



Middle Pleistocene age of the fossiliferous sedimentary sequence from Tarija, Bolivia

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ABSTRACT

The highly fossiliferous sediments of the Tolomosa Formation from Tarija, southern Bolivia, represent one of the most important localities in South America that documents the Great American Biotic Interchange. Over the past several decades, chronostratigraphic studies have indicated a middle Pleistocene age for the Tolomosa Formation from ~1.1 to 0.7 Ma. This interval correlates to the Ensenadan South American Land Mammal Age as it is characterized from classic localities in Argentina. Recently, however, a new interpretation based on AMS ¹⁴C ages indicates that the fossiliferous sediments from Tarija are latest Pleistocene, i.e., <44 ka, and thus of Lujanian age. Here we report a new age of 0.76 ± 0.03 Ma (2σ) based on 11 U–Th/Pb and U–Th/He individual determinations from the Tolomosa Formation. This is indistinguishable from the age published from the same ash in 1983, and was originally used to calibrate the magnetostratigraphic section at Tarija. The new age confirms that the age of the Tolomosa Formation is middle Pleistocene, and not latest Pleistocene. The age of the Tarija Fauna has significant implications with regard to the stage of evolution biochronology for Pleistocene fossil mammals in South America, and in particular, the classic and important reference sections in Argentina.

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Introduction

Fossil bones and teeth of extinct mammals have been collected for six centuries from the extensive badlands exposures surrounding the city of Tarija, southern Bolivia (Fig. 1). This so-called Tarija Fauna has become one of the most thoroughly described (e.g., Boule and Thévenin, 1920) and best-known Pleistocene assemblages in South America that characterizes the Great American Biotic Interchange (GABI). The importance of Tarija for understanding the biochronology of Pleistocene mammals rivals the classic localities and faunas from Argentina, the latter of which provide the foundation for development of the South American Land Mammal Age (SALMA) chronology. Based on stage of evolution biochronology, the Tarija Fauna has been generally considered to be Ensenadan SALMA, or middle Pleistocene in age (e.g., Marshall et al., 1984; Flynn and Swisher, 1995), although the possibility that this sequence spans upwards into post-Ensenadan (Bonaerian, Lujanian, *sensu* Cione and Tonni, 1999) time cannot be ruled out (Marshall et al., 1984; Tonni et al., 2009). The Ensenadan is particularly important to understand the faunal dynamics of GABI because of the high diversity of North American immigrants that first occur during this time interval (e.g., Woodburne, 2010). As such, and because the Tarija Fauna is one of the richest known from the middle Pleistocene of South America, the calibration of its age is

of broad significance with regard to distinct dispersal phases within the GABI.

MacFadden et al. (1983) presented the magnetic polarity stratigraphy of a ~280-m-thick composite section the fossil-bearing Tolomosa Formation from the Tarija basin (Fig. 2), which includes the Tarija Fauna. The pattern of magnetic polarity stratigraphy indicated that the polarity of the lower ~110 m of their measured section is dominantly reversed, but includes a short (~10-m thick) interval of normal polarity. The upper ~200 m of this composite section is entirely of normal polarity. Assuming a middle Pleistocene age based on the Ensenadan fauna, an unambiguous correlation to the Geomagnetic Polarity Time Scale (GPTS) indicated that: (1) The lower reversed zones represent the younger part of the Matuyama reversed chron (C1r), with the Jaramillo subchron (C1r.1n). (2) The overlying Matuyama–Brunhes transition (in 1983 thought to be at 0.73 Ma, now calibrated to 0.78 Ma: e.g., Gee and Kent, 2007) is found ~110 m above the base of the section. (3) The upper two-thirds of the Tolomosa Formation represent an interval of unspecified duration within the Brunhes normal chron (C1n). In support of this correlation to the GPTS, MacFadden et al. (1983) presented a fission-track (zircon) age determination from a prominent 1–2 m thick tuffaceous horizon interbedded in the measured San Blas section (Fig. 2) that yielded an age of 0.7 ± 0.2 Ma (also see below). This is the same San Blas ash (unit 20) from which we present new data here.

The lower age limit of the Tarija Fauna is constrained by the magnetostratigraphic correlation to the GPTS. Thus, the base of the Tolomosa from our composite section occurs about 20 m below

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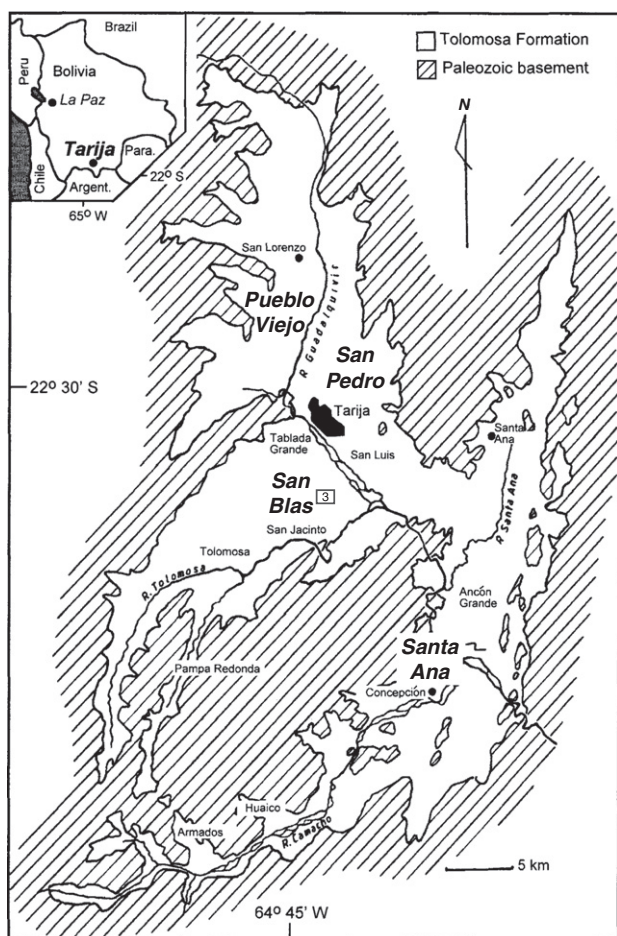


Figure 1. Map of the Tarija Basin, southern Bolivia showing the outcrop pattern of the fossil-bearing late Pleistocene Tolomosa Formation. From MacFadden (2000). The individually measured sections, originally published by MacFadden et al. (1983), are indicated in bold italics: Santa Ana, San Blas San Pedro and Pueblo Viejo. The area of the Google Earth® image presented in Fig. 3 is indicated by the gray box with the “3” inside it located to the right of the San Blas name.

the bottom of the Jaramillo subchron (C1r.1n), which is dated at 1.07 Ma. We therefore extrapolate the lower age to slightly older than 1.07 Ma, thus ~1.1 Ma. The upper age limit of the Tolomosa Formation has been problematical because other than the fact that it represents some amount of Quaternary time within the Brunhes, this duration is indeterminate. Based on stage of evolution biochronology (and not physical or magnetic polarity stratigraphy) the upper bounds were thought to be Ensenadan (MacFadden et al., 1983), although the transition to the younger Lujanian SALMA could not be ruled out. Based on analysis of stable isotope signatures from *in situ* fossil teeth from Tarija, MacFadden (2000) correlated the entire Tolomosa sequence as represented in the 280-m-thick composite section (MacFadden et al., 1983) to range from marine oxygen isotope stage (MIS) 29 to MIS 17 or 15. With this constraint, the upper bound of the Tolomosa would be about 0.7 Ma, and the entire Tarija Fauna would be Ensenadan SALMA based on geochronology.

To summarize, until recently, the age of the classic Tarija Fauna has generally been accepted to be middle Pleistocene (Ensenadan SALMA), and to have spanned an interval from ~1.1 to 0.7 Ma. However, recent papers (Coltorti et al., 2007, 2010) described below present new data that call into question the middle Pleistocene age for the Tolomosa Formation, and hence the Tarija Fauna. Based on AMS radiocarbon ages of interbedded peats and paleosol organics, these studies conclude that the section is only ~20 to 60 ka in age. Other studies, e.g., of the glyptodonts from the Tarija Fauna (e.g., Zurita et al., 2009) have had to

reinterpret the phylogeny and evolution of Pleistocene mammals in South America within the context of these highly conflicting chronologies (also see biochronological analysis by Tonni et al., 2009). The purpose of this paper is to: (1) address this new interpretation as it relates to the local age at Tarija, (2) present new radioisotopic age determinations for the critical San Blas ash, and (3) discuss implications for a broader understanding of the calibration of the Ensenadan SALMA as it relates to GABI.

New interpretation of the age of the Tarija Fauna and potential implications for SALMA chronology

Coltorti et al. (2007, 2010) presents a new age interpretation for the Tolomosa Formation that represents a significant departure from previously accepted chronologies. Coltorti et al. (2007) report 16 AMS ^{14}C dates taken from peat and humid paleosol layers within detailed measured sections for the Tolomosa Formation, including three that approximate the ones described in MacFadden et al. (1983), i.e., San Blas (= San Jacinto), Santa Ana, and San Pedro (= Monte Sur). Within their sections the AMS determinations yielded ages ranging from >44,000 to 22,000 ^{14}C yr BP, and appear to be in correct superpositional order. These would therefore represent the last glacial period during the Lujanian SALMA and are interpreted to represent MIS 4 and 2 (~62 and 20 ka, respectively). Coltorti et al. (2007) assert that (p. 293): “The new radiocarbon dates invalidate all previous chronological assessments of the Tarija mammal fauna (Takai 1982; MacFadden et al., 1983) and clearly indicate a Late Pleistocene age for the entire fossiliferous sequence.” They suggest an alternate interpretation for the magnetic polarity stratigraphy, one in which the entire sequence of MacFadden et al. (1983) represents the Brunhes normal chron (C1n), with the two reversed-polarity zones in the lower third of the section representing two short reversed magnetic excursions (Laschamps and Mono Lake). They end their analysis of the magnetic polarity stratigraphy presented by MacFadden et al. (1983) by stating that (p. 295): “Furthermore, the problems of remagnetization of the sediments cannot be excluded.” We address these statements in the Discussion section below.

Several papers have since been written that depend upon the veracity of these new age estimates for the Tolomosa Formation and Tarija Fauna (e.g., Gasparini et al., 2009; Zurita et al., 2009). In a detailed, synthetic analysis of the biochronology of the Tarija Fauna, Tonni et al. (2009) posit that three successive SALMAs could be represented from the Tolomosa Formation, although they recognize that most of the collections from the Tarija Basin lack *in situ* biostratigraphic provenience. The biochronology of the Tarija Fauna will likewise be discussed below.

Our recent field work: 2011

The San Blas ash (unit 20) that we dated in MacFadden et al. (1983, see Fig. 6) produced a fission-track (zircon) age of 0.7 ± 0.2 Ma (2σ) that calibrated the correlation of the composite section of the Tolomosa Formation to the GPTS (Fig. 2). Although the analytical error of 0.2 Ma is relatively large by today's standards, it produced an internally consistent date. Nevertheless, we returned to the Tarija basin to re-collect and re-analyze the San Blas ash to test which age model, our earlier one or the ^{14}C one, is correct.

On 7 July 1983 we collected about 100 kg of the 1–2-m-thick ash layer from unit 20 of our San Blas measured section (MacFadden et al., 1983), which we located at ~21° 35' S; 64° 43' W (Tarija Quadrangle, 1:50,000, Hoja 6629 II, Series H731, Carta Nacional de Bolivia) and map grid reference 12–13 N, 23–24 E. Using our original field notes from 1983 and these reference coordinates, on 11 August 2011 we relocated the San Blas ash (unit 20) and collected ~50 kg from two laterally correlative outcrops (Figs. 3, 4). The first sample is from GPS (WGS84) 21.576389°S; 64.724167°W at an elevation of 1876 m asl, and the second is from 21.573889°S; 64.725278°W at an elevation of

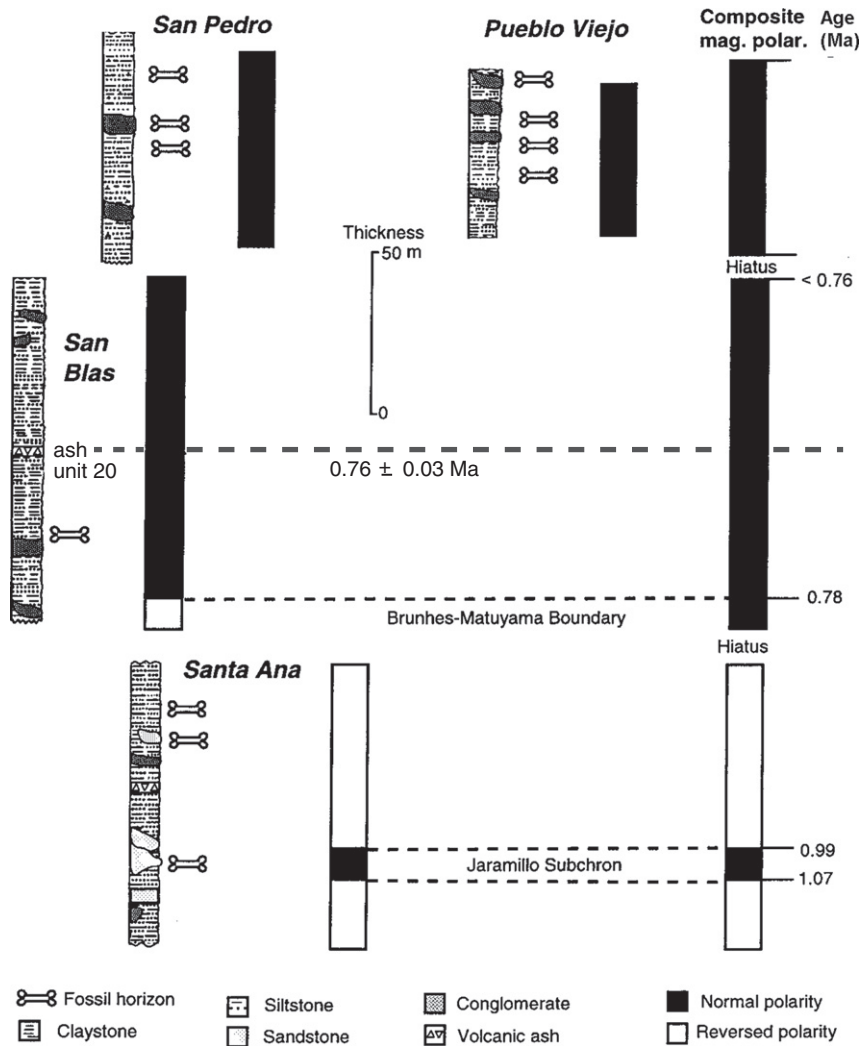


Figure 2. Litho- and magnetostratigraphy, location of the San Blas ash (unit 20) and correlation of the four measured sections of the Tolomosa Formation based on the work of MacFadden et al. (1983).



Figure 3. Google Earth® image of the San Blas section (also see location in Fig. 1) showing the exact localities of the two sub-samples collected from the San Blas ash, unit 20 (*sensu* MacFadden et al., 1983). Sample 1 is from lat. -21.576389° , long. -64.724167° , elev. 1876 m, and sample 2 is from lat. -21.573889° , long. -64.725278° , elev. 1874 m. For scale, the distance between the two samples is 0.32 km.

1874 m asl. Based on the senior author's field notes, sample 2 was collected from what likely is the exact locality from which we collected the original ash in 1983.

Geochronology

The bulk of the ash was composed of largely devitrified glass, with small numbers of small euhedral grains of vermiculitized biotite and also very small grains of plagioclase. Both subsamples together yielded a total of several hundred grains of small (~100–200 μm), clear, euhedral glass-encrusted zircons (Fig. 5). A few rounded, darker-colored zircons were present in both subsamples, suggesting the possibility of some detrital input into the ash. To discriminate between the previously reported fission-track age (MacFadden et al., 1983) and the very young result of Coltorti et al. (2007), we had hoped to use $^{40}\text{Ar}/^{39}\text{Ar}$ dating of other phases. However, the biotites were too altered for dating, and we also rejected the ~125 μm plagioclases found in the sample, which with their K contents of <0.2% would have too much potential for detrital contamination, given the multigrain aliquots required to distinguish the proposed ages of ~0.05 Ma (Coltorti et al., 2007) and 0.7 Ma (MacFadden et al. (1983)). However, the euhedral nature of the biotites and the clear, euhedral glass-encrusted zircons clearly suggested that these are primary air-fall components. We therefore decided to date the zircons by both the U–Th/He and U–Pb methods. The Appendix (Supplemental Materials) provides a description of the standard methods employed during these analyses.

U–Th/He analysis

We dated four aliquots of 2–3 grains each. Of the four aliquots dated, three give consistent results and one was clearly an outlier, probably reflecting either detrital contamination or loss of some zircon during handling prior to U–Th determination. The three consistent aliquots give an inverse-variance weighted mean age of 0.72 ± 0.12 Ma (2σ) that we take to be our best U–Th/He estimate for the age of the San Blas ash. Supplementary Tables 1 and 2 present the data for these analyses.

U–Th/Pb analysis

We analyzed 12 single grains by laser-ablation multi-collector inductively coupled plasma mass spectrometry. Data were corrected for common lead using the method of Andersen (2002). Correction for excess ^{230}Th follows the method of Crowley et al. (2007) assuming



Figure 4. Exposure of the San Blas ash (unit 20). Samples for radioisotopic dating were collected from this locality in 1983 and 2011.

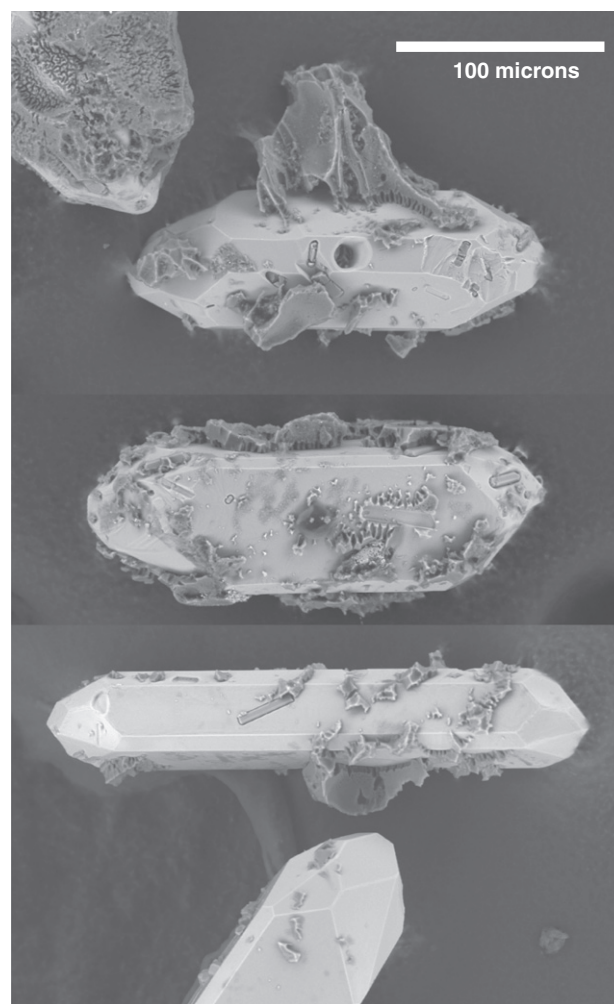


Figure 5. SEM images of zircons separated from the San Blas ash (unit 20) showing encrustation of glass shards.

$\text{Th}/\text{U}_{[\text{magma}]} = 3.0$. Eight of the grains define a younger and coherent population and four are clearly older. The four older ages likely reflect an inherited component in some grains. The eight youngest grains yield an inverse-variance weighted mean average $^{206}\text{Pb}/^{238}\text{U}$ age of 0.76 ± 0.02 (2σ , $\text{MSWD} = 3.4$). Supplementary Tables 1 and 3 present the data for these analyses.

Age of the San Blas ash

We argue that the San Blas ash is a primary volcanic deposit (Fig. 5) with possibly some minor detrital contamination acquired during deposition and preservation in subaqueous conditions. Minor and major phases in the ash look igneous in origin, and there are no younger volcanic rock units in local or regional watersheds that could contribute these minerals as a secondary contaminating assemblage. Any possible source rocks from the surrounding basin highlands are Ordovician through Devonian in age (Pareja et al., 1978), and the local topography and structure make it implausible that such young fission-track and U–Th/He ages could be cooling ages. Therefore, the zircons in San Blas ash should provide a reliable and robust age estimate for deposition for the ash. Pooling all available geochronological data for these zircons and weighting the ages by the inverse of their variance, we conclude that the San Blas ash has an age of 0.76 ± 0.03 Ma (2σ ; Table 1; Fig. 6).

Coltorti et al. (2007) rejected the fission-track age reported by MacFadden et al. (1983) since it disagreed with their consistent ^{14}C

dates; however, they provided no further justification. We do not have access to specific information about the samples Coltorti et al. (2007) sent for ^{14}C analysis, so we cannot be sure how such a large discrepancy between dating methods could arise. Based on our new dates, we believe that the evidence is unequivocal that the San Blas ash is a primary volcanic unit with a zircon age of $0.76 \text{ Ma} \pm 0.03 \text{ Ma}$. We suggest that: (1) the young ^{14}C ages reported by Coltorti et al. (2007) reflect contamination by modern carbon, giving samples from the older radiocarbon-dead peat units found in the Tarija section the appearance of being young, when in fact they are not; or (2) the dated peat horizons are younger than the age of the Tolomosa Formation. A possible way to reconcile, or corroborate these discrepancies would be to analyze the ^{14}C content of *in situ* fossil vertebrates from the Tolomosa Formation. Coltorti et al. (2007) state that they investigated this possibility, but did not find collagen preserved in the available fossils.

Discussion

Quality of the paleomagnetic data and correlation to GPTS

Coltorti et al. (2007) speculated that our paleomagnetic data may have been inaccurate if sediments from the Tolomosa Formation were remagnetized. We don't find evidence for this remagnetization. First, our paleomagnetic analyses included both alternating-field and thermal demagnetization and determination of the dominant carrier of the natural remanent magnetization. Second, after standard statistical filtering, our laboratory procedures effectively isolated two antipodal populations of paleomagnetic sites representing normal (Jaramillo, Brunhes) and reversed (Matuyama) polarities. Third, our magnetostratigraphic sampling protocol and stratigraphic documentation for the Tolomosa Formation exceed the minimal quality criteria for acceptable magnetostratigraphic data (*sensu* Opdyke and Channell, 1996), in which at least five out of ten criteria are satisfied (our study arguably had eight out of ten). Therefore, we continue to find our magnetostratigraphic age to be reliable.

Coltorti et al. (2007) suggested that the magnetostratigraphy of the Tolomosa Formation presented by MacFadden et al. (1983) can be correlated to the late portion of the Brunhes Chron as follows: The two reversed zones in the lower ~60 m of the composite section (Fig. 2) represent one or both of two short reversed magnetic excursions (Laschamps and Mono Lake) reported for this interval. This interpretation discounts the radioisotopic dating of the San Blas ash and relies instead on the independent chronology provided by the ^{14}C dates. In this scenario, it would seem that the lower reversed zone correlates to the Laschamps excursion at ~42 ka and the upper reversed zone to the Mono Lake excursion at 27–28 ka (*sensu* Opdyke and Channell, 1996). So far as they are known, each of these excursions has a duration of ~1–2 ka. Given their stratigraphic thicknesses of ~12 and 50 m, respectively, within the composite magnetostratigraphic section of the Tolomosa Formation, the correlation of Coltorti et al. (2007) seems to require large hiatuses between the two purported excursions and unrealistic fluctuations in sedimentation rate for which there is no physical stratigraphic evidence. We therefore contend that the interpretation of Coltorti et al. (2007) is not substantiated.

Table 1

Summary of geochronological analyses of the San Blas ash (unit 20, *sensu* MacFadden et al. (1983) from the Tolomosa Formation, Tarija Basin, Bolivia.

Method	N*	Age (Ma)	Error (\pm Ma, 2σ)	Notes
Fission track		0.7	0.2	MacFadden et al. (1983)
U–Th/He	3	0.72	0.12	Supplemental Table 1
U–Th/Pb	8	0.76	0.02	Supplemental tables 2, 3
Pooled age of San Blas ash: $0.76 \pm 0.03 \text{ Ma}$ (2σ)**				

*N = number of individual new analyses that contributed to age determination, see supplemental Tables 1–3.

**Also see Fig. 6.

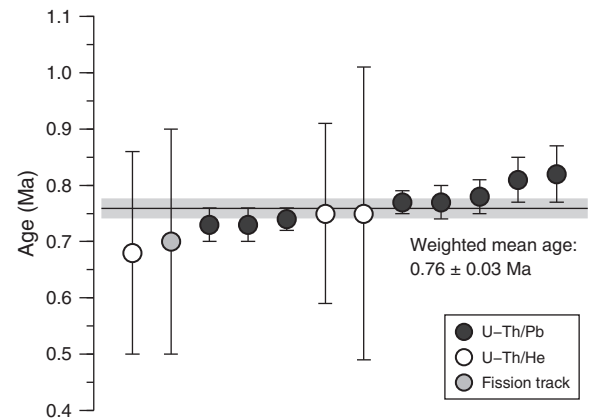


Figure 6. Graphic depiction of the age of the San Blas ash (unit 20), based on the pooled data described in the text and Supplementary Materials.

Another possible scenario is that both interpretations are correct, i.e., the base of the Tolomosa Formation is middle Pleistocene but the upper part of the section, which is younger than the Matuyama/Brunhes boundary at 0.78 Ma, is much younger than previously recognized by MacFadden et al. (1983) and MacFadden (2000). The ^{14}C ages of Coltorti et al. (2007) could then be used to date the upper part of the composite measured section described by MacFadden et al. (1983; Fig. 2 herein). From Coltorti et al. (2007: Fig. 2), most of their ^{14}C dates are taken from stratigraphic levels in the upper part of the Tolomosa Formation, and therefore one might argue that this entire stratigraphic package extends into the latest Pleistocene, i.e., within the age resolution of AMS dating (~<50 ka). This scenario, however, is falsified if one accepts an age equivalency of the San Jacinto and Santa Ana sections of Coltorti et al. (2007) with the San Blas and Santa Ana sections of MacFadden et al. (1983), despite being able to make a one-to-one match for units in both of these schemes. ^{14}C ages of $>44,860$ ^{14}C yr BP and $34,070 \pm 940$ ^{14}C yr BP occur, respectively, half and two-thirds of the way up the Santa Ana section, which in MacFadden et al. (1983) and subsequent interpretations have the Jaramillo subchron (1.07–0.99 Ma) preserved in this section. Likewise, Coltorti et al. (2007) measured two ^{14}C dates of $43,490 \pm 690$ ^{14}C yr BP and $39,100 \pm 980$ ^{14}C yr BP from the middle of their San Jacinto section. If these are equivalent to our San Blas section, then they approximate the stratigraphic horizons of the Brunhes/Matuyama boundary at 0.78 Ma and the San Blas ash at $0.76 \pm 0.03 \text{ Ma}$. In summary, unless the stratigraphic sections are not actually equivalent, the Tolomosa Formation cannot accommodate both age interpretations, those presented here (also MacFadden et al., 1983; MacFadden, 2000) and those of Coltorti et al. (2007). We believe that our unique correlation to the GPTS, in which our composite section of the Tolomosa Formation spans from just below the Jaramillo subchron (C1r.1n) at ~1.1 Ma to within the Brunhes chron (C1n) at ~0.7 Ma, is the correct one.

Biostratigraphy, SALMAs, and biochronology of the Tarija Fauna

Because of the abundance of fossils, the age of the Tarija Fauna is critical to understanding Pleistocene faunal evolution in South America. The collections from Tarija made over the past six centuries typically lack provenience data with regard to specific localities within the basin, and biostratigraphic data associated with individual measured sections are essentially non-existent, except for a few more recent studies, including Takai (1982, 1984), Coltorti et al. (2007), and MacFadden et al. (1983). As such, assessments of the age of the Tarija must be based on the entire fauna lumped as a single, integrated faunal biochron. MacFadden et al. (1983) and MacFadden (2000) assert that the age of the Tarija Fauna is Ensenadan, although the possibility that it also could be younger (either Bonaerian or Lujanian,

depending upon which biochronological scheme is followed) cannot be ruled out. The biochronological requirements of the very young Tarija Fauna posited by [Coltorti et al. \(2007\)](#) would have significant ramifications for SALMA biochronology. In a conservative interpretation, [Tonni et al. \(2009\)](#) state that as they are known from the Pampean region of Argentina, species attributable to Ensenadan, Bonaerian, and/or Lujanian SALMAs occur in the Tarija Fauna.

As described above, resolution of the biochronological age of the Tarija Fauna requires a detailed biostratigraphic study of individual taxonomic occurrences within the Tolomosa Formation. This level of resolution, while theoretically possible from this fossiliferous sequence, is a large task that has not yet been undertaken for the entire fauna. MacFadden has recently analyzed the biostratigraphic distribution of the horses (Family Equidae) from the Tarija Fauna, but this work has not yet been published. Similar studies of other taxa that occur from Tarija need to be done in order to further resolve the biochronology of the SALMAs as they are represented from this important sequence.

Concluding comments

Our new date of 0.76 ± 0.03 Ma ([Table 1](#)) for the age of the San Blas ash within the Tolomosa Formation corroborates the magnetostratigraphic correlation to the GPTS posited by [MacFadden et al. \(1983\)](#). This correlation confirms a middle Pleistocene age for the Tolomosa Formation between ~1.1 to at least 0.7 Ma and appears to refute the much younger, late Pleistocene (~60–20 ka) age for the same sections of the Tolomosa Formation based on ^{14}C dates and ([Coltorti et al., 2007](#)).

We suggest that, with regard to the SALMA biochronology and based on the chronostratigraphy independent of the faunal biochronology, the age of the Tarija Fauna is principally late Ensenadan, a SALMA which is believed to range from ~2 to 0.7 Ma ([Flynn and Swisher, 1995](#); [Soibelzon et al., 2009](#); [Woodburne, 2010](#)). As we document elsewhere ([MacFadden, 2000](#)) and in this paper above, we cannot rule out the possibility that the upper parts of the Tolomosa Formation are represented by younger faunal levels of Bonaerense and Lujanian SALMA (but not so young to accommodate the ^{14}C dates of [Coltorti et al., 2007](#)). For example, based on bulk biochronological analyses, [Tonni et al. \(2009\)](#) suggest that the Tarija Fauna contains individual taxa that are characteristic of either the Ensenadan, Bonaerian, and/or Lujanian as they are known from the stratigraphic sections in Argentina. Further refinements, and resolution of the full age range encompassed within the Tolomosa Formation by the Tarija Fauna will require biostratigraphically documented collections tied to measured sections, like those originally presented by [MacFadden et al. \(1983\)](#).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.yqres.2012.12.009>.

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