Mass extinctions of life and catastrophic flood basalt volcanism

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Extinctions have played an important role in the history of life by clearing out niches and fostering adaptive radiations. Major mass extinctions involving 70% to more than 90% of extant species occurred at least five times during the last 540 million years. The discovery by Alvarez et al. (1) that the end-Cretaceous (65 Mya) mass extinction coincided with evidence for the impact of an asteroid or comet ~10 km in diameter focused interest in the causes of the other mass extinctions. It was expected that evidence of a similar impact might be found at other mass extinction events. Such evidence, however, has been slow in coming (2). At the same time, episodic massive continental flood basalt eruptions were suggested as another possible cause of mass extinctions (3, 4). This connection is illustrated by a study by Whiteside et al. (5) that provides evidence that the eruption of the Central Atlantic magmatic province (CAMP) basalts, with a preserved volume greater than 1×10^6 km^3 and covering more than 7×10^6 km^2, coincided with the end-Triassic extinction event (ETE) (201.4 Mya) on land and in the oceans.

The report by Whiteside et al. (5) presents carbon-isotope results obtained from leaf wax n-alkanes, wood, and total organic carbon from two nonmarine sections from the Newark and Hartford Basins in the eastern United States, which include the CAMP basalts and which are tightly constrained by magnetic reversals, orbital cycles, and pollen studies. The correlation utilizes the levels of the ETE and coincident carbon-isotope excursion and the Hettangian-Sinemurian boundary 1.8 Mya later, which bracket the CAMP episode. The sections are calibrated at high (20-ky) precision. These data are matched to orbitally forced carbon-isotope data from the marine St Audrie's Bay, UK section, showing that the sharp initial negative carbon-isotope shift and extinction horizon are synchronous in marine and nonmarine sections. The oldest CAMP basalts in the Newark and Hartford Basins slightly postdate the extinction horizon (by ~20 ky), but in similar Moroccan sections the basalts may be simultaneous with the extinction horizon (6, 7).

As precise radiometric ages have become available, it has been determined that flood basalt episodes are brief and severe (with peak output of more than 1 million cubic kilometers over less than 1 million years, in most cases) (4). Two other major mass extinctions have been correlated with flood basalt episodes: the end-Cretaceous event (65 Mya) with the Deccan basalts of India and the end-Permian event (251 Mya) with the Siberian basalts. However, the Deccan eruptions now are known to have started before the end-Cretaceous mass extinction/impact event, and the Siberian flows still are only roughly correlated with the end-Permian die off (4).

Flood basalt episodes may be major causes of climatic and biologic change.

Lesser extinctions and paleoclimatic events are correlated with the 55-Mya North Atlantic basalts (with the Paleocene-Eocene Thermal Maximum or PETM) and the 183-Mya Karoo basalts (with an Early Jurassic warming and extinction event). To determine a cause-and-effect relationship, what we need now are tightly constrained stratigraphic studies similar to that of Whiteside et al. (5) linking the lava flows to the records of the extinctions and other environmental perturbations in marine and nonmarine sections.

Causes of Extinction

What is the mechanism causing extinction? Climatic cooling from volcanic aerosols in the upper atmosphere has been suggested, as has warming resulting from magmatic carbon dioxide emissions. However, magmatic emissions of CAMP carbon dioxide probably were too small to have affected the climate greatly, and the long-term cooling from aerosols is very uncertain (8). The initial negative δ^{13}C isotopic excursions in the Newark, Hartford, and St Audrie's Bay sections suggest a massive input of ^{13}C-depleted methane coincident with the onset of CAMP, and the duration of the initial carbon-isotope excursion is estimated at only 20–40 ky. [The longer period of ^{13}C-depleted values during the CAMP extrusion might be the result of the biotic crisis itself (9).] A carbon dioxide super-greenhouse is supported by paleobotanical studies (10) and evidence of a crisis among calcareous organisms in the oceans (11).

The most likely source of greenhouse gases may be rapid release from reactions between igneous intrusions accompanying the flows and surrounding sediments. For example, Svensen et al. (12) proposed that the PETM and associated negative carbon-isotope excursion resulted from explosive release of ^{13}C-depleted methane from intrusion of concurrent basaltic sill complexes into organic-rich sediments. Further support for this idea comes from the presence of unusual igneous rocks produced by melting of sediments in contact with the North Atlantic intrusions (13). More recently, a similar model has been suggested for release of greenhouse gases from the eruption of the Siberian and Karoo basalts, where intrusions are accompanied by pipes of highly fractured rock that indicate explosive release of thermogenic gases from the intruded sediments (14, 15).

Catastrophes

Whatever the ultimate cause of the extinctions and climatic perturbations, the results of Whiteside et al. (5) provide a convincing link between the ETE and the CAMP basalts. The recognition that catastrophic events such as large impacts or flood basalt episodes may be major causes of climatic and biologic change represents a sea change in the geological sciences. James Hutton (1726–1797) is said to have discovered deep time—the almost unimaginable length of geologic time—and Charles Lyell (1797–1875) interpreted deep time as accommodating the idea that the directly observable slow and steady geological processes working over the long ages might explain great geological and biological changes. By contrast, natural events of various kinds in the real world tend to follow an inverse-power law relationship between frequency F and magnitude M so that $F = 1/M^D$, where D is positive (see, for example, refs. 16, 17). Thus, small-magnitude events (e.g., earthquakes, volcanic eruptions, impacts) tend to happen much more frequently than potentially

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catastrophic large-magnitude events. The reasons are variable, but in general, a probabilistic relationship exists between the magnitude and frequency of events.

Thus, the notion of deep time must take into account the fact that the events with the greatest magnitude should happen very infrequently; in fact, tens to hundreds of millions of years could elapse between the greatest events. The significance of deep time is that, even though we expect extremely large events only very infrequently, the long geologic time scale virtually guarantees that potential catastrophes such as large-body impacts and flood basalt volcanism will happen from time to time (perhaps quite "often" compared with the length of geological time), and the results of these very energetic events should be an important aspect of the geologic and biologic records.

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