

Giant Lava Flows, Mass Extinctions, and Mantle Plumes

Paul E. Olsen

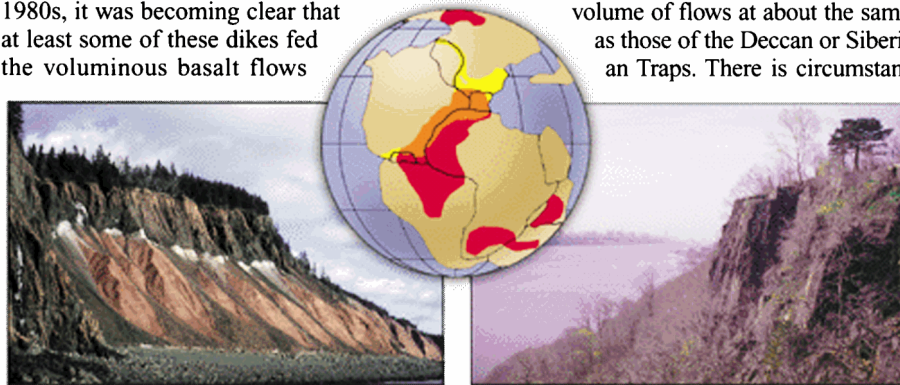
What are the consequences and origins of the largest volcanic events known on Earth? These include the so-called large igneous provinces (or LIPs) that comprise enormous edifices of basaltic lava and associated igneous rocks formed over a relatively brief time interval

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(1). Two of the largest LIPs, the Siberian Traps ($\sim 2.5 \times 10^6 \text{ km}^3$) and Deccan Traps ($\sim 2.6 \times 10^6 \text{ km}^3$), were extruded onto the land surface (2) and are often termed continental flood basalts. Each is also associated with a mass extinction, the Siberian Traps with the extinction at the end of the Permian (250 million years ago) and the Deccan Traps with the extinction at the end of the Cretaceous (65 million years ago). In recent years, a third giant continental LIP associated with a mass extinction has been identified in the long-studied Triassic-Jurassic (~ 201 million years ago) lavas and igneous intrusions that mark the rifting of the supercontinent of Pangea and the formation of the Atlantic Ocean. As reported by Marzoli *et al.* on page 616 of this issue (3), this Central Atlantic Magmatic Province (CAMP) may be the largest LIP of all, at least in area. Before the formation of the Atlantic Ocean, it extended over 7 million km^2 , from France to southern Brazil, covering substantial portions of four tectonic plates (see the figure). And yet this igneous activity probably occurred over less than a few million years. The origin of this LIP bears on the mechanisms of mass extinction, continental breakup, and the motive force behind continental drift itself.

The author is at the Lamont Doherty Earth Observatory of Columbia University, Palisades, New York 10964, USA. E-mail: polsen@ldeo.columbia.edu

Recognition of this Triassic-Jurassic LIP has been long in coming, perhaps delayed by the fact it was dismembered during formation of the Atlantic Ocean, either deep eroded or deeply buried, and is difficult to precisely date. However, as long ago as 1971, May (4) showed that the numerous linear dikes of basaltic composition in eastern North America, Africa, southwestern Europe, and South America made up a giant radiating dike swarm when placed in their predrift positions, their focus being near Florida. This is in fact the largest radiating dike swarm known in the solar system (5). By the 1980s, it was becoming clear that at least some of these dikes fed the voluminous basalt flows



Big lava. (Left) Basalt flow (brown) in the CAMP on top of the Triassic-Jurassic boundary (white) on Triassic rift lake sediments (reddish brown). (Center) Pangea during the Late Triassic–Early Jurassic with four terrestrial LIPs (north to south: Siberian Traps, CAMP basalts, Deccan Traps, and Karroo lavas). (Right) The Palisades Sill, an intrusive part of the CAMP event, exposed along the shores of the Hudson River, near New York City.

and sills in the Triassic-Jurassic rift basins on the Atlantic Margin (6) and that the age of this dike system is about 201 million years (7). Paleontological data established that the flows were very close in time to the Triassic-Jurassic boundary and hence to its purported mass extinction event and that the flows in fact date the boundary (8). As was true for the events at the end of

the Permian and the Cretaceous, the temporal association of the extensive basalt flows and a mass extinction has led to speculation that the eruption of the lavas triggered ecologically catastrophic climate change through massive input of volatiles into the atmosphere (9).

As with the other two events, however, the proposed links between the CAMP LIP and mass extinction remain very controversial, with substantial volume, timing, and mechanism problems. Although the pre-erosion extent of the Deccan and Siberian lavas probably exceeded $2.0 \times 10^6 \text{ km}^3$, the present volume of CAMP lavas in the rift basins is more than an order of magnitude smaller. However, all of the exposed rifts are deeply eroded to depths of several kilometers (10). Assuming that the distribution of dikes and other intrusions is a guide to the pre-erosion extent of the associated lavas,

Marzoli *et al.* (3) estimate the original volume of flows at about the same as those of the Deccan or Siberian Traps. There is circumstan-

tial evidence (11) that the recently recognized seaward-dipping reflectors (12) off the eastern United States may also be part of the CAMP, although their age is very poorly constrained. The volume of these basaltic, purportedly terrestrial, flows would raise the total to about 4 million km^3 . This excludes the volume of intrusive CAMP rocks, which could add about the same amount again.

So it is plausible that the actual volume of CAMP basalts was as great or greater than that of the Siberian or Deccan Traps. Superficially, however, the timing of the CAMP event has seemed wrong for the extinctions at the end of the Triassic. In recent years, the Triassic-Jurassic boundary, marking the extinction, has been identified with considerable precision, but at all of the places in which the boundary and the lavas have been seen in superposition, from Virginia to Nova Scotia, the boundary always lies below the oldest lavas (8). Although these observations cover only a small part of the CAMP, it is hard to argue causation if the cause occurs after the supposed effect. However, the mostly normal magnetic polarity of the igneous rocks (13) and the statistical properties of polarity stratigraphy around the Triassic-Jurassic boundary (13, 14) argue for a brief (less than 2 million years) igneous episode with some magmatic activity preceding the boundary, and half could have occurred before and could have caused the extinctions.

A number of plausible mechanisms linking the mass extinctions at the end of the Triassic with LIPs have been proposed, with strong parallels being drawn with the events at the end of the Permian and the Cretaceous (15). These include massive emissions of CO₂ or SO₂ aerosols from LIPs (16), rapid sea-level change (17), and a bolide impact (18).

CO₂ input could have produced substantial global warming and SO₂ global cooling if introduced over a sufficiently brief interval. Both should leave a discernible geochemical record in marine and lacustrine sediments, fossil soils (19), and fossil plant anatomy (20). Thus far, the available data from the terrestrial record are consistent with an abrupt and strong disruption of the carbon cycle, specifically with an increase in CO₂, although explanations of its origin are diverse. There is as yet no evidence of an SO₂-induced cooling.

In the sea-level change scenario, thermal doming associated with the initiation of Pangean rifting followed by collapse during CAMP eruption produced a very rapid regression-transgression couplet that presumably disrupted marine communities, resulting in the observed marine mass extinction (17). Hallam and Wignall (17) have indeed argued that sea-level change was the major cause of all of the major extinctions of the past 500 million years. It is difficult to see how the sea-level change would cause the terrestrial extinctions, however.

A viable alternative for a CAMP-induced extinction at the end of the Triassic is a bolide impact. The overall extinction pattern and associated floral effects at the Triassic-Jurassic boundary do parallel those

associated with the Cretaceous-Tertiary Chicxulub impact (21). Evidence includes the presence of a massive increase of spores at the Triassic-Jurassic boundary (8), which has been attributed, as in the case of the very similar "fern spike" at the Cretaceous-Tertiary boundary, to impact-induced massive ecological disruption (22). In addition, shocked quartz has been reported from two marine boundary sections (23), although both are disputed (17). However, concerted efforts to find shocked quartz in continental sections at the Triassic-Jurassic boundary have yet to be carried out.

Conventional theories of the origin of LIPs involve mantle dynamics, in particular, mantle plumes and hot spots (1). In these models, the deep mantle generates a hot, upwelling plume of relatively low-density material that rises and eventually ponds at the base of the lithosphere, generating melt. Rifting in the region of the CAMP was occurring for at least 30 million years before the magmatic episode, so the crust was thinning in advance. According to Marzoli *et al.* (3), their new age and geochemical data are consistent with a plume head separated from its tail and spread over an extremely large area. Structural data from rift basins in the southeastern United States suggest that they ceased subsidence and underwent tectonic inversion (under compression in the same direction in which they were previously under extension) close to the focus of the CAMP before or at the time of its emplacement (11). Simultaneously, rift basins farther north actually accelerated in subsidence. Sequentially, over the next 145 million years, the pattern of initial sea floor and seaward-dipping reflector formation and concomitant rift basin inversion seems to have proceeded north and probably south from the locus of CAMP igneous activity (11). All this suggests strong, if poorly understood, links behind the CAMP, core-mantle processes, and plate motions.

Presently, virtually all aspects of the CAMP LIP are controversial. Major problems that need to be addressed in the near term include (i) establishing the precise age range of the igneous event by direct dating of CAMP dikes in eastern North America by multiple methods; (ii) determining the magnetic polarity of a large suite of dikes, sills, and flows over a major portion of the CAMP; (iii) establishing the relative stratigraphic position, age, and magnetic polarity of the basalt flows in the southeastern United States; (iv) direct sampling and dating of the deeply buried, seaward-dipping reflectors offshore of the southeastern United States; and (v) searching for biological, geochemical, and mineralogical proxies of events related to the CAMP event, impacts, and the Triassic-Jurassic boundary.

As has long been noted, the implications of bolide impacts and massive volcanism can be very similar (24). The Cretaceous-Tertiary Chicxulub bolide, for example, struck marine limestone and sulfate, so a massive input of both CO₂ and SO₂ has been proposed as a major cause of the extinctions and ecosystem disruption (25), the same cause proposed for the effects of terrestrial LIPs. Indeed, an impact origin for both the Triassic-Jurassic and Cretaceous-Tertiary LIPs has been hypothesized (26), although plausible linkages with the specific events seem hard to come by. Nonetheless, the coincidence of the three largest Phanerozoic mass extinctions with the three largest continental LIPs—two possibly with giant bolide impacts—does demand very close scrutiny.

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