Extensive 200-Million-Year-Old Continental Flood Basalts of the Central Atlantic Magmatic Province

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The Central Atlantic Magmatic Province (CAMP) is defined by tholeiitic basalts that crop out in once-contiguous parts of North America, Europe, Africa, and South America and is associated with the breakup of Pangea. $^{40}Ar/^{39}Ar$ and paleomagnetic data indicate that CAMP magmatism extended over an area of 2.5 million square kilometers in north and central Brazil, and the total aerial extent of the magmatism exceeded 7 million square kilometers in a few million years, with peak activity at 200 million years ago. The magmatism coincided closely in time with a major mass extinction at the Triassic-Jurassic boundary.

Many aspects of the genesis and consequences of continental flood basalt provinces (CFBPs) remain poorly known and controversial. The definition of a CFBP, as well as their genetic relations with other phenomena such as rifting of continents, hot spot tracks, and mass extinctions, commonly hinges on geochronology. Such is the case for the Central Atlantic Magmatic Province (CAMP), which is associated with the disruption of Pangea and the opening of the central Atlantic Ocean (*1–3*). The CAMP (Fig. 1) is represented by tholeiitic dikes, sills, and lava flows in North and South America, Africa, and Europe. Components of the CAMP have been studied for decades, but only through recent high-precision geochronologic analysis can magmatism represented by this province now be related to a single brief magmatic episode. $^{40}Ar/^{39}Ar$ (*4*) and U/Pb (*5*) data permit recognition of extensive basaltic magmatism in West Africa, eastern North America, and northernmost South America at 200 ± 4 million years ago (Ma), with an estimated original extent of the volcanism over an area of at least 4.5×10^6 km^2 (*4–7*). Here we present $^{40}Ar/^{39}Ar$ data that indicate that CAMP basalts are widespread also in northern and central Brazil, over a previously unrecognized area of about 2.5×10^6 km^2.

Most of the South American CAMP magmatism occurred far inland, up to 2000 km from the Atlantic margin, in northern and central Brazil. These tholeiitic flows, sills, and dikes occur in Archean–Early Proterozoic cratonic areas and Late Proterozoic to Paleozoic basins. Lava flows (for example, in the Maranhão, Anari, and Tapirapuã subprovinces) are mostly preserved in the Paleozoic sedimentary basins and presently cover a relatively restricted area of 3×10^5 km^2, reaching a maximum thickness of 300 m and a total estimated volume of 6×10^4 km^3 (*8*, *9*). The sills of the Amazonian basin cover an area of $\sim 1 \times 10^6$ km^2 and have an average thickness of ~500 m and an estimated volume of $\sim 4 \times 10^5$ km^3 (*10*). The only known extrusive remnant of the Amazonian magmatism is in the Maranhão basin, where the so-called Mosquito basalts are geochemically similar to the Amazonian sills (*9*, *10*). About 0.4×10^6 km^2 of strongly weathered and deeply eroded areas in the Guyana and Amazonian cratons are intruded by dominantly north-south–striking dike swarms. Some of these swarms (for example, in the Roraima and Cassiporé subprovinces) are characterized by a high density of dikes 200 to 300 m thick and up to 300 km long and therefore are comparable to feeder dike swarms of other CFBPs (*11–13*).

The basalts in Brazil have compositions similar to those of CAMP magmatic rocks from North America and West Africa. They range in composition from tholeiitic basalts to andesitic basalts, and alkaline and silicic rocks are scarce. CAMP tholeiites are characterized by low TiO_2 concentrations (typically <2 weight %), negative mantle-normalized Nb anomalies (relative to K and La), and moderately to strongly enriched rare Earth element patterns (*6*, *8*, *9*, our data). No systematic compositional differences are noted between the different regions of CAMP. Despite this common signature, relatively few evolved tholeiites from single localities in Brazil as well as West Africa and eastern North America have relatively variable trace element and isotopic compositions (Fig. 2). Such compositional variations cannot be attributed uniquely to low-pressure differentiation processes and suggest [as inferred for other Gondwana CFBPs (*12*, *13*)] important contributions of heterogeneous, possibly lithospheric mantle in the petrogenesis of these rocks.

We dated fresh tholeiitic dikes from Roraima and Amapá (Cassiporé dikes), tholeiitic lava flows from the Maranhão basin and the Anari-Tapirapuã region, and one alkaline lava flow from Lavras da Mangabeira basin (Ceará) of northern and central Brazil by $^{40}Ar/^{39}Ar$ incremental heating (*11*). Ages were calculated relative to an age of 28.02 Ma for the Fish Canyon sanidine (FCs) neutron fluence monitor (*14*).

Plateau ages, defined by 10 to 45 contiguous steps and by 50 to 84% of total ^{39}Ar released, were obtained for 10 samples (Fig. 3). Apparent age spectra for lava flows are little affected by argon loss or excess argon

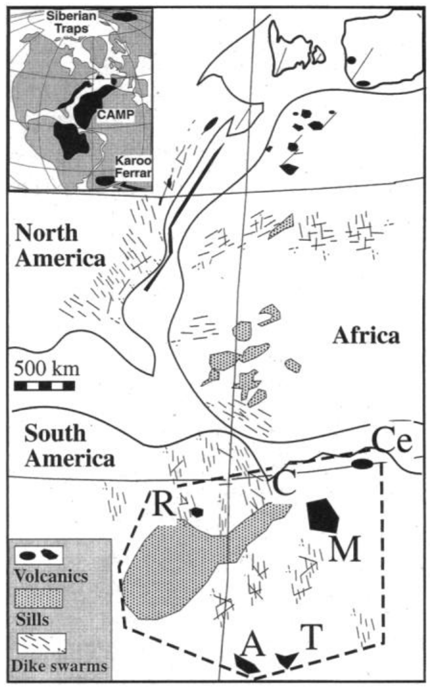

Fig. 1. Location map of the CAMP (*4–7*, present data) in a Pangea reconstruction at 200 Ma, also showing the Siberian and Karoo-Ferrar CFBPs in the inset. The area presently recognized as being part of CAMP is shown by a dashed contour, with sample sites indicated: R, Roraima; M, Maranhão; C, Cassiporé; Ce, Ceará; A, Anari; and T, Tapirapuã.

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and yield plateau ages ranging from 190.5 ± 1.6 to 198.5 ± 0.8 Ma (Maranhão, Mosquito basalts) and from 196.6 ± 1.8 to 198.0 ± 0.8 (Tapirapuã and Anari samples, respectively). The alkaline basalt lava flow from Ceará yields a plateau age of 198.4 ± 1.4 Ma. Dikes from Roraima and Cassiporé, which intrude Proterozoic basement, yield saddle-shaped age spectra typical of excess argon contamination, as is common for plagioclases of dikes intruding wall rocks of much greater age. Nonetheless, detailed step heating (32 to 84 steps for each sample) allowed definition of plateaus on two Roraima (8818 and 8820) and three Cassiporé (8026, 8034, and 8041) dike samples. Moreover, one dike from Roraima (8804) yields a near plateau, defined by 43% of total ^{39}Ar released and 16 contiguous steps. In some of the dikes, $^{39}Ar/^{40}Ar$ versus $^{36}Ar/^{40}Ar$ isotope correlation plots confirm the presence of substantial excess ^{40}Ar and permit determination of isochron ages, which tend to be slightly younger than plateau ages (Fig. 3). In these cases, to minimize the possible effect of excess argon, we adopted isochron ages for the dikes (samples 8026, 8804, 8818, and 8820). In summary, ages for Roraima and Cassiporé dikes range from 197.4 ± 1.9 to 201.1 ± 0.7 and from 191.5 ± 0.9 to 202.0 ± 2.0 Ma, respectively.

All available radioisotopic dates for the CAMP (*4*, *5*, present data) are between 191 and 205 Ma, with a mean age of 199.0 ± 2.4 Ma and the peak at 200 Ma (Fig. 4). Our data show that tholeiites from Brazil are similar in age to those of the CAMP in Africa and North America. The two distinguishably younger samples (5013 and 8034, from the Maranhão and Cassiporé, respectively) are from the northernmost portion of the Brazilian CAMP. A similar relation is shown on the African continental margin in Guinea (*4*). Thus, after the main pulse, magmatism may have continued further toward the future rifted margin of each continent [for example, (*15*)].

Paleomagnetic data from widely distributed sites in the South American CAMP occurrences provide further evidence of a brief coeval magmatic event in the circum-Atlantic region (Fig. 5). Paleomagnetic poles for South America are available from the Maranhão, Guacamaya, Anari, and Tapirapuã volcanic rocks and the Guyana, Bolivar, Penatecaua, and Cassiporé dikes (*9*, *16*, *17*). Data from seven independent sites in low-Ti tholeiitic dikes and flows from Roraima yield a paleomagnetic pole located at 235.0°E, 80.1°S ($N = 7$; 95% confidence angle $\alpha_{95} = 6.6$; concentration parameter $k = 84$). Considering uncertainties in the Euler poles used to enact the continental reconstructions, the average of these poles is in good agreement with contemporaneous poles from western

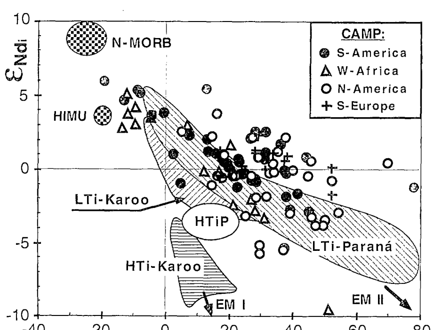

Fig. 2. Initial (200 Ma) εSr-εNd isotopic compositions of CAMP basalts (*6*, *8*, and 32 data samples from the present study). Compositions of low-TiO_2 (LTi) and high-TiO_2 (HTi) basalts from the Paranà (*12*) and the Karoo (*13*) Mesozoic Gondwana CFBPs, as well as mantle components [EM, enriched mantle; HIMU, high-μ ($^{238}U/^{204}Pb$ normalized for radioactive decay to the present) mantle] and normal mid-ocean ridge basalt (N-MORB) fields (*29*), are shown for comparison. HTiP, Paranà high-TiO_2 basalts.

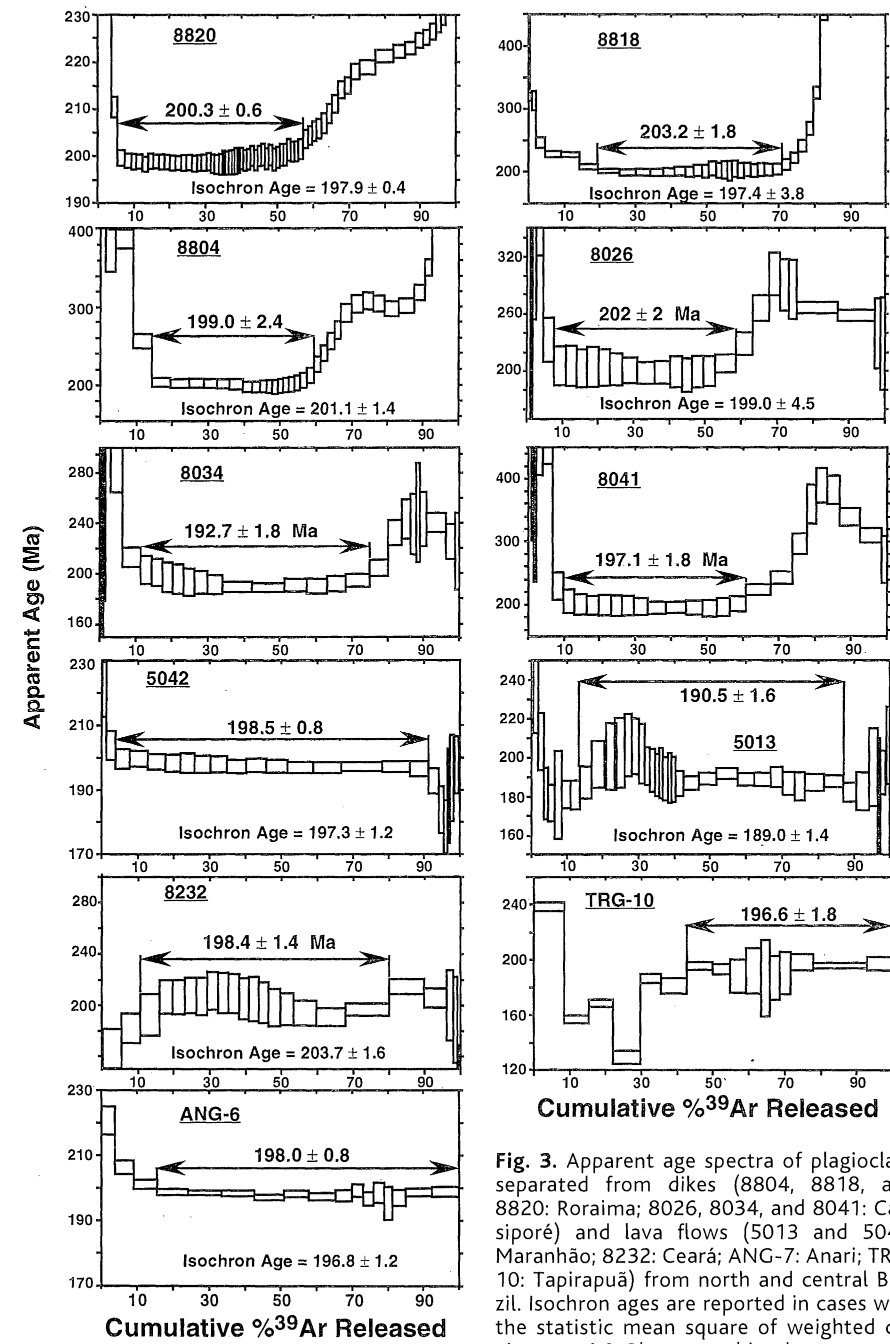

Fig. 3. Apparent age spectra of plagioclase separated from dikes (8804, 8818, and 8820: Roraima; 8026, 8034, and 8041: Cassiporé) and lava flows (5013 and 5042: Maranhão; 8232: Ceará; ANG-7: Anari; TRG-10: Tapirapuã) from north and central Brazil. Isochron ages are reported in cases with the statistic mean square of weighted deviates < 1.0. Plateau and isochron ages are given in million years ago (Ma) with 2σ errors, which include analytical uncertainty in neutron fluence parameter *J* value.

Africa, southern Europe, and eastern North America (*18–20*). Magnetizations of most CAMP tholeiites from South America (*9*, *16*, *17*, present data), eastern North America (*20*), southern Europe (*18*), and West Africa (*19*) are of normal polarity. A ~4- to 5-million-year normal polarity interval characterizes the latest Triassic [uppermost Rhaetian (*20*)] and earliest Jurassic [lower Hettangian (*21*)] and is preceded and followed by long intervals of reversed polarity or very frequent polarity reversals (*20*, *21*). Thus, the CAMP paleomagnetic data provide independent support for brevity of peak magmatism.

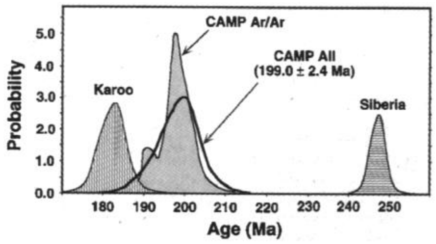

Fig. 4. Age probability spectra for CAMP (*4*, *5*, present study) from North America (five data samples), West Africa (20 data samples), and South America (16 data samples). The curve labeled "CAMP All" (41 data samples) allows comparison of the $^{40}Ar/^{39}Ar$ with the U/Pb data by including uncertainties in decay constants, errors in K-Ar data for $^{40}Ar/^{39}Ar$ standards, and 2σ analytical errors (*14*). The curve labeled "CAMP Ar/Ar" (36 $^{40}Ar/^{39}Ar$ data samples) includes only 1σ analytical errors and provides the best estimate of duration of a brief magmatism, similar to those of the Karoo (*23*) and Siberian Traps (*22*) CFBPs. All $^{40}Ar/^{39}Ar$ data are normalized to the same standard basis [FCs = 28.02 Ma (*14*)].

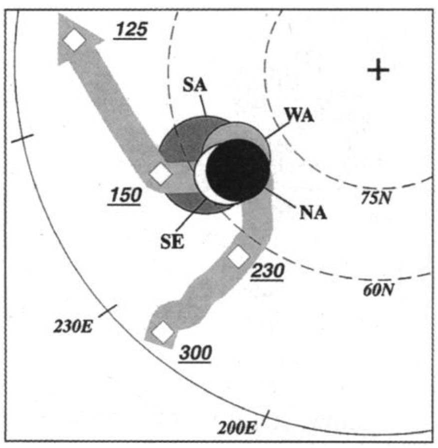

Fig. 5. Circles show the mean paleomagnetic poles (95% confidence) of CAMP tholeiites of South America (SA) (*9*, *16*, *17*, present data), southern Europe (SE) (*18*), western Africa (WA) [compiled by (*19*)], and North America (NA) (*20*). The Apparent Polar Wander Path from 300 to 125 Ma (open diamonds) for North America is shown for comparison (*30*). Rotation poles of South America to Africa and North America to Africa are after (*17*) and (*31*), respectively.

The CAMP thus includes the $\sim 2.5 \times 10^6$ km^2 widespread magmatism in central and northern Brazil and had a total extent of at least 7×10^6 km^2. Assuming conservatively that preserved volcanic sections averaging 200 to 300 m thick in distal portions of the CAMP are representative (*6*, *8–10*), an original volume of 2×10^6 km^3 is implied. The geochronological and paleomagnetic data suggest that most of this widespread magmatism occurred in a few million years, with a peak at ~200 Ma. Similarly widespread and short-lived tholeiitic magmatism characterizes other well-studied CFBPs, for example, the Siberian Traps (*22*) or the Karoo-Ferrar (*23*, *24*) (Fig. 4).

Such brief and extremely widespread tholeiitic magmatism, occurring up to 2000 km from the continental margin, implies that anomalously hot mantle extended over a very wide area and melted extensively. Considering the geochemical and isotopic compositions of CAMP basalts, an important contribution of lithospheric mantle is suggested. The debate concerning the origin of CAMP is open, and various models have been proposed invoking the presence of either a mantle plume (*1*, *2*, *25*) or a shallow thermal anomaly (*7*). In general, our data and previous (*4–6*, *8–10*) geochemical and geochronological data on CAMP are consistent with models that suggest that an upwelling plume head was trapped beneath the lithosphere and separated from the plume tail (*25*), with plume material spread over a very large area by ambient mantle flux (*2*). However, these models require modification to account for CAMP magmatism not only in North America and Africa but also in South America.

The Triassic-Jurassic (T-J) boundary is one of the five major Phanerozoic mass extinction events and involved marine and terrestrial genera and families (*26*). The timing of the huge CAMP magmatic event overlaps within errors with modern estimates for the age of the T-J boundary. CAMP basaltic dikes and flows (for example, the 201 Ma Palisades and Gettysburg sills and the Orange Mountain flow) of eastern North America essentially define this boundary in the Culpeper, Fundy, and Newark basins (*5*, *20*, *27*) of North America. Documentation of the enormous spatial extent of the CAMP, and its temporal brevity, support the possibility of a genetic relation with the T-J extinctions (*28*).

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