Large igneous provinces include the famous Deccan and Siberian Traps. The term 'trap' comes from the Swedish word for stairs ('trappa'), referring to the step-like hills formed by the Siberian Traps. Columnar basalts emplaced by intrusive flows create formations like the famous Giant's Causeway in northern Ireland.

Photo of the Giant's Causeway showing step-like weathering of basalt columns, leading to the term 'traps'. This deposit is part of the North Atlantic Igneous Province.

What are large igneous provinces (LIPs)?

- >100 000 km^2 mafic igneous rock formed over 1 – 5 million years
- NOT a normal eruption
- Underwater or on continents

Basalt flows roughly the area of Iceland or larger are considered LIPs

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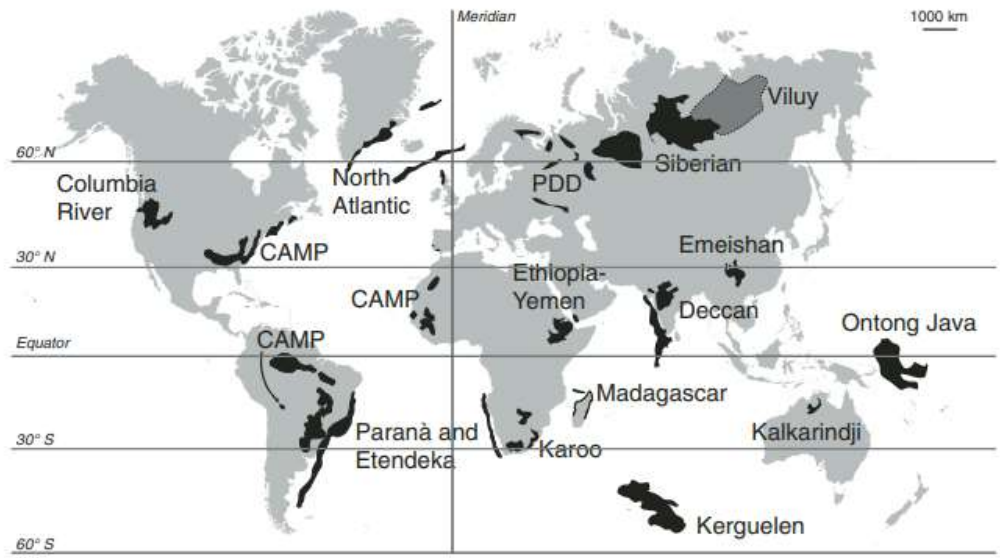
Large igneous provinces (LIPs) are very different from any volcanic eruptions that have occurred in human history. They involve at least 100 000 km^2 of mafic magma that is either erupted in large flows or emplaced in the crust as massive sills and dykes. This takes place within a few million years, which is over a much longer timespan than modern volcanic eruption sequences.

Eruptions may be on continents or in oceans. We are more familiar with continental 'traps' because of the distinctive geology of these areas.



Some of the large igneous provinces (Bond & Wignall 2014, DOI:10.1130/2014.2505(02))

A world map of well-known LIPs. Some occur within continents, such as the Siberian and Deccan Traps. Others are associated with rifting events, such as the Central Atlantic Magmatic Province (CAMP) which was the first big rift in the breakup of Pangea.

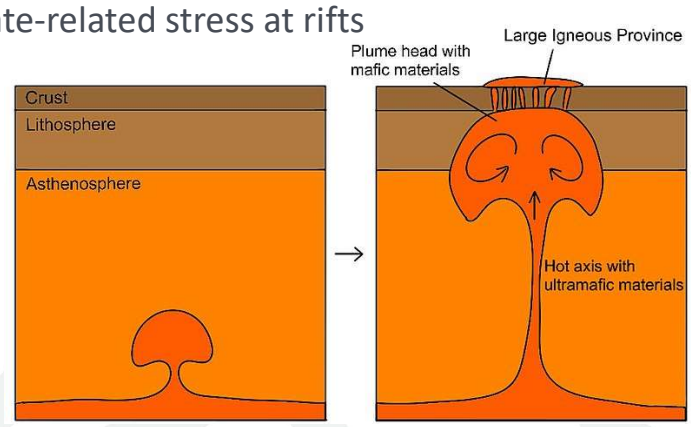
References:

Bond DPG, Wignall PB (2014). Large igneous provinces and mass extinctions: An update, *in* Keller G, Kerr AC, eds., *Volcanism, Impacts, and Mass Extinctions: Causes and Effects: Geological Society of America Special Paper 505*, p 29-55. doi:10.1130/2014.2505(02)

For a more detailed map with the age of LIPs, see the Large Igneous Provinces Commission Download page: http://www.largeigneousprovinces.org/downloads

Possible causes of LIPs

- Mantle plumes → magma up to 10x of a Mid-Ocean Ridge OR
- Plate-related stress at rifts



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Most geologists consider LIPs to be due to mantle plumes and NOT normal plate tectonic processes. The magma production of LIPs can be up to ten times that at a mid-ocean ridge. This process is related to that of hot spots, but on a much larger scale.

The other major alternative is that rifting stress and fracture of the crust may allow melt to reach the surface, driven by convection of the upper mantle. This is separate from convection driving tectonic plate motion.

For further reading, the Wikipedia article about Large Igneous Provinces is well written and thoroughly referenced.
https://en.wikipedia.org/wiki/Large_igneous_province

LIP eruption characteristics

- Pyroclastic material
- Degassing of CO_2, SO_2 and halogens from extrusive and intrusive basalts
- Gases released from heated sedimentary rocks (evaporites and coal)

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Eruption characteristics will vary depending upon the location of the LIP. On land, pyroclastic material may be ejected into the atmosphere in the initial years of the eruption, causing cooling. However, the major climate effect is caused by the release of gases from both the extrusive and intrusive basalts, as well as heated sedimentary rocks.

Carbon dioxide is the main gas released in high volumes for 10s of thousands to millions of years. It has an enormous impact on climate and ocean chemistry.

How much carbon dioxide do LIPs produce?

- 200 000 Mt/y CO_2 from CAMP flood basalts (end Triassic) compared to 3 000 Mt/y from normal flood basalts
- This additional CO_2 is from magmas in crust and volatile-rich sedimentary rock

For comparison…

- Kilauea averages 3 Mt/y
- Burning of fossil fuels 33 000 Mt/y

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The production of flood basalts and crustal basalts in large igneous provinces releases millions of tonnes of carbon dioxide every year. The Central Atlantic Magmatic Province (CAMP) is calculated to have released 100 000 giga-tonnes of CO_2 over 500 years (200 000 Mt/y). This LIP broke up Pangea.

An average amount of 3 000 million tonnes per year (Mt/y) has been calculated for generalised flood basalts. More carbon dioxide is released by sills and dykes in the crust. Sedimentary rocks rich in volatiles (such as coal and evaporites) will also release more carbon dioxide as they are heated by magma.

For comparison, the world's most active basaltic volcano, Kilauea, releases an average of 3 Mt of carbon dioxide per year.

Human fossil fuel burning releases 33 giga-tonnes (33 000 Mt) each year.

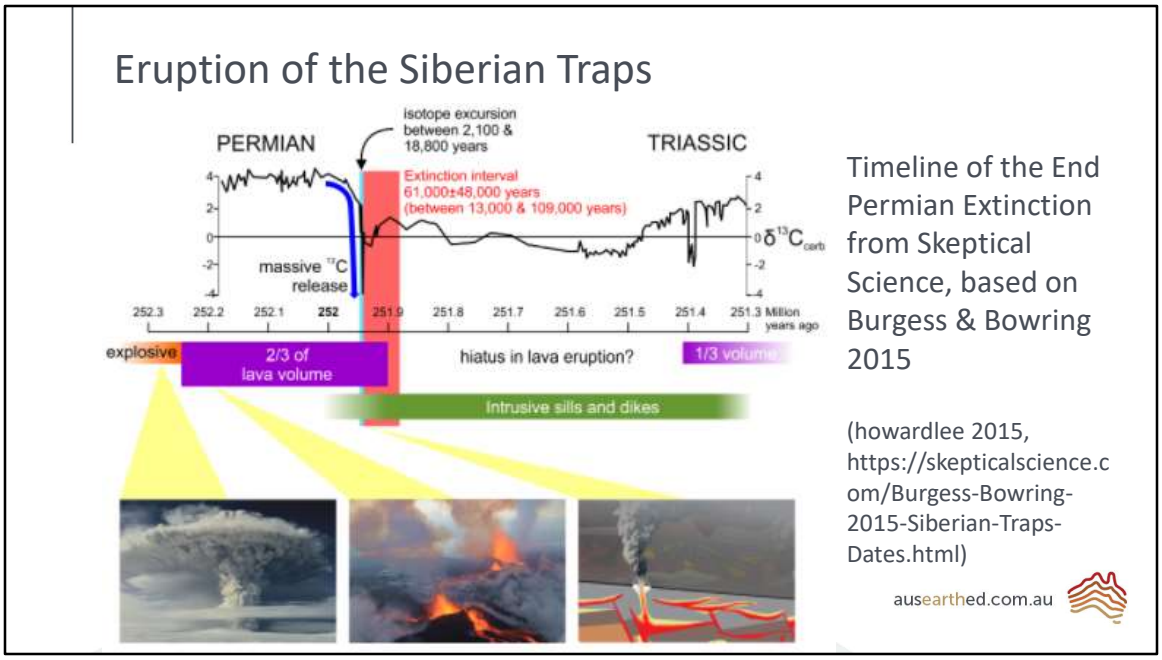
References:

Black BA, Gibson SA (2019). Deep carbon and the life cycle of large igneous provinces. *Elements* **15**: 319-324. Accessed from http://www.elementsmagazine.org/archives/e15_5/4-black_gibson.pdf

Gerlach TM, McGee KA, Elias T, et al. (2002). Carbon dioxide emission rate of Kilauea volcano: implications for primary magma and the summit reservoir. *Geophysical Research Atmospheres* **107**(9). http://dx.doi.org/10.1029/2001JB000407

Wheeling K (2020). How modern emissions compare to ancient, extinction-level events. https://stateimpact.npr.org/pennsylvania/2020/04/20/how-modern-emissions-compare-to-ancient-extinction-level-events/

World Nuclear Association (2021). Carbon dioxide emissions from electricity. https://www.world-nuclear.org/information-library/energy-and-the-environment/carbon-dioxide-emissions-from-electricity.aspx



The eruption of the Siberian Traps has been extensively studied, because it is linked to the greatest extinction ever known, at the end Permian. This diagram summarises the explosive phase (short) followed by flood basalts and intrusive basalts.

The Siberian Traps released enormous amounts of carbon dioxide and also triggered the release of carbon from other sources at the end of the Permian. Recent calculations show that pCO_2 increased from 426 ppmv to 2507 ppmv in about 75 000 years (appx 6x). The subsequent extinction is known as The Great Dying.

References:

Howardlee (2015). Earth's worst extinction "inescapably" tied to the Siberian Traps, CO2 and climate change. https://skepticalscience.com/Burgess-Bowring-2015-Siberian-Traps-Dates.html

Wu Y, Chu D, Tong J, et al. (2021). Six-fold increase of atmospheric pCO_2 during the Permian-Triassic mass extinction. *Nature Communications* **12** article 2137. https://www.nature.com/articles/s41467-021-22298-7

Effect of carbon dioxide from LIPs

- **Warming**
- Ocean acidification
- Acid rain
- Ocean anoxia

→ **Extinction**

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The enormous release of carbon dioxide from LIPs causes global warming.

As carbon dioxide dissolves in the oceans, they become more acidic. This results in the loss of shelled organisms. On land, acid rain and soaring temperatures cause extinction.

Gases are less soluble in warmer water. As the oceans warmed, they became starved of oxygen, increasing marine extinctions.

Extinctions related to LIPs

Extinction event	LIP	Extinction of…
End Cretaceous	Deccan Traps*	60% of species
End Triassic	CAMP	76% of species
End Permian	Siberian Traps	90% marine, 75% terrestrial species
Late Devonian	Viluy Traps & Pripyat-Dnieper-Donets	50% of genera

*Deccan Traps pushed extinction process before bolide impact

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<u>End Cretaceous</u>
Before discovery of the iridium layer and Chicxulub impact, scientist thought that the Deccan Traps caused the end Cretaceous mass extinction that famously killed the non-avian dinosaurs. However, it is still accepted that the eruptions kicked off the extinction event before the impact sealed the fate of 60% of species.

<u>End Triassic</u>
The Central Atlantic Magmatic Province (CAMP) extends across four continents and may have covered 10 000 000 km^2. The CAMP is evidence of the first major rift in the breakup of Pangea. This triggered extinction of reef communities and up to 85% of plants in the Greenland record

<u>End Permian</u>
The most devastating event of all occurred when the Siberian Traps erupted. The eruption triggered runaway warming from gas releases by the basalts, as well as from coal heated by intrusive magmas. Ocean acidification and anoxia led to widespread death of marine organisms. Hydrogen sulfide degassing from anoxic waters is thought to have been a major terrestrial killer in the wake of ecosystem crises caused by warming. Ozone depletion caused by halogen emissions also increased UV-B

radiation, contributing to terrestrial extinction.

Late Devonian

The late Devonian saw at least two distinct extinction events, also known as the Frasnian-Famennian mass extinction. There were two discrete anoxic ocean events that caused the massive marine extinctions. These appear to be associated with the Viluy Traps and the Pripyat-Dnieper-Donets rift system.

References:

Bond DPG, Wignall PB (2014). Large igneous provinces and mass extinctions: An update. *in* Keller, G., and Kerr, A.C., eds., Volcanism, Impacts, and Mass Extinctions: Causes and Effects: Geological Society of America Special Paper 505, p. 29–55, doi:10.1130/2014.2505(02)

Voosen P (2019). Did volcanic eruptions help kill off the dinosaurs? https://www.sciencemag.org/news/2019/02/did-volcanic-eruptions-help-kill-dinosaurs

Do LIPs always cause mass extinction?

- No
- Climate effect depends upon:
  - Location of LIP
  - Amount of gas released in eruptions
  - Timescale of gas release
  - Degassing of sedimentary rocks
  - Feedback loops and destabilisation of clathrates

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Large igneous provinces do not always cause mass extinction.

Most oceanic plateau LIPs are not associated with significant extinctions. Eruptions near the equator are more likely to cause global cooling during the initial explosive release of sulfur aerosols.

If pulses of volcanic activity are relatively small and/or spread out, there is time for ecosystems to recover.

Large pulses of gases that not only warm climate (CO_2), but also destroy ozone (Cl and F in particular) are particularly damaging.

Sedimentary rocks, especially coal, may release more carbon dioxide when they are impacted by lava and magma. This was a major factor in carbon release caused by the Siberian Traps.

Warming may also trigger a positive feedback loop and release of methane from clathrates.

Reference:

Bond DPG, Wignall PB (2014). Large igneous provinces and mass extinctions: An update. *in* Keller, G., and Kerr, A.C., eds., Volcanism, Impacts, and Mass Extinctions: Causes and Effects: Geological Society of America Special Paper 505, p. 29–55, doi:10.1130/2014.2505(02)


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