Paraná flood basalts: Rapid extrusion hypothesis confirmed by new $^{40}Ar/^{39}Ar$ results

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ABSTRACT

The duration of volcanism in the Paraná continental flood basalt (CFB) province, essential information to assess models of melt generation, eruption rates, continental breakup, and volcanism-driven extinction events, remains unresolved due to conflicting sets of $^{40}Ar/^{39}Ar$ geochronology data. Some results suggest that the Paraná CFB volcanism began at 134.7 ± 1 Ma and lasted <1 m.y. Another set of results reveals an extrusion interval of 11 m.y., from ca. 140 Ma to ca. 129 Ma. To resolve this controversy, we reanalyzed three of the exact hand specimens that previously yielded the oldest and youngest ages in the protracted 11 m.y. range. Our new ages are statistically indistinguishable from each other and the previous 134.7 ± 1 Ma result and indicate a short eruption event. A rapid extrusion for the Paraná CFB and the lack of a major cotemporal extinction event challenge proposed direct links between CFB volcanism and mass extinctions and refute petrological models that rely on a protracted extrusion of the Paraná CFB.

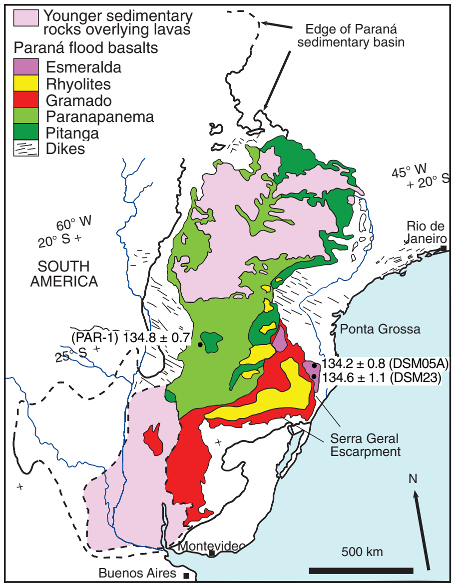

Figure 1. Map of eastern South America showing extent of Paraná magmatism relative to Paraná sedimentary basin (after Stewart et al., 1996). Localities and ages of samples dated are shown.

INTRODUCTION

Continental flood basalts (CFB) are infrequent and extraordinarily large volcanic accumulations (Courtillot and Renne, 2003; Kelley, 2007; Renne et al., 1992; Wignall, 2001) that often have extrusion volumes in excess of 1 × 10^6 km^3. Modern high-resolution $^{40}Ar/^{39}Ar$ geochronology (Courtillot and Renne, 2003) for four of the largest CFB provinces (i.e., Emeishan Traps, Siberian Traps, Central Atlantic Magmatic Province, Deccan Traps) show both rapid extrusion rates and temporal overlaps between volcanism and major mass extinction events, leading to suggestions (Courtillot and Renne, 2003; Kelley, 2007; Wignall, 2001) of a causal relationship between CFB volcanism and mass extinction. However, the comparably sized Paraná CFB, 2.35 × 10^6 km^3 (Gladczenko et al., 1997), appears to be an exception, as no major extinction event overlaps the proposed time of volcanism. The age and duration of Paraná volcanism, however, are disputed due to conflicting sets of $^{40}Ar/^{39}Ar$ geochronology data. One set of results (Renne et al., 1992, 1996a, 1996b, 1997) indicates that the Paraná flood volcanism began at 134.7 ± 1 Ma and lasted <2 m.y., based on the ±1 m.y. age error (ages cited in this paper are corrected [Renne et al., 1994] to the currently used [Kuiper et al., 2008] value of 28.201 ± 0.046 Ma for the Fish Canyon sanidine fluence monitor). Another set of results (Turner et al., 1994; Stewart et al., 1996) indicates an extrusion interval of 11 m.y., beginning ca. 140 Ma and ending ca. 129 Ma.

A difficulty in comparing both sets of previous $^{40}Ar/^{39}Ar$ data is the fact that each research group collected and analyzed distinct sample suites and employed different $^{40}Ar/^{39}Ar$ methodologies. The first group (Renne et al., 1992, 1996a, 1996b, 1997) analyzed samples collected along four vertical transects in the Serra Geral escarpment in Brazil (Renne et al., 1992) and the Etendeka in southwestern Africa (Renne et al., 1996b) and used the laser incremental heating method on plagioclase separates and whole-rock samples, retrieving geochronological information from plateau ages defined in cumulative % ^{39}Ar release spectra. The second group (Turner et al., 1994; Stewart et al., 1996) sampled a broader region in Brazil, Paraguay, and Uruguay, and used a combination of laser and furnace incremental heating analysis on mineral separates and whole-rock grains, and in situ laser total fusion of multiple spots in their samples. They derived age information by plotting the results obtained from incremental heating or spot total fusion analyses onto $^{39}Ar/^{40}Ar$ versus $^{36}Ar/^{40}Ar$ isotope correlation diagrams (inverse isochron method).

$^{40}Ar/^{39}Ar$ RESULTS

In order to test if the discrepancy in results derives from real variations in sample ages, or whether it results from the use of distinct analytical approaches, we redated, by the laser incremental heating method, three samples previously analyzed (Turner et al., 1994; Stewart et al., 1996). We dated, in triplicate, 1–2 mm total rock grains extracted from the exact hand specimens previously analyzed (Turner et al., 1994; Stewart et al., 1996), representing the oldest [140.2 ± 1.3 (1σ) Ma, sample PAR-1] and two of the youngest [129.4 ± 4.6 (1σ) Ma, sample DSM23; 131.1 ± 1.3 (1σ) Ma, sample DSM05A] samples in the 11 m.y. age range (Turner et al., 1994; Stewart et al., 1996) (Fig. 1). These three samples provide key geochronological constraints used (Turner et al., 1994; Stewart et al., 1996) to propose that the Paraná volcanism lasted 11 m.y., from 140 Ma to 129 Ma. Samples were dated using the procedures reported in the GSA Data Repository[1]; complete tabulated data from the analyses are listed in Table DR1.

The three grains from sample DSM23 (3446–01, 3446–02, and 3446–03; Figs. 2A–2C) yield statistically indistinguishable plateau ages (134.9 ± 1.7, 134.8 ± 1.7, and 134.0 ± 1.7 Ma). Similarly, three grains from sample DSM05A (3447–01, 3447–02, and 3447–03; Figs. 2E–2G) also yield reproducible plateau ages (133.7 ± 1.4, 134.3 ± 1.0, and 134.3 ± 1.1 Ma). Three grains from sample PAR-1 (3448–01, 3448–02, and 3448–03; Figs. 2I–2K) yield compatible plateau ages (134.8 ± 1.1 Ma, 134.8 ± 1.1 Ma, 134.9 ± 1.0 Ma). The combined plateau steps for the three grains from each sample (Fig. 2M) yield mean weighted ages for each sample of 134.6 ± 1.1 Ma for DSM23, 134.2 ± 0.8 Ma

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[1]GSA Data Repository item 2010203, supplementary methods and Table DR1 ($^{40}Ar/^{39}Ar$ numerical data), is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

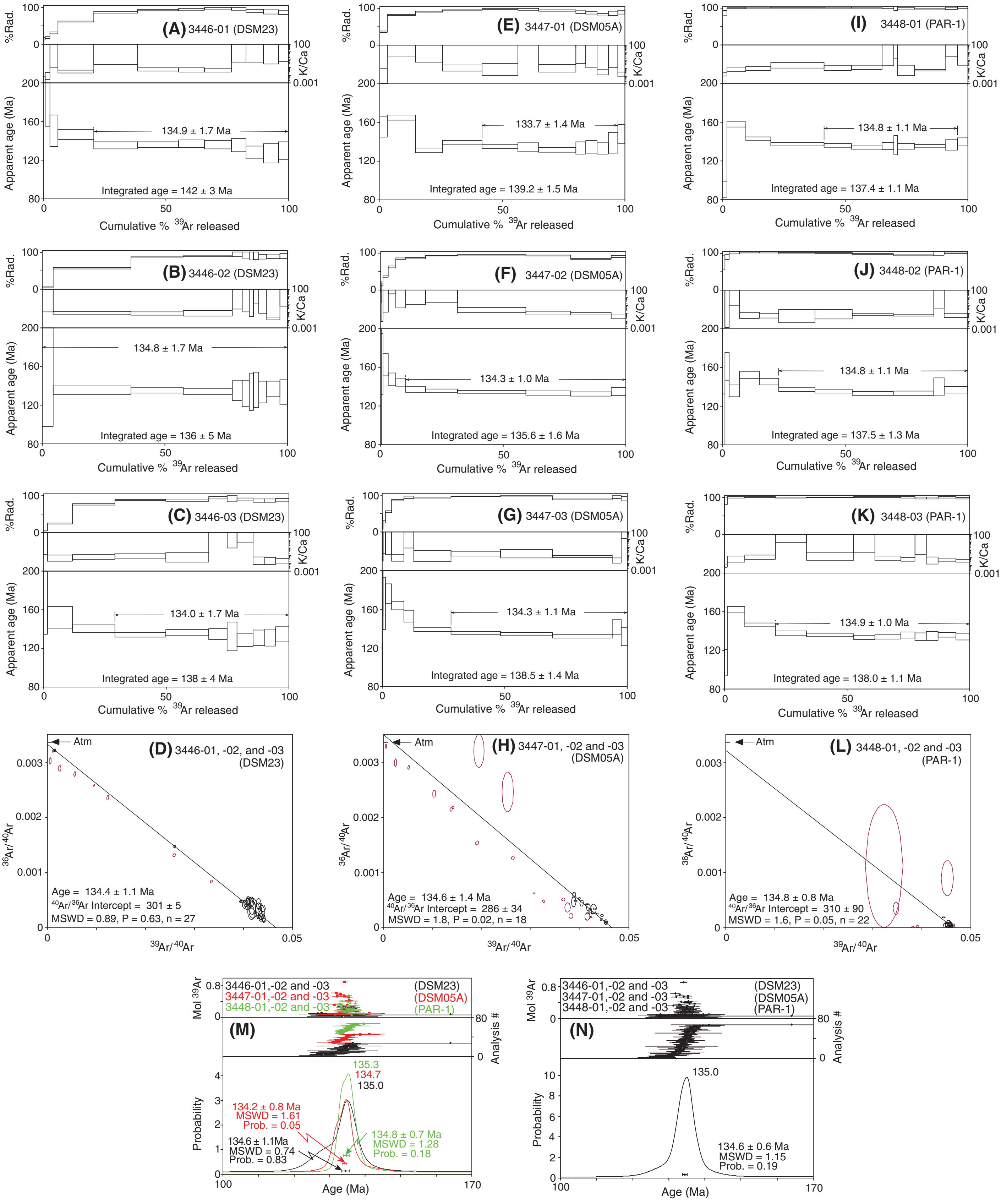

Figure 2 (*continued on following page*).

Figure 2 (*continued*). $^{40}Ar/^{39}Ar$ results. All nine incremental heating spectra for samples DSM23, DSM05A, and PAR-1 define compatible plateaus, where a plateau is defined as three or more consecutive steps, composing at least 50% of total ^{39}Ar released, where ages for each consecutive step are within 2σ error from variance-weighted mean (Fleck et al., 1977). An Isochron plotted for the plateau data from all three grains of sample DSM23 (A, B, and C) yields an isochron age of 134.4 ± 1.1 Ma (D) that is compatible at the 2σ confidence level with plateau ages. (MSWD—mean square of weighted deviates.) Isochron $^{36}Ar/^{40}Ar$ intercept (301 ± 5) is within error of the present atmospheric (Atm) value of 298.56. The low temperature steps for grains 3446–01 and 3446–03 (A, C) yield slightly older results, probably due to minor ^{39}Ar recoil losses. A probability (prob.) density plot for all plateau steps for the three grains of DSM23 (Fig. 2M) yields a maximum probability peak at 135.0 Ma, and defines a mean-weighted age of 134.6 ± 1.1 Ma, also compatible at 2σ level with the plateaus and isochron ages. Weighted mean age of 134.6 ± 1.1 (2σ) Ma is our best estimate for the age of sample DSM23. An isochron plotted for the plateau data from all three grains of sample DSM05A (E, F, and G) yields an age of 134.6 ± 1.4 Ma (H), compatible at 2σ confidence level with the plateau ages and defining a $^{36}Ar/^{40}Ar$ intercept (286 ± 34) within error of 298.56. Low-temperature steps for all three grains from sample 3347 (3347–01, 3347–02, and 3347–03) again yield slightly older results due to minor ^{39}Ar recoil losses. Probability density plot for all plateau steps from the three grains (M) yields a maximum probability peak at 134.7 Ma and defines a mean-weighted age of 134.2 ± 0.8 Ma (our best estimate for age of DSM05A) compatible at 2σ level with the plateaus and isochron ages. The first step for each of the three grains from sample PAR-1 (I, J, and K) shows minor low-temperature discordances that probably result from ^{40}Ar loss due to alteration. Subsequent steps for all three grains yield slightly older results due to minor ^{39}Ar recoil losses. Remaining steps define plateaus. An isochron plotted for plateau steps from all three grains (I, J, and K) yields an isochron age of 134.8 ± 0.8 Ma (L), compatible at 2σ confidence level with the plateau ages. The large error envelope in the $^{36}Ar/^{40}Ar$ intercept (310 ± 90), also within error of the present atmospheric value of 298.56, results from the fact that all the precise steps cluster at one end of the isochron. Probability density plot (M) for the plateau steps for all three grains has a maximum probability peak at 135.3 Ma, and it defines a mean-weighted age of 134.8 ± 0.7 Ma (best estimate for age of PAR-1) that is compatible at 2σ level with the ages defined by the plateaus and isochron. Probability density plot that combines the plateau steps for all nine grains (N) has a maximum probability peak of 135.0 Ma and it defines a mean-weighted age of 134.6 ± 0.6 Ma, our best estimate for the age of extrusion.

for DSM05A, and 134.8 ± 0.7 Ma for PAR-1, which we consider our best estimate for the age for each sample. A probability density plot for all the plateau steps from the nine grains analyzed yields an age of 134.6 ± 0.6 Ma (Fig. 2N), our best estimate for the age of the extrusion and possible duration (±0.6 m.y. or 1.2 m.y.) of volcanism for the Paraná CFB. All nine grains analyzed in this study are within error from each other and correspond, within error, to the narrow range of ages reported by the first group (Renne et al., 1992), confirming that the duration of the Paraná volcanism was <1.2 m.y. Our results also suggest that the widespread age distribution obtained by the laser total fusion spot method (Turner et al., 1994; Stewart et al., 1996) for the Paraná CFB is an artifact of the methodology used, and it does not represent a true spread in extrusion ages purportedly resulting from a more extensive and representative sample suite.

DISCUSSION

The discrepancy between the laser incremental heating and the laser total fusion spot analyses likely results from the averaging effect of the total fusion spot method when applied to whole-rock samples. Whole-rock samples may suffer ^{39}Ar recoil loss and ^{40}Ar loss by alteration (Renne et al., 1992), as we show here, and excess inherited argon (Renne et al., 1996a, 1996b). Loss of ^{39}Ar and excess inherited argon yield anomalously old results, whereas ^{40}Ar loss by alteration yields anomalously young results.

The laser total fusion spot method provides a single analysis for each spot, and the variable deleterious effects of recoil, inherited argon, and alteration are averaged together into the one analysis. In contrast, the laser incremental heating method, which provides a series of analyses for the same sample at progressively higher temperature steps, allows the gas fractions from the low temperature steps subject to recoil and alteration problems to be separated from the more pristine gas fractions extracted from the better crystallized and more retentive sites sampled by the high temperature steps. Thus an incremental heating profile provides direct evidence and quantification of the effects of recoil, alteration, and inherited argon that may affect the precision and accuracy of a $^{40}Ar/^{39}Ar$ age. This internal validation is not available from total fusion spot analyses. Attempts to evaluate the effects of recoil, argon loss, and excess argon by combining multiple total fusion spot analyses into a reverse isochron are inadequate because the individual gas fractions on the plot actually represent different proportions of gases extracted from different sample reservoirs, each subject to variable amounts of recoil, argon loss, and excess argon.

CONCLUSIONS

Our data confirm the previous results (Renne et al., 1992, 1996a, 1996b, 1997) of 134.7 ± 1 Ma for the extrusion of the Paraná CFB Province, suggesting that the duration of the Paraná volcanism was <1.2 m.y. Geomagnetic polarity reversals identified on Paraná-Etendeka stratigraphic sections (Ernesto and Pacca, 1988; Ernesto et al., 1990, 1999; Renne et al., 1992, 1996a), some of which represent vertical sections approaching 1000 m in thickness, show a maximum of 4 magnetic polarity reversals in any section (Renne et al., 1992, 1996a). The magnetic poles reversed polarity relatively frequently (an approximate average of every 400 k.y.) in the period between 140 and 120 Ma (Gradstein et al., 2004), which also supports a rapid extrusion of <1.2 m.y.

The laser total fusion spot analyses (Turner et al., 1994; Stewart et al., 1996) are the only modern $^{40}Ar/^{39}Ar$ results for the Paraná CFB that show significant deviation from the eruption age of 134.7 ± 1 Ma defined by previous laser incremental step heating studies (Renne et al., 1992, 1996a, 1996b, 1997) and this study, and from the paleomagnetic data interpretation (Renne et al., 1992, 1996a). Our new results for the samples previously analyzed (Turner et al., 1994; Stewart et al., 1996), however, suggest that the laser total fusion spot analysis dates for the Paraná are unreliable and should not be further considered in the interpretation of petrological models for the extrusion of the Paraná CFB province.

A narrow time window for the Paraná extrusion raises questions about the causal relationship between CFB volcanism and extinction events (Courtillot and Renne, 2003; Wignall, 2001; White and Saunders, 2005) and refutes petrological models (Garland et al., 1996; Peate, 1997; Hawkesworth et al., 2000; Guedes et al., 2005; Jerram and Widdowson, 2005, Gibson et al., 2006) that rely on a protracted extrusion of the Paraná CFB. Some researchers (Courtillot and Renne, 2003; Erba et al., 2004; Gröcke et al., 2005) have correlated the Valanginian Weissert oceanic anoxic event (OAE) with the Paraná extrusion, but there are doubts (Wignall, 2001; Courtillot and Renne, 2003) on whether the Valanginian OAE actually represents an extinction event. In addition, work (Gröcke et al., 2005) on the timing of the OAE relative to the most recent time scale (Gradstein et al., 2004) suggests that the Valanginian OAE started at the boundary between the lower and upper Valanginian at 138.6 Ma, peaked ca. 137.8 Ma, and had terminated ca. 134.7 Ma. This study places the age of the Paraná extrusion at 134.6 ± 0.6 Ma, suggesting that major volumes of Paraná CFB extrusion initiated after the start of the Valanginian OAE and possibly ended after the termination of the OAE.

The protracted duration for the Paraná CFB volcanism, as proposed by Turner et al. (1994)

and Stewart et al. (1996), would result in much lower eruption rates for the Paraná as compared to other CFB provinces, and it has provided a convenient solution for the lack of a temporal relation between the Paraná CFB and any major extinction event (Wignall, 2001; Courtillot and Renne, 2003). However, the new results presented here reveal a minimum average magma eruption rate of ~2.0 km^3/yr, calculated from a Paraná-Etendeka volume of 2.35×10^6 km^3 (Gladczenko et al., 1997) extruded over 1.2 m.y., which is comparable with extrusion rates of CFBs (e.g., Emeishan Traps, Siberian Traps, Central Atlantic Magmatic Province, Deccan Traps) correlated with mass extinctions. These new results invalidate the interpretation that the lack of extinction events associated with the Paraná CFB province results from its purportedly lower eruption rates, and suggest that the direct environmental consequences of CFB volcanism, at least those equal to or smaller in volume than the Paraná CFB, may not be drastic enough to drive mass extinction. Drastic environmental effects of CFB volcanism may be a function of degassing of associated sedimentary deposits, as recently proposed (Ganino and Arndt, 2009), but not the direct effect of volcanism. Alternatively, the Valanginian Weissert OAE may actually represent a mass extinction event, and its age must be revised in light of the new results for the Paraná CFB volcanism.

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