Magmatism

Fossil fuel, mercury and the end-Palaeozoic catastrophe June 2020)

Siberian flood-basalt flows in the Putorana Plateau, Taymyr Peninsula, Russia. (Credit: Paul Wignall)

The end of the Permian Period (~252 Ma ago) saw the loss of 90% of marine fossil species and 70% of those known from terrestrial sediments: the greatest known extinction in Earth's history. In their naming of newly discovered life forms, palaeontologists can become quite lyrical. Extinctions, however, really stretch their imagination. They call the Permo-Triassic boundary event 'The Great Dying'. Why not 'Permageddon'? Sadly, that was snaffled in the 1980s by an astonishingly short-haired heavy-metal tribute band. Enough bathos … The close of the Palaeozoic left a great many ecological niches to be filled by adaptive radiation during the Triassic and later Mesozoic times. Coinciding with the largest known flood-basalt outpouring – the three million cubic kilometres of Siberian Traps – the P-Tr event seemed to be 'done and dusted' after that possible connection was discovered in the mid 1990s. Notwithstanding, the quest for a gigantic, causative impact crater continues (see: Palaeobiology Earth-logs, May, September and October 2004), albeit among a dwindling circle of enthusiasts. The Siberian Traps are suitably vast to snuff the fossil record, for their eruption must have belched all manner of climate-changing gases and dusts into the atmosphere; CO_2 to encourage global warming; SO_2 and dusts as cooling agents. There is also evidence of a role for geochemical toxicity (see: Nickel, life and the end-Permian extinction, June 2014). The extinctions accompanied not only climate change but also a catastrophic fall in atmospheric oxygen content (see: Homing in on the great end-Permian extinction, April 2003; When rain kick-started evolution, December 2019). Recovery of the biosphere during the early Triassic was exceedingly slow.

Research focussed on the P-Tr boundary eventually uncovered an element of pure chance. Shales in Canada that span the boundary show major, negative $\delta^{13}C$ excursions in the carbon-isotope record that coincide with fly ash in the analysed layers. This material is similar in all respects to that emitted from coal-fired power stations (see: Coal and the end-Permian mass extinction, March 2011). The part of Siberia onto which the flood basalts were erupted is rich in Permian coal measures and oil shales that lay close to the surface 252 Ma ago. The coal ash and massive emissions of CO2 may have resulted from their burning by the flood basalt event. Now evidence has emerged that this did indeed happen (Elkins-Tanton, L.T. *et al*. 2020. Field evidence for coal combustion links the 252 Ma Siberian Traps with global carbon disruption. *Geology*, v. **48**, early publication; DOI: 10.1130/G47365.1).

The US, Canadian and Russian team found large quantities of burnt coal and woody material, and bituminous blobs in 600 m thick volcanic ashes at the base of the Siberian traps themselves. They concluded that the magma chamber from which the flood basalts emerged had incorporated sizeable volumes of the coal measures, leading to their combustion and distillation. This would have released CO_2 enriched in light ^{12}C due to isotopic fractionation by biological means, i.e. its $\delta^{13}C$ would have been sufficiently negative to affect the carbon locked up in the Canadian P-Tr boundary-layer shales that show the sharp isotopic anomalies. The magnitude of the anomalies suggest that between six to ten thousand billion tons of carbon released as CO_2 or methane by interaction of the Siberian Traps with sediments through which their magma passed could have created the global $\delta^{13}C$ anomalies. That is about one tenth of the organic carbon originally locked in the Permian coal measures beneath the flood basalts

Another paper whose publication coincided with that by Elkins-Tanton *et al*. suggests that environmental mercury appears to have followed the same geochemical course as did carbon at the end of the Palaeozoic Era (Dal Corso, J. and 9 others 2020. Permo–Triassic boundary carbon and mercury cycling linked to terrestrial ecosystem collapse. *Nature Communications*, v. **11**, paper 2962; DOI: 10.1038/s41467-020-16725-4). This group, based at Leeds and Oxford Universities, UK and the University of Geosciences in Wuhan, China, base their findings on biogeochemical modelling of the global carbon and mercury cycles at the end of the Permian. Their view is that the coincidence in marine sediments at the P-Tr boundary of a short-lived spike in mercury and an anomaly in its isotopic composition with the depletion in ^{13}C, described earlier, shows an intimate link between mercury and the biological carbon cycle in the oceans at the time. They suggest that this synergy marks ecosystem collapse and derives ‘from a massive oxidation of terrestrial biomass’; i.e. burning of organic material on the land surface. Their modelling hints at huge wildfires in equatorial peatlands but also a role for the Siberian flood-basalt volcanism and the incorporation of coal measures into the Siberian Trap magma chamber.

Influence of massive igneous intrusions on end-Triassic mass extinction (September 2020)

About 200 Ma ago, the break-up of the Pangaea supercontinent was imminent. The signs of impending events are spread through the eastern seaboard of North America, West Africa and central and northern South America. Today, they take the form of isolated patches of continental flood basalts, dyke swarms – probably the feeders for much more extensive flood volcanism – and large intrusive sills. Break-up began with the separation of North America from Africa and the start of sea-floor spreading that began to form the Central Atlantic Ocean: hence the name Central Atlantic Magmatic Province (CAMP) for the igneous activity. It all kicked off at the time of the Triassic-Jurassic stratigraphic boundary, and a mass extinction with a similar magnitude to that at the end of the Cretaceous. Disappearances of animals in the oceans and on continents were selective rather than general, as were extinctions of land plants. The mass extinction is estimated to have taken about ten thousand years. It left a great variety of ecological niches ready for re-occupation. On land a small group of reptiles with a substantial destiny entered some of these vacant niches. They evolved explosively to the plethora of later dinosaurs as their descendants became separated as a result of continental drift and adaptive radiation.

Flood basalts of the Central Atlantic Magmatic Province in Morocco (Credit: Andrea Marzoli)

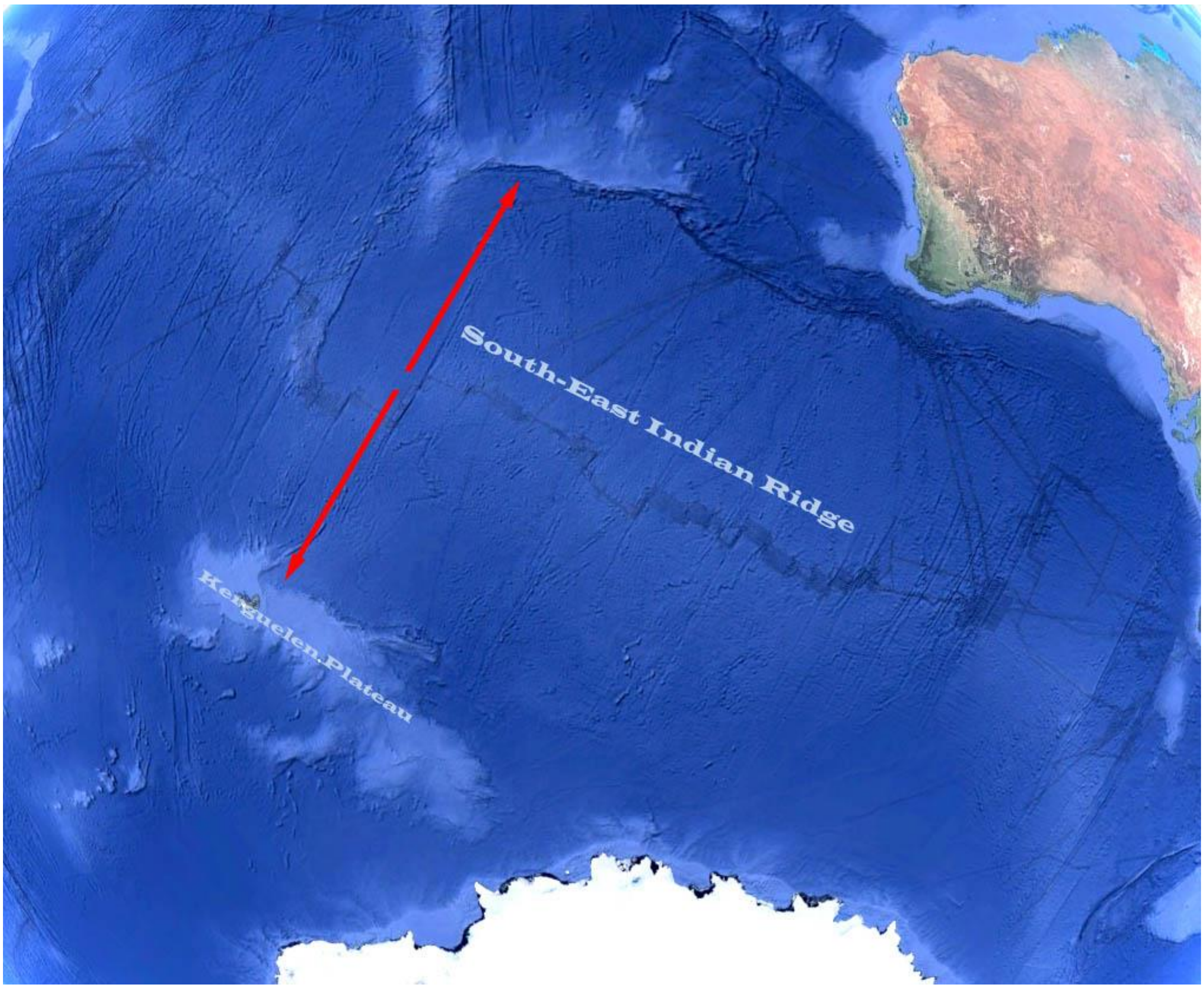
The end-Triassic mass extinction, like three others of the Big Five, was thus closely associated in time with massive continental flood volcanism: indeed one of the largest such events. Within at most 10 ka large theropod dinosaurs entered the early Jurassic scene of eastern North America. The Jurassic was a greenhouse world whose atmosphere had about five times more CO_2, a mean global surface temperature between 5 and 10°C higher and deep ocean temperatures 8°C above those at present. Was mantle carbon transported by CAMP magmas the main source (widely assumed until recently) or, as during the end-Permian mass extinction, was buried organic carbon responsible? A multinational group of geoscientists have closely examined samples from a one million cubic kilometre stack of intrusive basaltic sills, dated at 201 Ma, in the Amazon basin of Brazil that amount to about a third of all CAMP magmatism (Capriolo, M. and 11 others 2021. Massive methane fluxing from magma–sediment interaction in the end-Triassic Central Atlantic Magmatic Province. *Nature Communications*, v. **12**, article 5534; DOI: 10.1038/s41467-021-25510-w).

The team focussed on fluid inclusions in quartz within the basaltic sills that formed during the late stages of their crystallisation. The tiny inclusions contain methane gas and tiny crystals of halite (NaCl) as well as liquid water. Such was the bulk composition of the intrusive magma that the presence of around 5% of quartz in the basalts would be impossible without their magma having assimilated large volumes of silica-rich sedimentary rocks such as shales. The host rocks for the huge slab of igneous sills are sediments of Palaeozoic age: a ready source for contamination by both organic carbon and salt. The presence of methane in the inclusions suggests that more complex hydrocarbons had been 'cracked' by thermal metamorphism. Moreover, it is highly unlikely to have been derived from the mantle, partly because methane has been experimentally shown not to be soluble in basaltic magmas whereas CO_2 is. The authors conclude that both quartz and methane entered the sills in hydrothermal fluids generated in adjacent sediments. Thermal metamorphism of the sediments would also have driven such fluids to the surface to inject methane directly to the atmosphere. Methane is 25 times as potent as carbon dioxide at trapping heat in the atmosphere, yet it combines with the hydroxyl (OH^-) radical to form CO_2 and water vapour within about 12 years. Nevertheless during continuous emission methane traps 84 times more heat in the atmosphere than would an equivalent mass of carbon dioxide.

Calculations suggest about seven trillion tonnes of methane were generated by the CAMP intrusions in Brazil. Had the magmas mainly been extruded as flood basalts then perhaps global warming at the close of the Triassic would have been far less. Extinctions and subsequent biological evolution would have taken very different paths; dinosaurs may not have exploded onto the terrestrial scene so dramatically during the remaining 185 Ma of the Mesozoic. So it seems important to attempt an explanation of why CAMP magmas in Brazil did not rise to the surface but stayed buried as such stupendous igneous intrusions. Work on smaller intrusive sills suggests that magmas that are denser than the rocks that they pass through – as in a large, thick sedimentary basin – are forced by gravity to take a lateral 'line of least resistance' to intrude along sedimentary bedding. That would be aided by the enormous pressure of steam boiled from wet sedimentary rocks forcing beds apart. In areas where only thin sedimentary cover rests on crystalline, more dense igneous and metamorphic rocks, basaltic magma has a greater likelihood of rising through vertical dyke swarms to reach the surface and form lava floods.

Kerguelen Plateau: a long-lived large igneous province (November 2020)

It's easy to think of the Earth's largest outpourings of lava as being restricted to the continents: continental flood basalts with their spectacular stepped topography made up of hundreds of individual massive flows and intervening soil horizons. The Deccan Traps of western India are the epitome, having been so named by natural scientists of the late 18th century from the Swedish word for 'stairs' (*trappa*). Examples go back to the Proterozoic Era, younger ones still retaining much of their original form as huge plateaus. All began life within individual tectonic plates, although some presaged continental break-up and the formation of new oceanic spreading centres. They must have been spectacular events, up to millions of cubic kilometres of magma belched out in a few million years. They have been explained as manifestations of plumes of hot mantle rock rising from as deep as the core-mantle boundary. Unsurprisingly, the biggest continental flood-basalt outpourings coincided with mass extinction events. Otherwise known as large igneous provinces (LIPs), they are not the only signs of truly huge production of magma by partial melting in the mantle. The biggest LIP, with an estimated volume of 80 million km^3, lies deep beneath the Western Pacific Ocean. To the northeast of New Guinea, the Ontong Java Plateau formed over a period of about 3 Ma in the mid-Cretaceous (~120 Ma) and blanketed one percent of the Earth's solid surface with lavas erupted at a rate of 22 km^3 per year. Possibly because this happened on the Pacific's abyssal plains beneath around 4 km of sea water, there is little sign of any major perturbation of mid-Cretaceous life, but it is associated with evidence for global oceanic anoxia. Ontong Java isn't the only oceanic LIP. Bearing in mind that oceanic lithosphere only goes back to the start of the Jurassic Period (200 Ma) – earlier material has largely been subducted – they are not as abundant as continental flood-basalt provinces. One of them is the Kerguelen Plateau 3000 km to the SE of Australia, which is about three times the area of Japan and the second largest LIP of the Phanerozoic Eon. The Plateau was split into two large fragments while sea-floor spreading progressed along the Southeast Indian Ridge.



Bathymetry of the Indian Ocean south-west of Australia, showing the Kerguelen Plateau and South-east Indian Ridge. The red arrows show the amount of sea-floor spreading on either side of the Ridge since it began to open. The pale blue area at the NE end of the arrow was formerly part of the Plateau (credit: Google Earth)

Long regarded as a microcontinental fragment left when India parted company with Antarctica – based on isolated occurrences of gneisses – there is evidence that during the formation of the Kerguelen LIP the basalts rose above sea level. Because earlier radiometric dating of basalts from ocean-floor drill cores were of low quality, an Australian-Swedish group of geoscientists have re-evaluated those data and supplemented them with 25 new Ar-Ar dates from 12 sites (Jiang, Q. *et al*. 2020. Longest continuously erupting large igneous province driven by plume-ridge interaction. *Geology*, v. **48**, online; DOI: 10.1130/G47850.1). Rather than a cluster of ages around a short time range as expected from the short life of most other LIPs, those from Kerguelen span 32 Ma during the Cretaceous (from 122 to 90 Ma). The magmatic pulse began at roughly the same time as that of Ontong Java, but continued for much longer. Smaller oceanic LIPs do seem to have lingered for unusually lengthy periods, but all seem to have constructed in several separate pulses. Large-volume eruption at Kerguelen was continuous for *at least* 32 Ma; the drilling did not penetrate the oldest of the plateau basalts. It seems that the Kerguelen LIP is unique in that respect and requires an explanation other than simply a mantle plume, however large.

Jiang *et al*. suggest a model of continuous interaction between a long-lived plume and the development of the Southeast Indian Ridge oceanic spreading centre. Their model involves the line of continental splitting between India and Antarctic taking place close to a major deep-mantle plume at around 128 Ma. There is nothing unique about that; incipient ocean rifting in the Horn of Africa and formation of the Red Sea and Gulf of Aden ridges is currently associated with the active Afar plume. This was followed by a kind of tectonic shuffling of the Ridge back and forth across the head of the Kerguelen plume: not far different from the Palaeogene North Atlantic LIP, where the mid-Atlantic Ridge and the still-active Iceland plume, except the ridge and plume seem more intimately involved there. However, there are probably many subtle relationships between plumes and various kind of oceanic plate margins that are still worth exploring. Since the first discovery of mantle plumes as an explanation for volcanic island chains (e.g. the Hawaiian chain) where volcanism becomes progressively older in the direction of plate movement, there is still much to discover.

See also: Magma .conveyor belt' fuelled world's longest erupting supervolcanoes (*Science Daily*, 4 November 2020)