This suite of minerals implies that the

353 environment represented by the quarry was very likely reducing (Eby, 2004). High levels of

354 decaying organic matter, due at least in part to the abundance of decaying dinosaurs utilizing the

355   available dissolved oxygen, would contribute to a reducing environment, especially given the

356   ephemeral nature of the CLDQ pond.

357   The presence of calcite/barite nodules on the bones further supports the hypothesis that

358   the dinosaur remains were decaying in the CLDQ pond. Ligament and cartilage would be among

359   the last of the organic matter to decay, and the highest concentration of dissolved organic matter

360   would occur there (Madsen, 1976; Bilbey, 1999). The position of the calcite/barite nodules, most

361   commonly found where ligaments and cartilage attached to bone (Madsen, 1976), supports the

362   hypothesis that they formed during decay. Furthermore, in subaqueous settings barite formation

363   is associated with supersaturation of chemical microenvironments surrounding decaying organic

364   matter (Paytan and Griffith, 2007).

365   Despite suggestions of an abundance of available organic matter at the CLDQ, evidence

366   of scavenging is conspicuously rare, as previous authors have noted (e.g. Berner 1968; Bilbey

367   1998; Gates 2005). However, hypereutrophic conditions resulting from decaying dinosaur

368   carcasses, as evidenced by the presence and position of the calcite/barite nodules, is one possible

369   explanation of the lack of scavengers.

370   X-ray fluorescence and x-ray diffraction data show the quarry as enriched in heavy

371   metals, e.g. Mo, As, U, Pb, relative to the rest of the local outcropping of the Morrison

372   Formation. Some of these metals, Sr, Zn, Na and Mg, are known to easily replace Ca in biogenic

373   apatite during diagenesis (Trueman and Tuross, 2002; Goodwin et al., 2007). Furthermore,

374   Morrison formation bone is known to be enriched in U as a result of diagenesis, therefore

375   elevated levels of U detected in CLDQ sediment and bone is not anomalous (Hubert et al., 1996).

376   However, Gillette (1994) notes that U enrichment in dinosaur bone is most common in bones

377   buried within the local water table. High U concentrations seen here help to support the

378   hypothesis that the bones of CLDQ were deposited into a shallow pond which was in

379   hydrological contact with groundwater during deposition

380   Unfortunately, while studies of the geochemical compositions of fossil remains from

381   bone beds are common (e.g. Trueman and Benton 1997; Trueman and Tuross 2002; Rogers et

382   al., 2010), similar studies focusing on the sediments from bone beds are lacking in the literature.

383   One possible origin for the heavy metals at CLDQ is accumulation through diagenetic processes.

384   The high abundance of buried bone undergoing diagenetic dissolution may be responsible for the

385   elevated levels of As; elevated levels of As have been noted in *Dilophosaurus* bones from the

386   lower Jurassic Kayenta Formation (Goodwin et al., 2007). It is worth noting, however, that while

387   Goodwin et al (2007) found higher concentrations of As in bone than in the surrounding

388   sediment (200-500 ppm in bone, 10-20 ppm in sediment), the opposite was seen at CLDQ (18-28

389   ppm in bone, 50 ppm in sediment). Two of the three sediment samples from MMQ contained

390   more As than the bone from MMQ, following the pattern observed by Goodwin et al (2007).

391   Strong negative pairwise elemental correlations were observed for As and Fe in the CLDQ

392   sediment samples, similar to what has been observed in material from the Kayenta Formation

393   (Goodwin et al., 2007). This may reflect As desorption from iron oxides, given that Fe is low at

394   the CLDQ and higher elsewhere in the Morrison Formation; the negative correlation between Fe

395   and As at the CLDQ may be the result of desorption and absorption reactions during the

396   dissolution and weathering of the large accumulation of bones. Bone dissolution would produce

397   a high concentration of P, as observed via XRF, which can promote desorption of As (Goodwin

398   et al, 2007). It is possible that similar processes resulted in the high concentrations of other

399   metals in the sediments of CLDQ relative to concentrations seen in the rest of the Morrison

400   Formation analyzed here, however these elements were not considered by Goodwin et al (2007).

401   Elevated concentrations of metals seen in MMQ support the conclusion that diagenetic processes

402   contributed to the heavy metal signature observed at CLDQ.

403   A second possibility for the origin of the elevated heavy metals at the CLDQ is

404   bioaccumulation. Studies of modern grave soils suggest one potential source of heavy metals

405   detected in bone and sediment of the CLDQ which are not necessarily explained by apatite

406   diagenesis, i.e. Ni, Cu, Mo, As, Pb and W: the dinosaur carcasses themselves. Modern grave

407   soils have long been seen as potential ecological hazards and sources of organic and inorganic

408   pollutants (Aruomero and Afolabi 2014). While many studies of necrosols focus on burials with

409   caskets which are not relevant to a Mesozoic bone bed (e.g. Üçisik and Rushbrook 1998), some

410   studies have focused on geochemistry of mass graves and primitive burials lacking caskets and

411   burial goods (Kemerich et al. 2012; Amuno 2013). Kemerich et al. (2012) utilized XRF to find

412   elevated levels of Ba, Cu, Cr and Zn in the soil and groundwater associated with a mass grave in

413   Brazil. Amuno (2013) found elevated levels of As, Cu, Cr, Pb and Zn in necrosols within and

414   near to a mass grave site in Rwanda. While full soil development is not evident at the CLDQ, the

415   deposit is an analogous accumulation of quickly buried vertebrate remains in fine grained

416   sediment.

417   While it is highly unlikely that high concentrations of As, Cu, and Pb seen in CLDQ

418   sediments indicate these metals occurred at toxic concentrations in the bodies of the dinosaurs

419   which accumulated there (Goodwin et al, 2007), large numbers of carnivores decaying could

420   lead to the accumulation of these metals in the CLDQ pond. Carnivores are especially likely to

421   contribute heavy metals via trophic focusing of toxins as they are high level predators (e.g.

422   Vijver et al., 2004; Gall et al., 2015). During diagenesis these metals would then be held within

423   the sediments and bones of the deposit (Goodwin et al., 2007). While more extensive work is

424   required to interpret the geochemical signal of the bones recovered from the CLDQ, the

425   similarity of CLDQ sediment and preliminary bone geochemistry data, taken with the strong

426   contrast between geochemistry of sediments from the CLDQ and from surrounding Morrison

427   sediments, implies a unique setting for the CLDQ assemblage

428   The MMQ samples provide a significant comparison when considering bioaccumulation

429   as a source of the metals observed at the CLDQ. Some elements found in CLDQ sediments and

430   bone, specifically W, Cu, Ni and Cl, are found in higher concentrations in CLDQ materials than

431   MMQ materials. However, Zr, Rb, V and K are found in higher concentrations at MMQ than at

432   CLDQ. These differences could have arisen due to diagenetic differences, however

433   bioaccumulation and taphonomic differences may also explain the disparity in heavy metal

434   content between the CLDQ and MMQ. Further experimentation and sediment collection will be

435   required to determine the extent to which bioaccumulation and dinosaur decay contributed to the

436   metals present in CLDQ sediment and bone.

437   One further possibility for the elevated presence of heavy metals found at the CLDQ is

438   the dissolution of volcanic ash, which may have concentrated in the pond as it washed in during

439   flood periods. Hubert et al (1996) analyzed the chemical composition of "a large data base for

440   silicic obsidians that proxies for the unknown composition of the altered silicic ashes in the

441   Brushy Basin Member." The compositional data presented by Hubert et al (1996) contrast

442   significantly with the sediments of the CLDQ (Table 3). Given that the CLDQ sediment

443   geochemistry does not match well with that of the proxy obsidians (Hubert et al., 1996), the

444   metals present in the CLDQ are not likely sourced from local volcanic ashes emplaced during

445   bone burial.

446   Both XRD and XRF analyses, taken together, support the hypothesis that the CLDQ

447   represents an ephemeral pond that became hypereutrophic as dinosaur carcasses decayed. The

448   source the calcite/barite nodules on the bones and sulfide minerals present in the quarry but not

449   found in other Morrison sediments, is likely the decay and dissolution of the dinosaurs

450   themselves. Dinosaur decay could potentially have contributed to the heavy metal signature of

451   CLDQ sediments as well.

452   Hypereutrophy can explain the near total lack of microvertebrate remains, e.g. turtle, fish

453   and crocodilian fossils typically associated with pond deposits, and near total lack of scavenging

454   marks on CLDQ dinosaur bones. The typical freshwater fauna which would create

455   microvertebrate remains and also scavenge on the carcasses, e.g. fish, turtles and crocodilians,

456   would not have been able to tolerate the water column. Furthermore, as the carcasses rotted the

457   formation of calcareous soaps would have inhibited scavenging before leading to the formation

458   of calcite/barite nodules on bones. While both diagenetic processes and hypereutrophy are

459   possible sources of the heavy metals found at the CLDQ, given the evidence in support of

460   hypereutrophy of the CLDQ pond, diagenetic processes are not likely the primary cause of

461   elevated concentrations for all of the metals seen here. Furthermore, if the accumulation of heavy

462   metals seen at CLDQ is a result of apatite diagenesis associated with the large number of bones

463   at the site, the site-specific taphonomy of the CLDQ could have contributed to the heavy metal

464   signature, as metals which had bioaccumulated in a large number of top predators remained in

465   the CLDQ pond during decay and lithification.

466   Geochemical analysis of the JONS site strengthen the interpretation of the CLDQ as a

467   unique bone-bearing site. Typical indicators of eutrophy, e.g. elevated levels of metals, sulfide

468   minerals and calcite/barite nodules, are not present at JONS. Furthermore, a typical freshwater

469   microvertebrate assemblage of turtle and crocodilian remains are found at JONS. This data helps

470   to support the hypothesis that diagenesis is not the sole contributor to heavy metals at the CLDQ.

471   While JONS also contains large vertebrate bones, the heavy metal signatures seen at the CLDQ

472   are absent here. Metal concentrations would not be expected to be as high at JONS as at the

473   CLDQ, given the disparity in number of fossils found at each site. However, if diagenetic

474   processes were the dominant source of heavy metals in the sediments of the CLDQ, some

475   elevation in these metals would be expected at JONS.

476   Finally, analysis of MMQ sediment and bone provides meaningful contrast to that found

477   at CLDQ and again highlights the uniqueness of CLDQ. The bones of MMQ show extensive

478   evidence of biostratinomic alteration, implying the presence of scavengers. Although aquatic

479   vertebrate remains are rare at MMQ, as at CLDQ owing to the ephemeral nature of the pond

480   (Trujillo et al 2014), they are more numerous at MMQ. Furthermore, the sediments of MMQ

481   contain abundant carbonized plant fragments whereas CLDQ contains none. This is potentially

482   due to differences in local vegetation during the time of deposition, but could also be a

483   taphonomic effect. Bones recovered from MMQ are not associated with calcite/barite nodules.

484   Rates of organic matter decay at MMQ must not have been high enough to form the calcareous

485   soaps necessary for calcite formation. Taken together, these data imply that the MMQ pond was

486   not hypereutrophic, whereas the CLDQ pond was. The differences in preservation of bone and

487   plant material, the respective presence and absence of calcite/barite nodules, as well as

488   differences in biostratinomy and microvertebrate fossil abundance between the two sites are best

489   explained by variations in water chemistry: periodic hypereutrophic conditions at CLDQ, and an

490   oligotrophic pond at MMQ.

491   *Intramatrix Bone Fragments* - Previous studies have discussed distinct taphonomic

492   characteristics among microvertebrate fossils from localities with dissimilar facies (e.g.,

493   Behrensmeyer, 1975; Brinkman, 1990; Eberth, 1990; Blob and Fiorillo, 1996; Wilson, 2008;

494   Peterson et al, 2011). Peterson et al. (2011) reported on taphonomic variability of

495   microvertebrate assemblages collected from crevasse-splay and flood basin deposits from the

496   Late Cretaceous Hell Creek Formation of Carter County, Montana. The results suggested a

497   strong correlation between taphonomic processes such as transport, sorting, and weathering,

498   sedimentary facies, and physical characteristics of recovered fossils (Peterson et al., 2011). A

499   similar trend is observed in the collected intramatrix bone fragments from the CLDQ and the

500   JONS site in the upper Morrison Formation. Although both localities possess abundant bone

501   fragments that share a suite of physical characteristics (i.e. sizes < 0.5mm and comparable

502   relative densities), the variation in abrasion between the two sites is significant.

503   The average hydraulic equivalence for both localities corresponded with fine sand (Table

504   2E). This similarity may be due to the specific measurement method utilized; minor differences

505   in volume between angular and non-angular fragments may have been missed by standard

506   angular measurements. However, given the small sizes and homogeneous densities of the

507   fragments, the hydraulic equivalences of the assemblages are not expected to vary considerably

508   with alternative measuring methods.

509   The matrices of both localities are dominated by sediments much finer than the respective

510   hydraulic equivalence of bone fragments recovered from each site; the CLDQ is composed of a

511   calcareous mudstone whereas the JONS site is dominated by a silty mudstone, while the bone

512   fragments from both sites are hydraulically equivalent to fine sand. This particular disparity

513   between the hydraulic equivalence of bone fragments and the dominant lithologies suggest that

514   the intramatrix bone fragments at both localities are a mixture of locally-crushed, autochthonous

515   or parautochthonous fragments from locally-crushed larger bones and washed-in allochthonous

516   fragments, all of which accumulated on the flood basin or in a crevasse-splay (Behrensmeyer,

517   1975; Wilson, 2008; Peterson et al., 2011).

518   The significant variability in the extent of abrasion between the sites is explained by the

519   highly dynamic depositional conditions of the two localities. The JONS assemblage includes

520   IBFs that are more rounded than the fragments found in the CLDQ assemblage. This suggests

521   that the Johnsonville locality was subjected to relatively higher and more consistent energy.

522   While the sedimentological evidence does not indicate an in-channel depositional subsystem, the

523   silty mudstone lithology and the presence of abundant freshwater microvertebrate fossils (i.e.

524   crocodilian, turtle, and fish) support the interpretation of wet floodplain or crevasse-splay with a

525   generally higher water table (Bilbey, 1998).

526   Conversely, the CLDQ assemblage exhibits considerably greater diversity in the degree

527   of abrasion with a mixture of angular and rounded fragments. The matrix at the CLDQ is a fine

528   calcareous mudstone, representing a normally low-energy system that likely was ephemeral.

529   However, the fragments possess a hydraulic equivalence of fine sand, suggesting that some of

530   the fragments are autochthonous or parautochthonous remains of crushed local bones whereas

531   others are allochthonous and washed in from upstream (sensu Fernandez-Jalvo and Andrews,

532   2003). The physical characteristics of the bone fragments of CLDQ suggest variable taphonomic

533   histories among the fragments; angular fragments suggest a pulverization followed immediately

534   by burial while rounded fragments suggest prolonged exposure and local transport (Fernandez-

535   Jalvo and Andrews, 2003) (Figure 9A-D).

536   The majority of macrovertebrate remains at CLDQ possess no apparent signs of

537   weathering, suggesting an approximate subaerial exposure time of two years or less (*sensu*

538   Gates, 2005), with rapid burial or submersion in water halting the progression of weathering and

539   abrasion (Gifford, 1985). However, the variable angularity of the small bone fragments indicate

540   that some bones were exposed longer than others (Fernandez-Jalvo and Andrews, 2003).

541   Behrensmeyer's (1978) temporal scale for bone weathering in arid environments indicates that

542   remains can be broken down to fragments on a temporal scale of 6-15 years (Behrensmeyer's

543   Stage 5, 1978). Behrensmeyer (1978) also observed that rates of bone weathering can be

544   increased with the crystallization of salts (Na_2CO_3, NaCl) on bone surfaces, producing cracking,

545   splitting, and fragmentation. Similarly, Hare (1974) demonstrated that the organic breakdown of

546   bones can be enhanced by fluctuating temperature and humidity. The broad distribution and

547   variable angularity of bone fragments throughout the CLDQ matrix suggests that bones exposed

548   at the surface may have been similarly weathered and degraded during fluctuations in moisture,

549   and suggest that the CLDQ deposit may broadly represent a temporal range of at least 10-20

550   years for accumulation. However, the number of moisture cycles and depositional events are not

551   fully understood at this time.

552   Thin section analyses of IBFs within the CLDQ matrix show the presence of phosphate

553   crystallites within the void spaces of bone fragments (Figure 7). The morphology of the

554   crystallites is globular, indicative of microbially-mediated phosphate infilling of bone pore space

555   from the dissolution and re-precipitation of organic phosphates (i.e. bone) (Hirschler et al.,

556   1990), implying that the bone fragments were pedogenically reworked following initial

557   permineralization (Jennings and Hasiotis, 2006). This suggests that the total CLDQ assemblage,

558   both intramatrix fragments and the well-documented macrovertebrate fauna, formed from

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559 multiple depositional events - perhaps seasonal - and not from a single catastrophic episode

560 (sensu Gates, 2005). If the CLDQ had formed from a single event, multiple abrasion and

561 weathering signatures on bone fragments would not be expected. This interpretation is further

562 supported by the apparent lack of abundant identifiable freshwater microvertebrate remains; the

563 lack of permanent water would reduce the abundance of freshwater taxa such as fish, turtles, and

564 crocodilians. Meanwhile, seasonal fluctuations in the local water table related to the monsoonal

565 climate patterns of the Late Jurassic (e.g. Hallam, 1993; Rees et al., 2000; Sellwood and Valdes,

566 2008) would have rejuvenated mobilization of fragments that otherwise remained at the surface

567 (Figure 9D).

568 *Paleoecological Inferences* - While geochemical and sedimentological data can assist in

569 reconstructing the depositional environment and taphonomic history of the CLDQ (Figure 9A-

570 D), the question remains - Why is there a dominating abundance of *Allosaurus* remains at the

571 Cleveland-Lloyd Dinosaur Quarry?

572 Most multi-taxa bone beds in the Morrison formation are dominated by large herbivorous

573 dinosaurs (Dodson et al., 1980), though many Morrison bone beds also include remains of

574 theropods, commonly *Allosaurus* (Dodsen et al., 1980). However, predator-dominant localities

575 are known from other units in the Mesozoic system, such as the Upper Chinle *Coelophysis*

576 quarry from Ghost Ranch, New Mexico (Schwartz and Gillette, 1994) and the Upper Horseshoe

577 Canyon *Albertosaurus* bonebed from southern Alberta (Eberth and Currie, 2010). The nature of

578 these accumulations are both interpreted to be the result seasonally-influenced events; a drought-

579 induced death assemblage of *Coelophysis* carcasses that were transported post-mortem by

580 subsequent fluvial current (Schwartz and Gillette, 1994), and a storm-induced flooding event

581 either directly or indirectly resulting in the death of a population of *Albertosaurus* (Eberth and

582   Currie, 2010). Similarly, the CLDQ taphonomic data presented here also supports an

583   interpretation of a post-mortem attritional accumulation due to season fluctuations.

584   Previously, studies on Morrison climate and ecosystems suggest strong seasonality with

585   periods of aridity during weak monsoons to sub-humid conditions during stronger monsoons

586   similar to climates seen in modern savannahs (Turner and Peterson, 2004; Parrish et al., 2004;

587   Tanner et al., 2014). While such climate interpretations generally agree with taphonomic

588   reconstructions of various Morrison bone beds, including the CLDQ, they can also offer insight

589   into paleoecological interpretations that may have contributed to the quarry assemblage.

590   Fossil accumulations of multiple individuals of a single species are not necessarily

591   indicative of complex familial or social behaviors. In modern savannahs, seasonal aridity brings

592   grazing animals that are typically solitary together into larger groups near evaporating bodies of

593   water (Western, 1975). Extant archosaurs, such as the Common Ostrich (*Struthio camelus*) and

594   the Spectacled Caiman (*Caiman crocodilus crocodilus*) congregate in increased numbers during

595   extreme seasonal changes, either for breeding or following food sources, leading to increased

596   mortality during times of increased aridity or drought (e.g. Staton and Dixon, 1975; Knight,

597   1995). Furthermore, the reproductive cycles of many of these animals are tied to environmental

598   and seasonal fluctuations, where fecundity, ovulation, and birth occur near an oncoming wet

599   season (Hanks, 1979).

600   Breeding or nesting sites are relatively rare in the Morrison; only nine such localities

601   have been described to date (Bray and Hirsch, 1998). While there is no direct evidence of the

602   CLDQ being a breeding site for *Allosaurus*, a single fossilized egg was collected from the quarry

603   (Hirsch et al., 1989), and has been attributed to *Allosaurus* due to the high frequency of the taxon

604   in the quarry (Madsen, 1991). However, the CLDQ egg possesses an abnormally thick shell layer

605 (Hirsch et al., 1989), which is frequently caused by environmental or seasonal stress (Mills et al.,

606 1987; Hirsch, 2001). Though a single egg does not directly suggest that the CLDQ was a

607 breeding site for *Allosaurus*, eggs could potentially have survived short distance transport in a

608 fluvial system (e.g. Jackson et al 2013).

609　　　　Given the extreme seasonal variability in the Late Jurassic and the evidence described

610 here for an attritional accumulation for the CLDQ, *Allosaurus* may have been congregating

611 seasonally in the vicinity for a number of reasons, such as breeding, food, or water. With

612 increased aridity, mortality rates may have been higher, producing carcasses that would mobilize

613 during subsequent wet seasons similar to what is observed with extant archosaur carcasses

614 during strong seasonality (Weigelt, 1989; Knight, 1995; Staton and Dixon, 1975). Transport

615 processes and fluctuations in the water table could contribute to the disarticulated nature of the

616 caracsses in the deposit (Gates, 2005). Further geochemical and isotopic analysis of remains

617 recovered from CLDQ may help to evaluate whether *Allosaurus* were congregating before death

618 and deposition, giving the bones similar isotopic and trace metal signatures, or, alternatively,

619 were transported in from across the landscape post-mortem, bringing together a wide variety of

620 isotopic and trace metal signatures

621

622 CONCLUSIONS

623　　　　The Cleveland-Lloyd Dinosaur Quarry is a potentially significant source of data for

624 understanding Jurassic dinosaur paleoecology. However, interpretation is constrained by the

625 taphonomic and environmental framework the quarry represents. Two new lines of evidence,

626 sediment geochemistry and intramatrix bone fragment abrasion and weathering patterns, support

627 previous conclusions that the CLDQ represents and ephemeral, seasonally dry pond.

628 Furthermore, both data sets support the interpretation that the CLDQ was formed from multiple

629   depositional events. In addition, each data set can add to the current understanding of CLDQ

630   taphonomy.

631   New geochemical data show the quarry is enriched in heavy metals and sulfide minerals

632   in stark contrast with the surrounding Morrison Formation strata, including mudstones at the

633   same stratigraphic level surrounding the quarry deposit. While diagenetic processes certainly

634   contributed to the heavy metal composition of CLDQ materials, the presence of sulfides and

635   calcite/barite nodules in the CLDQ sediments suggest a hypereutrophic environment resulting

636   from the decay of many dinosaurs in a small depression. Significant numbers of rotting dinosaurs

637   in a body of standing water would potentially have contributed to the heavy metals composition

638   of the water column via bioaccumulation. High rates of organic matter decay would have led to

639   hypoxia or anoxia and the subsequent formation of sulfide minerals and the calcareous soaps

640   required to form calcite nodules.

641   Finally, hypereutrophy can help explain the near total lack of gnawing and other

642   biostratinomic effects seen in a typical freshwater ecosystem. While these new geochemical data

643   do not inform where the dinosaurs found at the CLDQ died, hypereutrophy related to dinosaur

644   carcass decay is one possible explanation for the lack of typical freshwater faunal remains and

645   feeding traces at the CLDQ. Initial geochemical data presented here suggest this taphonomic

646   framework, however a more extensive analysis of bone geochemistry is needed to support this

647   hypothesis. Analysis of sediment and bone from the Mygatt-Moore Quarry support these

648   conclusions by providing strong contrast. Although heavy metals are present in MMQ, as

649   expected from bone bed diagenesis, the other geochemical indicators of hypereutrophy are not

650   present. The unique preservation of bone found at CLDQ is a result of chemical conditions not

651   present in the more common depositional setting represented by MMQ.

652   Furthermore, quantitative and qualitative assessment of intramatrix bone fragments at the

653   CLDQ and the new Johnsonville site indicate subtle but important differences in the depositional

654   systems that produced the respective assemblages. While the bone fragments at both localities

655   suggests a comparable hydraulic equivalence, the differences in the local lithologies and average

656   abrasion profiles for bone fragments at each locality suggest considerable disparity in the genesis

657   of each site. In particular, the taphonomic characteristics of the IBFs of the CLDQ assemblage,

658   coupled with the quarry lithology, support the interpretation that the quarry assemblage was

659   produced by a series of separate depositional events punctuated by periodic aridity. The IBF data

660   presented here contribute to former taphonomic assessments of the CLDQ by providing

661   previously uninvestigated sedimentological and micro-taphonomic insight into the origins of the

662   quarry assemblage. Unidentifiable fossil fragments are often overlooked. While small, the

663   utilization of IBF data in conjunction with associated macro-taphonomic and sedimentologic

664   data, has the potential to improve the resolution of complex and perplexing taphonomic

665   questions.

666

667   ACKNOWLEDGMENTS

682

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924 FIGURES
925   1. Regional stratigraphy of the CLDQ vicinity. A) Stratigraphic column of the Morrison
926   Formation in the area around the Cleveland-Lloyd Dinosaur Quarry (CLDQ) and the
927   Johnsonville (JONS) sites, shown in meters above the basal contact of the Salt Wash
928   Member of the Morrison Formation with the upper Summerville Formation. Standard
929   USGS symbols of rock units are used in the diagram. B) Map showing sites, stratigraphic
930   section line, and regional stratigraphy in context of the San Rafael Swell.
931
932   2. Vertebrate fauna of the Cleveland-Lloyd Dinosaur Quarry, illustrating the 3:1 ratio of
933   predators to prey and minimum number of individuals for each taxa, based on left
934   femoral count. Modified from Gates, 2005.
935
936   3. Fossils of the Johnsonville site. A) Sauropod caudal vertebra; B) Shed theropod teeth
937   (left), crocodilian vertebra (center), and turtle shell (right). Scale bar equals 5 cm.
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939   4. Schematic diagram of the sediment processing tanks. Sediment was placed into the
940   meshed boxes and submerged with gentle air agitation for approximately 48-72 hours.
941
942   5. Examples of fragment abrasion stages, based on Wilson, 2008. Stage 0 – angular
943   fragments; Stage 1 – subangular fragments; Stage 2 – subrounded fragments; Stage 3 –
944   rounded fragments. Scale bar equals 5mm.
945
946   6. X-ray Fluorescence results. The concentrations of selected metals detected in sediment
947   and bone collected from the CLDQ are compared with those of sediments local Morrison
948   Formation strata, labeled "Strat" and sediment and bone from MMQ. CLDQ sediments
949   and bone stand out in contrast to most other elements, yet are similar to those found at
950   MMQ. All values are given in ppm, and abbreviations are as follows: min - minimum;
951   avg - average; max - maximum.
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953   7. Intramatrix bone fragment in petrographic thin section. Arrows annotating the location of
954   phosphate crystallites in porous cavities within the fragment. Scale bar equals 10 μm.
955
956   8. Distribution of abrasion stages of intramatrix bone fragments at the CLDQ (gray) and
957   JONS (white) localities. Error bars represent standard error.
958
959   9. Conceptual model of the CLDQ depositional system. A) Dinosaur carcasses are washed
960   into the CLDQ deposit during a flood stage. High rates of organic matter decay leads to
961   hypereutrophy, calcite and barite precipitation, and discourages biostratinomic
962   influences. B) As water levels recede during drier conditions, bones that were not buried
963   during the flood stage remain at the surface. C) During arid conditions, bones present at
964   the surface undergo weathering and abrasion, generating the intramatrix bone fragments
965   present at the CLDQ. D) Floodstage returns, incorporating new carcasses and re-worked
966   bones and fragments to the deposit. The cycle repeats until the deposit maintains a higher
967   water table, producing the limestone above the bone-bearing siltstone.
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970 TABLES
971   1. XRD data. All minerals identified in every sample analyzed from the stratigraphic
972   column are presented. A) XRD data from stratigraphic column; B) XRD data for CLDQ
973   samples. CLDQ stands out given the presence of barite and sulfide minerals.
974

975   2. Taphonomic characteristics and comparisons of intramatrix bone fragments of the CLDQ
976   and JONS sites. Characteristics include A) dominant lithology, B) depositional
977   interpretation, C) percentages of 60kg matrix sample represented by fossil fragments, D)
978   abrasion stages (based on Wilson, 2008), and E) hydraulic equivalence calculation
979   results.
980

981   3. Obsidian chemistry vs CLDQ chemistry. This table shows the contrasting geochemistry
982   of metals detected in CLDQ sediments with that of obsidians which act as proxies for
983   ashes emplaced locally during the Jurassic (Hubert et al., 1996). The contrasting
984   elemental profiles suggest that volcanic ashes are not the source of metals detected at the
985   CLDQ.
986

987 SUPPLEMENTARY DOCUMENT AND TABLES

988 Table S1: XRF data. The chemical composition of all samples analyzed via XRF is given in

989 ppm. Missing values represent metals not detectable by the pXRF located at Indiana University

990 of Pennsylvania

991 Table S2: CLDQ IBF Measurements and data.

992 Table S3: JONS IBF Measurements and data.

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Figure 1

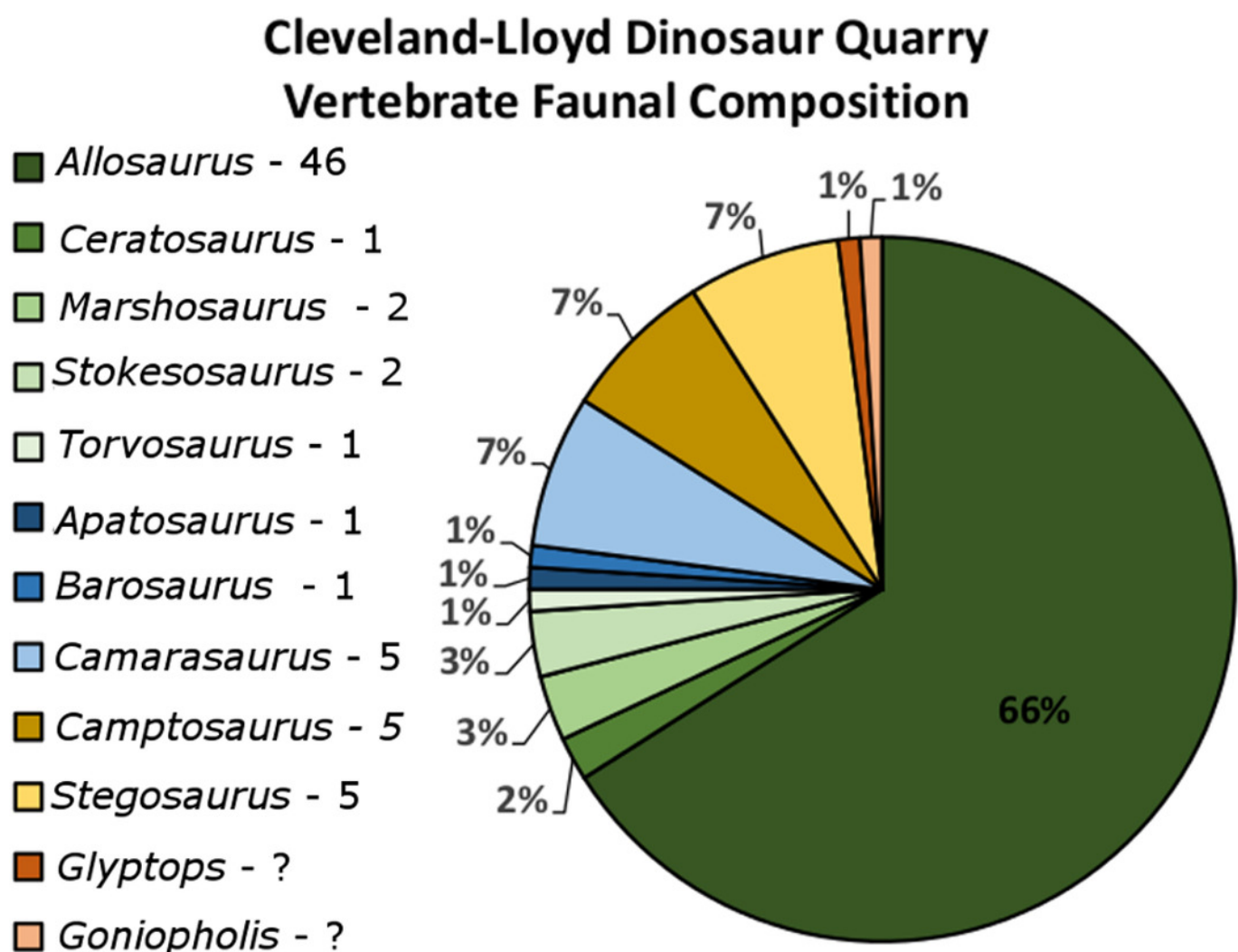Regional stratigraphy of the CLDQ vicinity.

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.
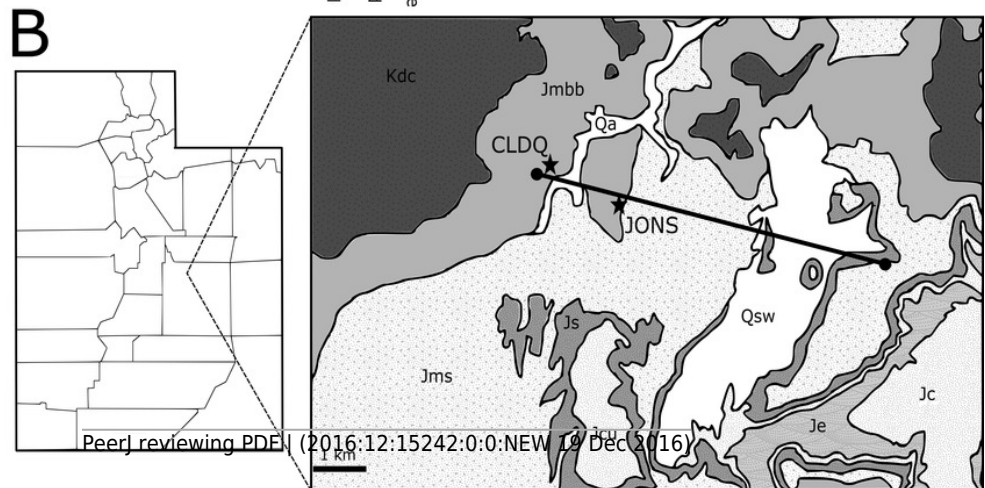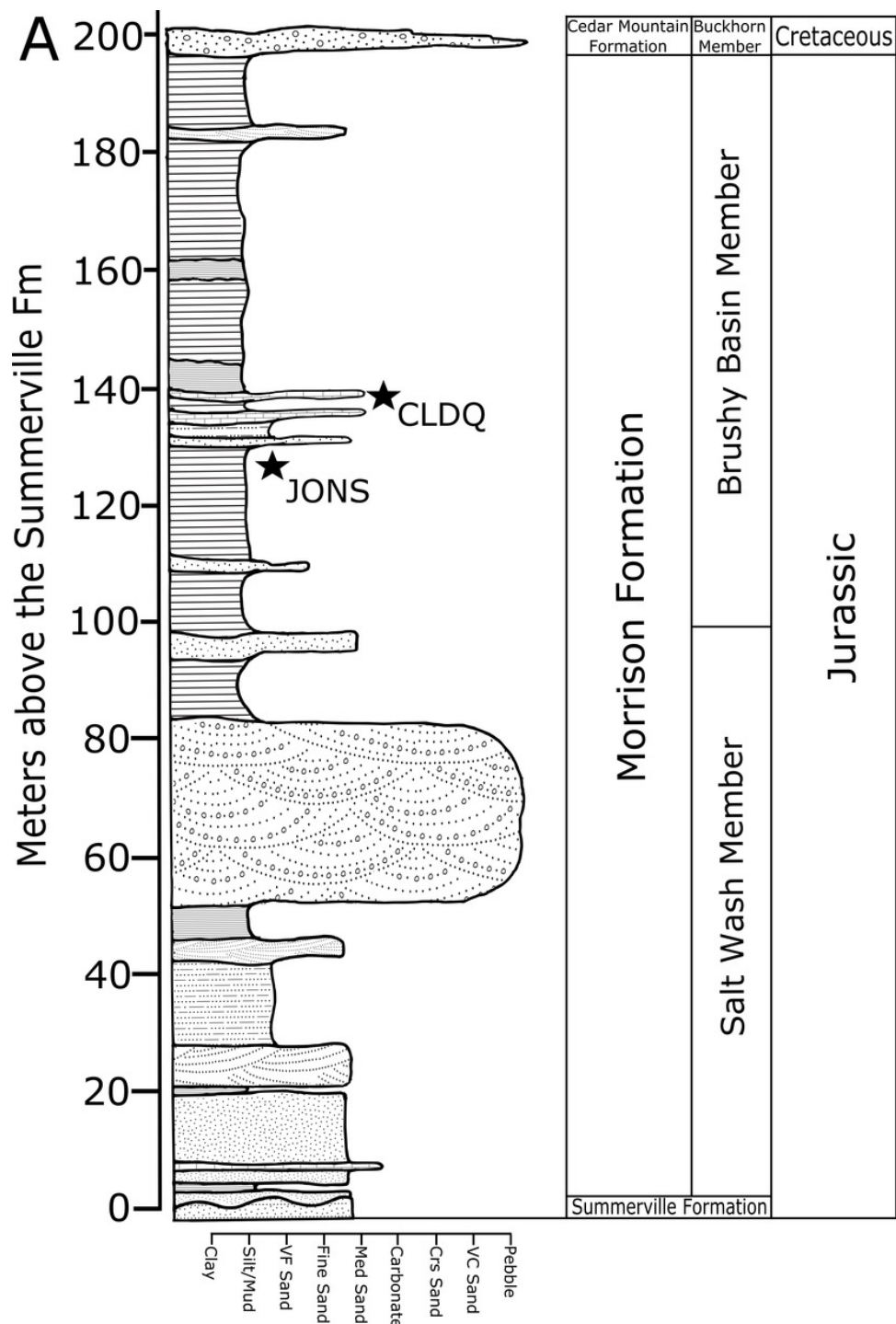
Figure 2

Vertebrate fauna of the Cleveland-Lloyd Dinosaur Quarry

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.

**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 - ?

Figure 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.
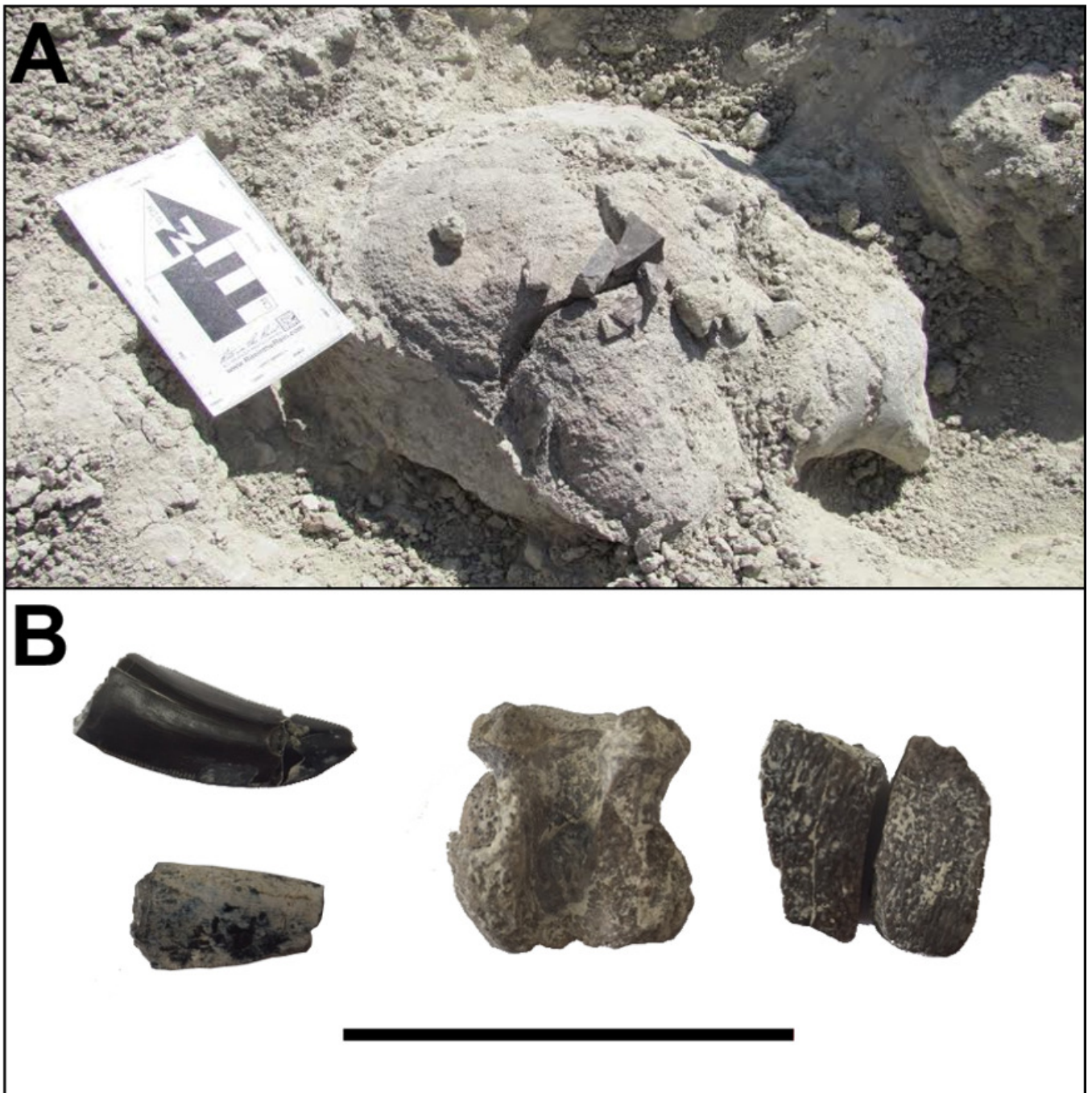
Figure 4

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.
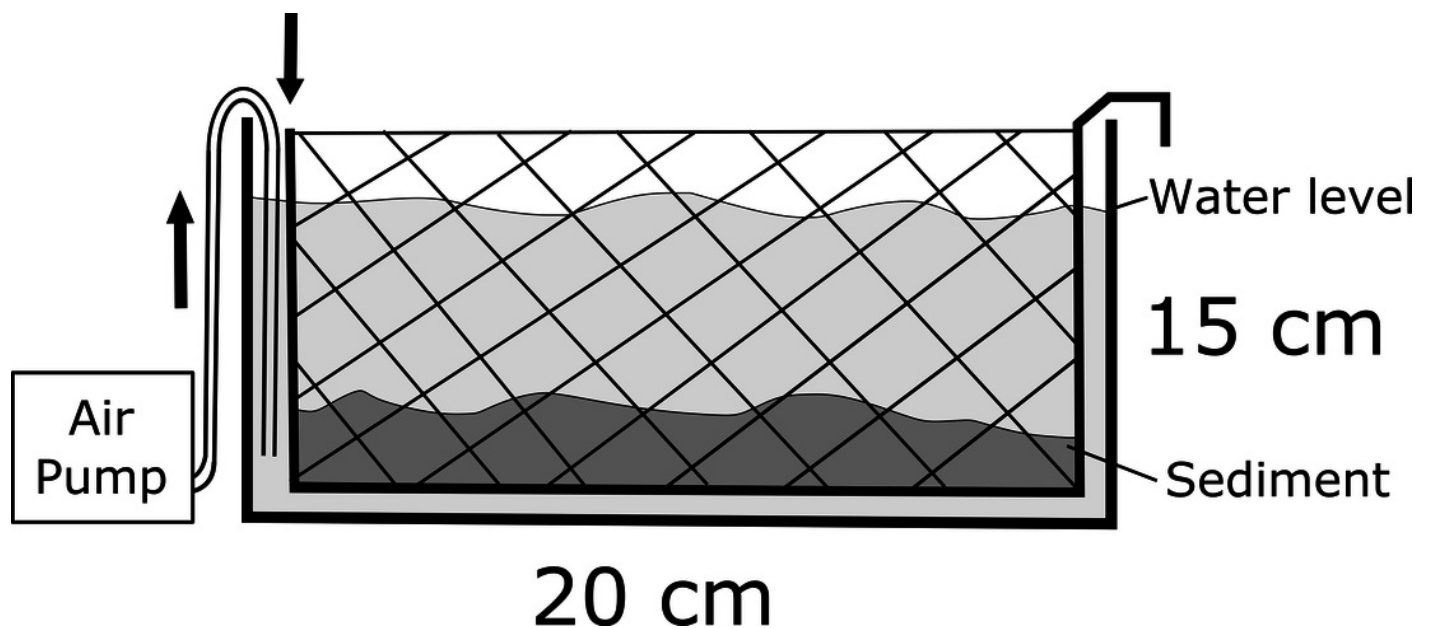
Figure 5

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.
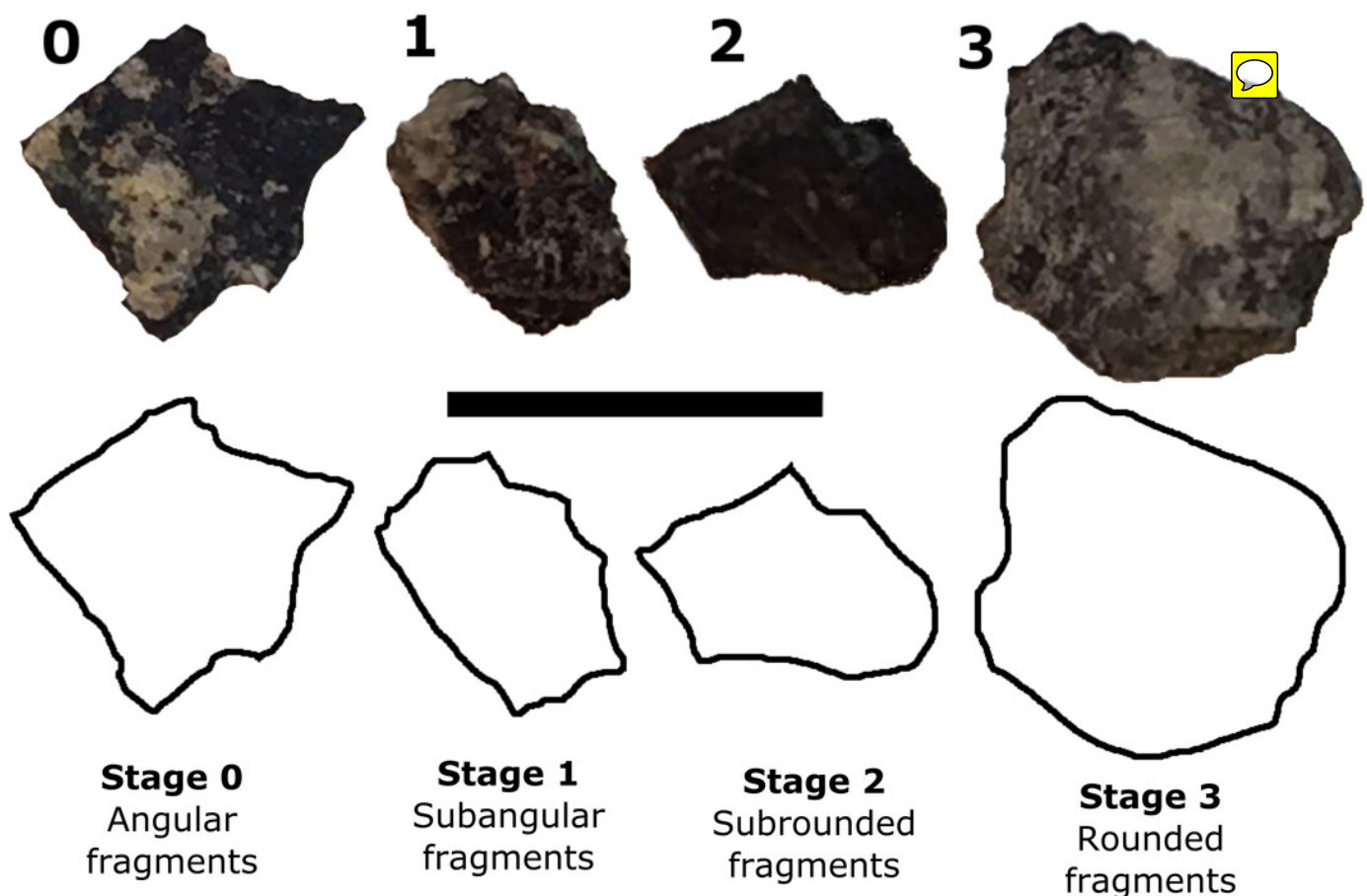
Figure 6

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.
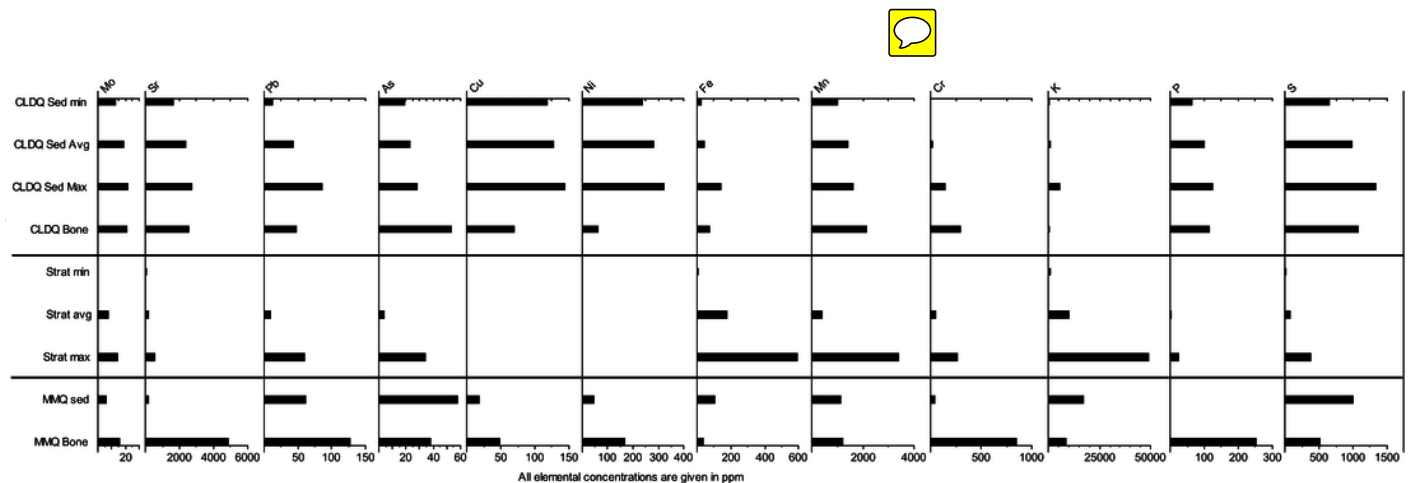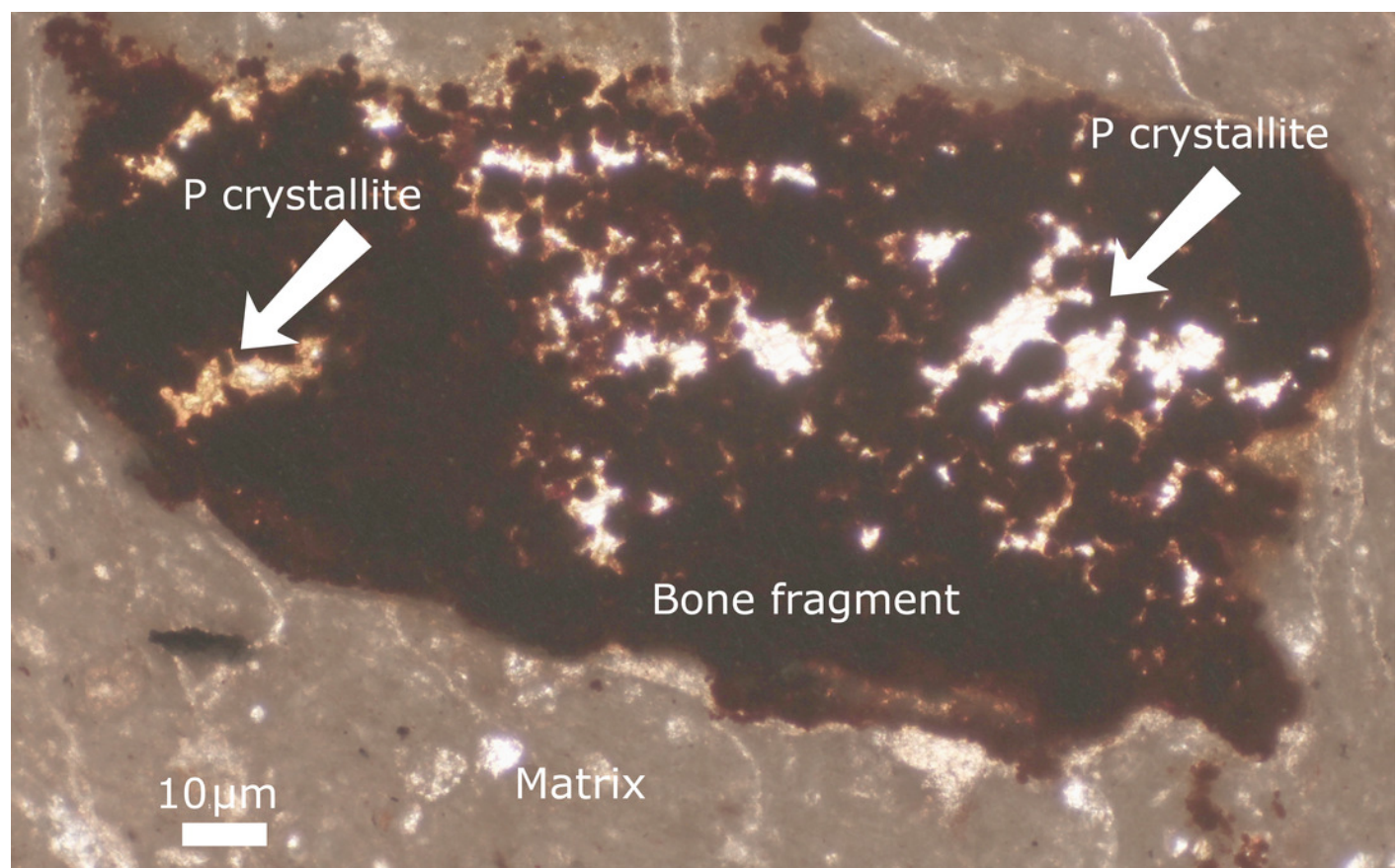
Figure 7

Intramatrix bone fragment in petrographic thin section.

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.

Note: Auto Gamma Correction was used for the image. This only affects the reviewing manuscript. See original source image if needed for review.
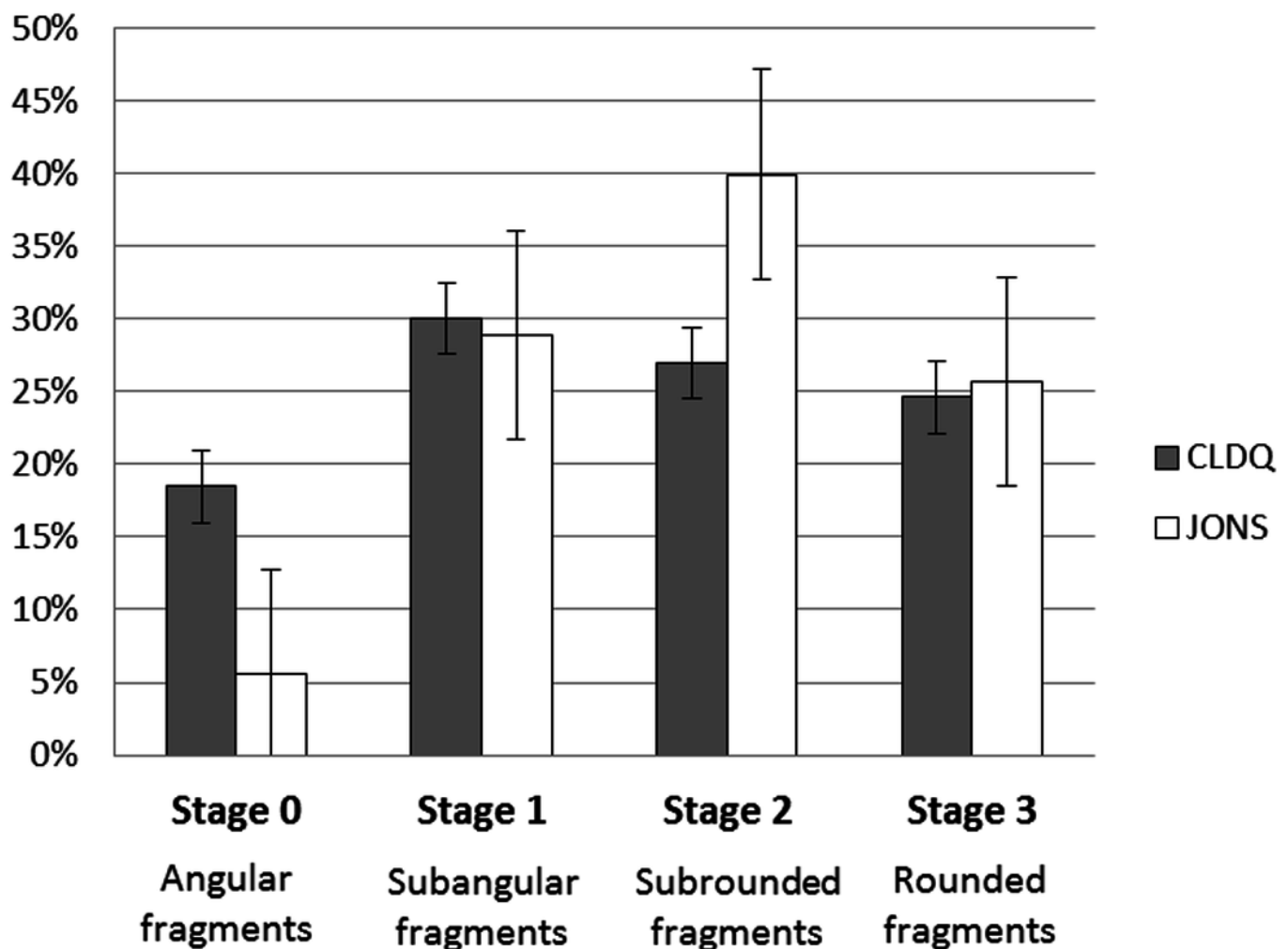
Figure 8

Distribution of abrasion stages of intramatrix bone fragments.

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

Figure 9

Conceptual model of the CLDQ depositional system.

A) Dinosaur carcasses are washed into the CLDQ deposit during a flood stage. High rates of organic matter decay leads to hypereutrophy, calcite and barite precipitation, and discourages biostratinomic influences. B) As water levels recede during drier conditions, bones that were not buried during the flood stage remain at the surface. C) During arid conditions, bones present at the surface undergo weathering and abrasion, generating the intramatrix bone fragments present at the CLDQ. D) Floodstage returns, incorporating new carcasses and re-worked bones and fragments to the deposit. The cycle repeats until the deposit maintains a higher water table, producing the limestone above the bone-bearing siltstone.
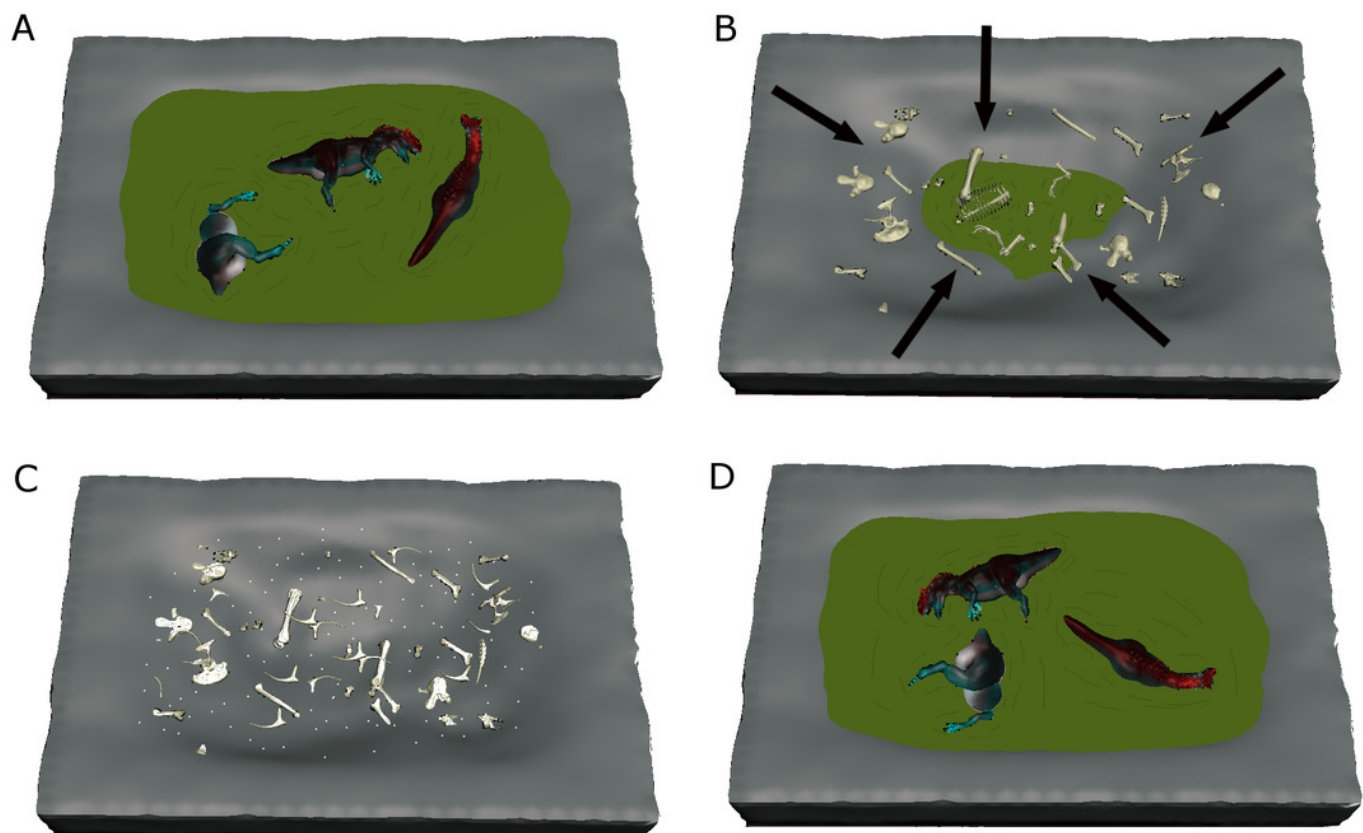
Table 1(on next page)

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.

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

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26 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

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Table 2(on next page)

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.

		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

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Table 3(on next page)

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.

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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