The end-Permian mass extinction and the Siberian Traps eruptions

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What are Flood Basalts?

At least three of the five biggest mass extinction events occurred at the same time as flood-basalt eruptions. These were extensive volcanic eruptions that occurred over millions of years. Most of the lava flowed from fissures or vents in valleys or plains rather than from volcanic mountains, and crystallized into a rock called basalt as it cooled. Even after millions of years of weathering and erosion, layers of basalts from these eruptions extend over an area tens of thousands to millions of square kilometers across and several km thick. Some of these deposits are large enough to be seen on a world map (Fig. 1). In addition to flood basalts on continents, there are large basalt plateaus in the ocean, including the Kerguelen and Ontong Java Plateaus, which may be the result of sub-marine flood-basalt eruptions.

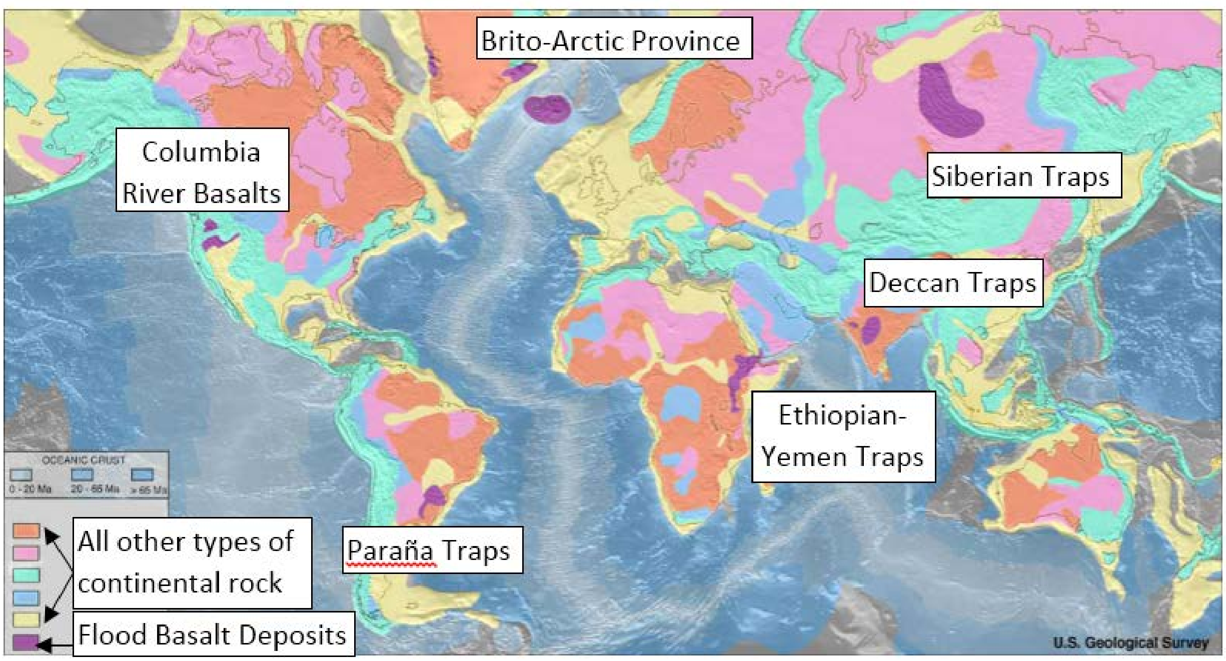

Figure 1: Major geologic provinces across the world (base map from the USGS, 2005). Note that some continental crust is currently flooded, including the continental shelves.

Flood basalt eruptions are poorly understood because they occur rarely, even in the geologic record. The most recent one ended over two million years ago, so they've never been directly witnessed by human beings.

These extensive basalt plateaus are called often called "traps" from an old Germanic word for stairs, because weathering carves the rocks into formations that look like giant stairs (Fig. 2). Individual vent eruptions often lasted tens or perhaps hundreds of thousands of years, and these plateaus were deposited by multiple eruptions. For comparison, the longest continuous volcanic eruption in human history is still going on at Kilauea in Hawai'i, but it only began in 1983.

One feature they share is that the minerals that make up continental flood basalts have an unusual chemistry. The lavas that crystallized into these basalts contained a lot of material from the Earth's mantle, which is very unusual for continental eruptions. Under the continents, Earth's crust is thick, about 30-40 km thick on average. Consequently it's very difficult for magma from the mantle to force its way to the surface without being heavily diluted by molten continental rock. Most flood basalt eruptions are believed to have occurred over "hot spots" in the mantle, like the ones under modern-day Hawai'i and Yellowstone. The causes of these "hot spots" are under debate by the geological community.

Figure 2: Three Devils Grade on the Columbia River Plateau (public domain).

How Could a Flood-Basalt Eruption Cause a Mass Extinction?

Magma is a mixture of molten rock and hot, pressurized gas. If magma erupts from a volcanic vent, the gas is released to the atmosphere, and the remaining material, called lava, eventually crystallizes into glass or igneous rock. It is this gas, even more than the huge lava flows from a flood-basalt eruption, that can cause a global extinction. It's a mixture of water vapor, carbon dioxide, sulfur-rich gases, and a variety of others (but never free oxygen). Carbon dioxide absorbs heat and later releases it, warming the climate.

At the same time, the sulfur-rich gases become tiny particles of sulfate. These are usually suspended in the atmosphere as aerosols. On their own, they reflect some sunlight back into space before it reaches Earth's surface so that it doesn't get as warm as it usually does, especially in summer. Those aerosol particles provide a surface where water vapor can condense, forming clouds that will also reflect sunlight, and dissolve the sulfate, creating sulfuric acid. As this acid, even heavily diluted, falls as rain, it can dissolve the calcareous shells not just of familiar marine creatures like clams, but also of tiny plankton that are the base of the food web, killing them. As plankton populations decline, many other marine animals starve. The warming caused by carbon dioxide and the cooling caused by sulfate aerosols aren't likely to cancel each other out evenly.

Although human beings have never witnessed a flood-basalt eruption, we do have records of a very destructive set of fissure eruptions on a much smaller scale in Iceland from June 1783 to February 1784. The lavas themselves erupted in an isolated valley called Lakagígar and did little, if any, direct damage to the human population. But the gases, particularly hydrogen fluoride and the sulfate gases, were deadly in both the long and the short term. At least half of the livestock, grazing out in the open, died over the next several months, poisoned by the acids formed by these gases. When inhaled, hydrofluoric acid reacts with teeth and bones, starting to dissolve them. The dissolved material can be absorbed into the bloodstream, where it can then block blood vessels. Sulfuric acid, even diluted, makes it difficult for plants to take up nutrients with their roots, and over time can burn plant leaves.

Many of the people of Iceland starved over the next several months, and they still refer to this disaster as the Mist Hardships. Millions of tons of sulfate spread across the whole Northern Hemisphere.

Sulfate aerosols were visible as brown clouds in Europe, and the 1783-84 winter was extremely cold in Europe and North America according to Benjamin Franklin and other writers of the time. And that eruption lasted less than a year. Imagine if it had lasted for hundreds or thousands of years. Fortunately, Lakagígar was not a true flood-basalt eruption.

History records a number of “years without a summer” when stratovolcanoes like Mount Pinatubo or Krakatoa erupted, forcing tons of ash into the atmosphere, where it can be suspended for months after the eruption, and not just reflect, but also block incoming sunlight. The mineralogy of stratovolcanic eruptions is very different from those of flood-basalt eruptions. Scientists who argue that flood-basalt eruptions are not major causes of mass extinctions in the past point out that basaltic eruptions in general produce very little volcanic ash. However, the sulfate aerosols alone reflect a lot of sunlight. Moreover stratovolcanoes generally disrupt only one or two summers in a row, whereas individual flood-basalt eruptions continue for thousands of years, and flood-basalt deposits are made by multiple eruptions spanning millions of years.

Name	Age (millions of years ago)	Approximate Remaining Area (km^2)	Associated Extinction Event
Columbia River Basalt (N.W. U.S.)	17-15 & 14-5	200,000	none
Ethiopian and Yemen Traps	28-31	800,000	none
Brito-Arctic Province	59-56	1,500,000	end-Paleocene (minor)
Deccan Traps (N.W. India)	67-63	500,000	end-Cretaceous
Paraña-Etendeka Traps (E. S. America, W. Africa)	131-134	750,000	none
CAMP - Central Atlantic Marine Province (Morocco, E. Canada & U.S., Brazil, W. Europe)	200-201	uncertain	end-Triassic
Siberian Traps (Russia)	249-252?, 240?	2,000,000	end-Permian
Emeishan Traps (China)	258-260?, 251?	250,000	possibly end-Permian

Table 1: Characteristics of several relatively well-known continental flood basalt deposits – buried deposits add great uncertainty to estimates of modern areas.

Another problem is that some large flood-basalt deposits are not associated with extinction peaks (Table 1). One example is the extensive Columbia River Basalt, which formed from a set of eruptions that occurred 16 million years ago. The effects of these eruptions on the biosphere may depend on other factors, such as:

- global air and ocean circulation patterns
- climate (global and in the regional),
- other environmental stresses on critical communities such as continental-shelf plankton,
- or the composition of the gases that came out of the magma, particularly their sulfur levels.

The older mass extinctions, the end-Ordovician and Devonian, are not associated with known flood basalts, but this may be because basalt weathers easily compared to most surface rock types. If there had been a flood-basalt eruption during those times, most of the basalt is likely to have been buried or eroded away by now. Older flood-basalt deposits are rare, small, and often hard to identify. For example, the Yakutsk-Viluy igneous province contains basalts that erupted as lava during the late Devonian mass extinction (Ricci et al., 2013), but much of it may be buried under the Siberian Traps, making its size difficult to estimate.

What is the Evidence for a Flood-Basalt Eruption at the End of the Permian?

The Siberian Traps are the largest exposed continental flood-basalt deposit in the world, even though they've been undergoing weathering for about 250 million years of weathering and are partly buried by younger sedimentary rock. Layers of basalt stack up to 3 km thick in some places. Another unusual feature of the Siberian Traps was that some of its eruptions produced a lot of ash, like stratovolcanic eruptions.

During the more intense eruptions, the Siberian fissures would have emitted far more gas than the Lakagígar eruption. The sulfates alone could formed acid rain concentrated enough to acidify the oceans. Even in weakly acid oceans many organisms can't form calcium carbonate shells. As waters grew more acidic, species of corals, shellfish and many types of photosynthetic plankton would have died out. The animals that fed on them would have starved to death.

In the modern world, photosynthetic plankton produce most of our oxygen. Reduced oxygen production at the end of the Permian would not only have made survival harder for large animals on land, but would have resulted in lower levels of dissolved oxygen in the oceans. Marine oxygen levels vary from place to place, depending on how winds and currents mix the water and on the consumption of oxygen by decomposers. Huge areas of the end-Permian ocean could have become uninhabitable (except to bacteria). Soils and marine sediments that formed at or just after the end of the Permian show chemical evidence for low oxygen levels.

Enormous sulfate emissions could also have affected the ozone layer, which ordinarily keeps a significant amount of harmful ultraviolet radiation from reaching Earth's surface. If the occasional ashy eruptions forced sulfate high into the atmosphere, it could react with the ozone. Ultraviolet-B radiation wavelengths contain a lot of energy. Not only can these wavelengths sunburn and gradually blind land animals, they also damage DNA. Tiny plankton living at the surface of the ocean are very vulnerable to UV-B light.

The Siberian Traps would also have released huge amounts of carbon dioxide. The late Permian atmosphere contained a much higher concentration of carbon dioxide than the modern atmosphere, and the global climate was much warmer. But the addition of even more carbon dioxide could have made water in some habitats too warm for most species, and oxygen is less soluble in warmer water than in colder water.

To make matters worse, the Emeishan Traps in what is now China had begun a second phase of eruptions at the end of the Permian. At that time, Siberia was north of its current position, approximately 60° latitude, and the Emeishan Traps erupted near what was then the equator. Between them, their emissions could spread across the whole planet.

However, uncertainties in the radiometric ages of the basalts weakens the argument that the end-Permian was caused exclusively by flood-basalt eruptions. For years, dates from a limited area of Siberia indicated that the whole volume of the Siberian Traps, millions of cubic kilometers of basalt, was deposited relatively quickly, over a period of less than 2 million years. Such intense eruptions would have added huge amounts of carbon dioxide and sulfates to the atmosphere every year. But new dates taken from a wider area of the huge expanse of the Siberian Traps show that the eruptions occurred in multiple pulses, and that the most intense eruptions happened after the end-Permian extinction had ended (Ivanov et al., 2013). How intense do flood-basalt eruptions have to be to trigger a mass extinction? This is a hard question to ask since we've never directly observed one.

References

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