doi:10.1130/G32944Y.1

Forum Reply

Direct U-Pb dating of Cretaceous and Paleocene dinosaur bones, San Juan Basin, New Mexico

James E. Fassett[1], Larry M. Heaman[2], and Antonio Simonetti[3]
[1]Independent Research Geologist, 552 Los Nidos Drive, Santa Fe, New Mexico 87501, USA
[2]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta T6G 2E3, Canada
[3]Department of Civil Engineering and Geological Sciences, Cushing Hall, Notre Dame University, Notre Dame, Indiana 46556, USA

LUDWIG COMMENT

The Ludwig (2012) Comment on our paper (Fassett et al., 2011) primarily focuses on the U-Pb data treatment used to arrive at the original fossilization dates for our two dinosaur bone samples—specifically, the method we used to correct for the presence of common lead in dinosaur bone. As noted in our Reply (Fassett et al., 2012) to Koenig et al. (2012), the ^{207}Pb-method was used to correct for common Pb because the exact abundance of ^{204}Pb in these analyses is difficult to determine by the LA-ICP-MS technique, due to the presence of isobaric interferences, which are quasi impossible to quantify accurately. The ^{207}Pb-method is the well-established and preferred method for making such corrections in sample materials that contain abundant common lead using in-situ ion beam and laser ablation techniques (e.g., Williams, 1998; Storey et al., 2006). A manuscript now in preparation by Heaman, Simonetti, and Fassett (Heaman, 2012, personal commun.) will provide a more detailed description of the procedures used by Fassett et al. (2011), and describes in detail the geochemistry and isotope systematics of some regions within bone 22799-D, disturbed by one or more post-fossilization uranium-enrichment events. The discussions in that paper clearly demonstrate that the low ^{238}U/^{204}Pb domains typically do preserve dates in accordance with the well-constrained depositional age of the host rock, and thus provide an accurate estimate of the fossilization date. The fact that the date of 73.6 Ma that we obtained for control bone 22799-D is virtually the same as a single-crystal ^{40}Ar/^{39}Ar age of 73.04 Ma obtained for sanidine crystals from a proximal, altered volcanic ash bed (Fassett and Steiner, 1997; Fassett, 2000) at the same stratigraphic level as bone 22799-D further validates our laser-ablation U-Pb dating procedures, and the dates we reported.

RENEE AND GOODWIN COMMENT

Our responses to specific comments by Renne and Goodwin (2012) are as follows:

1. "The samples were fossils, not bones composed of unaltered hydroxyapatite, and as such they have been open systems whose uranium and lead uptake/leaching histories are conjectural."

This statement infers that the fossilization and emplacement of trace elements in bone never results in a closed geochemical system; however, a growing body of data has shown that the uptake of U and rare earth elements (REE) at the time of fossilization and the concurrent elimination of bone porosity occurs soon after the animal dies (within a few tens of thousands of years), trapping these elements in a tightly closed system (see references in Fassett et al., 2011). Our analysis shows that the chemistry in parts of bone 22799-D has remained closed from shortly after the time of fossilization (ca. 73.6 Ma) to the present. This conclusion is confirmed by the similarity of our age to the ^{40}Ar/^{39}Ar age of a nearby ash bed at the same stratigraphic level, as discussed above.

2. "Both samples analyzed (22799-D and BB1) are fossil bone fragments rather than articulated fossil skeletons and are therefore suspect *a priori* of being reworked."

Both of our dated bone samples came from strata with known ages, and our age determinations precisely matched those ages; therefore, what strata could these samples have been possibly reworked from, to give them these ages? Further, is the implication here that small bone fragments must always be "suspect *a priori*" of being reworked? If so, can we then assume that large bones are not suspect *a priori* of being reworked? The facts are that the Cretaceous sample 22799-D came from a badly fragmented, but very large limb bone, and Paleocene sample BB-1 was obtained from a meter-long section of a femur of *Alamosaurus sanjuanensis* (Fig. 1A). In addition to its size, the cortical surface of the BB-1 bone was pristine, making its reworking highly unlikely to impossible.

3. "To date, no . . . fossils unlikely to survive reworking unrecognized—are recorded in museum collections across North America from these or contemporaneous formations."

This assertion is incorrect. Fassett (2009, p. 57, fig. 38) discussed an assemblage of 34 fossil bones from a single hadrosaur discovered in the Paleocene Ojo Alamo Sandstone (Hunt and Lucas, 1991) that could not possibly have survived

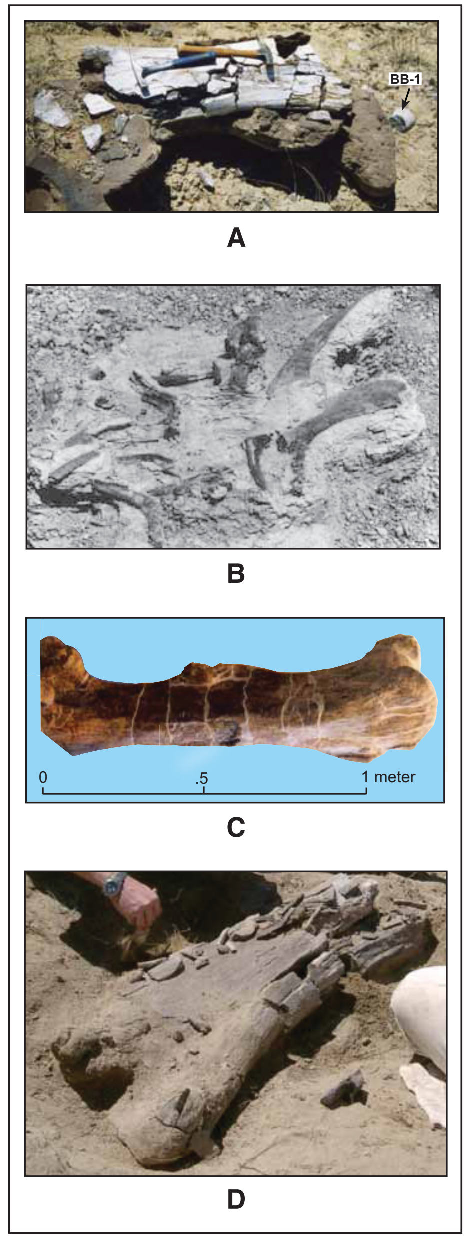

Figure 1. Photographs of four dinosaur bones (or bone-sets) from the Paleocene Ojo Alamo Sandstone of the San Juan Basin, New Mexico. Sample localities are in Fassett (2009). A: *Alamosaurus sanjuanensis* femur showing fragment BB-1 collected for analysis by Fassett in 1998 (photograph by J.E. Fassett). B: 34 skeletal elements from a single hadrosaur (note hammer for scale); photograph from S.G. Lucas. C: Hadrosaur femur from San Juan River site of Fassett (2009); photograph by S.G. Lucas. D: *Alamosaurus sanjuanensis* femur being excavated near Barrel Spring (photograph from R.M. Sullivan).

reworking (Fig. 1B). These bones have been in the collection of the New Mexico Museum of Natural History and Science in Albuquerque, New Mexico, for 20 years. In addition, a pristine massive hadrosaur femur in excess of one meter in length was collected from the Ojo Alamo Sandstone 15 m above the base of this formation (Fassett and Lucas, 2000) and this prepared specimen has been on display at the University of New Mexico since 1988 (Fig. 1C). Two Paleocene index palynomorphs (*Momipites tenuipolus* and *Brevicolporites colpella*) were identified from a coaly carbonaceous shale bed 5 m below the level of this hadrosaur femur (Fassett and Lucas, 2000; Fassett, 2009). In addition, a recent paper by D'Emic et al. (2011) described seven foot bones and parts of the tibia and fibula of *Alamosaurus sanjuanensis* collected from the Ojo Alamo Sandstone in 1978 and these bones were "transferred from the University of Arizona to the New Mexico Museum of Natural History in 2005" (p. 1073); these museum specimens could not possibly have been reworked from underlying Cretaceous strata.

4. "As in the 'Bug Creek Problem,' it is entirely possible that the fossil fragments studied by Fassett et al. were reworked postmortem."

The so-called "Bug Creek Problem" refers to an instance where dinosaur teeth were discovered in a few channel-sandstone beds reported to be of Paleocene age in the Hell Creek Formation in the small Bug Creek area in northeastern Montana (Sloan et al., 1986; Rigby et al., 1987). As Renee and Goodwin point out, this claim of Paleocene dinosaurs was subsequently challenged by other workers based partly on the suggestion that these relatively small teeth were probably reworked. Renee and Goodwin imply that the samples analyzed by us were "fossil fragments" and thus also subject to reworking in the same manner as was suggested for the fossil dinosaur teeth in the Bug Creek area. This comparison is not valid. As discussed above, the two dinosaur bones we dated from the Ojo Alamo Sandstone are quite large (see the photo of BB-1 in Fig. 1A), and other Ojo Alamo dinosaur bones discovered in the Ojo Alamo are even larger (Figs. 1C and 1D). In addition, the Ojo Alamo Sandstone is present in a relatively continuous outcrop (and can be traced on geophysical logs throughout the subsurface) as a unique and discrete rock unit throughout most of the New Mexico part of the San Juan Basin, thus this formation is in no way comparable to the isolated channel sandstones containing relatively small dinosaur teeth in a small area in Montana. In any event, the possible reworking of dinosaur teeth—"the Bug Creek problem"—in Montana has no relevance whatsoever to our study, which consisted of the laser-ablation U-Pb dating of two dinosaur bones.

5. "Even if such data could be used to date early postmortem diagenesis, taphonomic and stratigraphic evidence must be used to establish that the age of U-uptake places a valid constraint on the age of the animal."

Regarding taphonomic evidence, as stated above, most recent work indicates that bone fossilization and trace-element emplacement occurs shortly after death and burial. As for stratigraphic evidence, Fassett et al. (2002) and Fassett (2009) have shown that, based on detailed palynologic and paleomagnetic data, the dinosaur-bearing Ojo Alamo Sandstone is entirely Paleocene in age throughout the San Juan Basin. The in-situ U-Pb technique that we have developed provides a sensitive record of U-addition events post-fossilization, so the only question is whether the oldest dates that are obtained approach the fossilization date or not; based on sample 22799-D, we demonstrate that the oldest dates we obtained match the depositional age of the host rock.

GENERAL COMMENT ON REWORKING

Fassett et al. (2002) and Fassett (2009) tackled the possible reworking of Cretaceous Kirtland Formation dinosaur-bone fossils into Paleocene Ojo Alamo Sandstone strata by conducting chemical analyses of 15 bone samples from each of these formations. It was found that these two suites of bones each had distinctive concentrations of U and REE: very low U and high REE for Kirtland samples, and high U and low REE for Ojo Alamo samples. These authors accordingly concluded that these suites of bones had been mineralized while immersed in distinctly different mineral-bearing solutions, and had retained their original mineral fingerprints ever since, indicating that the Paleocene dinosaur bones of the Ojo Alamo had not been reworked from Cretaceous strata. These results also confirmed that the sampled areas of the bones we analyzed represented closed geochemical systems from the time of their original mineralization to the present.

REFERENCES CITED

D'Emic, M.D., Wilson, J.A., and Williamson, T.E., 2011, A sauropod dinosaur pes from the latest Cretaceous of North America and the validity of *Alamosaurus sanjuanensis* (Sauropoda, Titanosauria): Journal of Vertebrate Paleontology, v. 31, no. 5, p. 1072-1079.

Fassett, J.E., 2000, Geology and coal resources of the Upper Cretaceous Fruitland Formation, San Juan Basin, New Mexico and Colorado, *in* Kirschbaum, M.A., Roberts, L.N.R., and Biewick, L.R.H., eds., Geologic Assessment of Coal in the Colorado Plateau: Arizona, Colorado, New Mexico, and Utah: U.S. Geological Survey Professional Paper 1625-B, Chapter Q (published in digital form on CD-ROM), http://pubs.usgs.gov/pp/p1625b/Reports/Chapters/Chapter_Q.pdf (last accessed January 2012).

Fassett, J.E., 2009, New geochronologic and stratigraphic evidence confirms the Paleocene age of the dinosaur-bearing Ojo Alamo Sandstone and Animas Formation in the San Juan Basin, New Mexico and Colorado: Palaeontologia Electronica, v. 12, 146 p., http://palaeo-electronica.org/2009_1/149/index.html (last accessed January 2012).

Fassett, J.E., and Steiner, M.B., 1997, Precise age of C33n-C32r magnetic polarity reversal, San Juan Basin, New Mexico and Colorado, *in* Anderson, O.J., Kues, B.S., and Lucas, S.G., eds., Mesozoic Geology and Paleontology of the Four Corners Region: New Mexico Geological Society 48th Field Conference Guidebook, p. 239–247.

Fassett, J.E., and Lucas, S.G., 2000, Evidence for Paleocene dinosaurs in the Ojo Alamo Sandstone, San Juan Basin, New Mexico, *in* Lucas, S.G., and Heckert, A.B., eds., Dinosaurs of New Mexico: New Mexico Museum of Natural History and Science (Albuquerque, New Mexico), Bulletin 17, p. 221-230.

Fassett, J.E., Zielinski, R.A., and Budahn, J.R., 2002, Dinosaurs that did not die: Evidence for Paleocene dinosaurs in the Ojo Alamo Sandstone, San Juan Basin, New Mexico, *in* Koerble, C., and McLeod, K.G., eds., Catastrophic Events and Mass Extinctions: Impacts and Beyond: Geological Society of America Special Paper 356, p. 307–336.

Fassett, J.E., Heaman, L.M., and Simonetti, A., 2011, Direct U-Pb dating of Cretaceous and Paleocene dinosaur bones, San Juan Basin, New Mexico: Geology, v. 39, p. 159–162, doi:10.1130/G31466.1.

Fassett, J.E., Heaman, L.M., and Simonetti, A., 2012, Direct U-Pb dating of Cretaceous and Paleocene dinosaur bones, San Juan Basin, New Mexico: Reply: Geology, e263, doi:10.1130/G32758Y.1.

Hunt, A.P., and Lucas, S.G., 1991, An associated Maastrichtian hadrosaur and a Turonian ammonite from the Naashoibito Member, Kirtland Formation (Late Cretaceous: Maastrichtian), northwestern New Mexico: New Mexico: Journal of Science, v. 31, p. 27–35.

Koenig, A.E., Lucas, S.G., Neymark, L.A., Heckert, A.B., Sullivan, R.M., Jasinski, S.E., and Fowler, D.W., 2012, Direct U-Pb dating of Cretaceous and Paleocene dinosaur bones, San Juan Basin, New Mexico: Comment: Geology, e262, doi:10.1130/G32154C.1.

Ludwig, K.R., 2012, Direct U-Pb dating of Cretaceous and Paleocene dinosaur bones, San Juan Basin, New Mexico: Comment: Geology, e258, doi:10.1130/G32503C.1.

Renne, P.R., and Goodwin, M.B., 2012, Direct U-Pb dating of Cretaceous and Paleocene dinosaur bones, San Juan Basin, New Mexico: Comment: Geology, e259, doi:10.1130/G32521C.1.

Rigby, J.K., Jr., Newman, K.R., Smit, J., Van DerKaars, S., Sloan, R.E., and Rigby, J.K., 1987, Dinosaurs from the Paleocene part of the Hell Creek Formation, McCone County, Montana: Palaios, v. 2, p. 296–302, doi:10.2307/3514679.

Sloan, R.E., Rigby, J.K., VanValen, L.M., and Gabriel, D., 1986, Gradual dinosaur extinction and simultaneous ungulate radiation in the Hell Creek Formation: Science, v. 232, p. 629–633, doi:10.1126/science.232.4750.629.

Storey, C.D., Jeffries, T.E., and Smith, M., 2006, Common lead-corrected laser ablation ICP-MS U-Pb systematics and geochronology of titanite: Chemical Geology, v. 227, p. 37–52, doi:10.1016/j.chemgeo.2005.09.003.

Williams, I.S., 1998, Chapter 1. U-Th-Pb geochronology by ion microprobe, *in* McKibben, M.A., Shanks III, W.C., and Ridley, W.I., eds., Applications of Microanalytical Techniques to Understanding Mineralizing Processes: Reviews in Economic Geology, v. 7, p. 1–35.