How volcanic eruptions caused Earth’s greatest mass extinction...

...and what that tells us about its future

David Bond,
University of Hull

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So, what is extinction?
What is a “mass extinction”?

“A substantial increase in the amount of extinction suffered by more than one geographically wide-spread higher taxon during a relatively short interval of geologic time”

Jack Sepkoski, 1996
Carl Linnaeus, botanist, 1707-1778
You have to kill a lot of species before you kill a genus / family

and actually Ford’s have radiated – no diversity loss
Jack Sepkoski (l) and Dave Raup: pioneers in extinction studies in the 1980s
Number of genera through time (database of > 30000 fossil marine genera)

<table>
<thead>
<tr>
<th>Event</th>
<th>Time (Myr)</th>
<th>Extinction Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. End Permian</td>
<td>250</td>
<td>96%</td>
</tr>
<tr>
<td>2. End Triassic</td>
<td>200</td>
<td>75%</td>
</tr>
<tr>
<td>2. End Cretaceous</td>
<td>66</td>
<td>75%</td>
</tr>
<tr>
<td>4. Late Devonian</td>
<td>370</td>
<td>70%</td>
</tr>
<tr>
<td>5. End Ordovician</td>
<td>440</td>
<td>60%</td>
</tr>
<tr>
<td>“Anthropocene”</td>
<td>0</td>
<td>0%</td>
</tr>
</tbody>
</table>
“mass extinctions and lesser calamities”

the “Anthropocene”? 
Has the Earth’s sixth mass extinction already arrived?

inflated due to “at risk” taxa being assessed first and <3% total species assessed... but! includes IUCN-assessed “at risk”
Are we living in a new geological age characterised by human-driven extinctions?

The Trinity test, 1945: the start of the Anthropocene?
If extinction has happened before, it could happen again.

But what might it look like?
## Extinction metrics and severity

<table>
<thead>
<tr>
<th>#</th>
<th>Event</th>
<th>%&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Event</th>
<th>%&lt;sup&gt;2&lt;/sup&gt;</th>
<th>Event</th>
<th>%&lt;sup&gt;3&lt;/sup&gt;</th>
<th>Severity ranking&lt;sup&gt;4&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>End Permian</td>
<td>−58</td>
<td>End Permian</td>
<td>−57</td>
<td>End Permian</td>
<td>−83</td>
<td>End Permian</td>
</tr>
<tr>
<td>2</td>
<td>End Ordovician</td>
<td>−49</td>
<td>End Ordovician</td>
<td>−43</td>
<td>End Triassic</td>
<td>−73</td>
<td>End Cretaceous</td>
</tr>
<tr>
<td>3</td>
<td>Capitanian</td>
<td>−47</td>
<td>Capitanian</td>
<td>−36</td>
<td>End Ordovician</td>
<td>−52</td>
<td>End Triassic</td>
</tr>
<tr>
<td>4</td>
<td>End Triassic</td>
<td>−40</td>
<td>End Cretaceous</td>
<td>−34</td>
<td>End Devonian</td>
<td>−50</td>
<td>Frasnian-Famennian</td>
</tr>
<tr>
<td>5</td>
<td>End Cretaceous</td>
<td>−39</td>
<td>End Triassic</td>
<td>−33</td>
<td>End Cret., Fras-Fam.</td>
<td>−40</td>
<td>Capitanian</td>
</tr>
<tr>
<td>6</td>
<td>Frasnian-Famennian</td>
<td>−35</td>
<td>Frasnian-Famennian</td>
<td>−22</td>
<td>N.A.</td>
<td>NA</td>
<td>Serpukhov.</td>
</tr>
<tr>
<td>7</td>
<td>Givetian</td>
<td>−30</td>
<td>Serpukhovian</td>
<td>−13</td>
<td>Serpukhovian</td>
<td>−39</td>
<td>End Dev., End Ordovician</td>
</tr>
<tr>
<td>8</td>
<td>End Devonian</td>
<td>−28</td>
<td>Givetian</td>
<td>−10</td>
<td>Givetian</td>
<td>−36</td>
<td>NA</td>
</tr>
<tr>
<td>9</td>
<td>Eifelian</td>
<td>−24</td>
<td>End Dev., Ludford.</td>
<td>−7</td>
<td>Eifelian</td>
<td>−32</td>
<td>Givetian</td>
</tr>
<tr>
<td>11</td>
<td>N.A.</td>
<td>NA</td>
<td>Eifelian</td>
<td>−6</td>
<td>Ludfordian</td>
<td>−9</td>
<td>NA</td>
</tr>
</tbody>
</table>

% marine genera extinct: ¹Sepkoski (1996), ²Bambach et al. (2004) and ³McGhee et al. (2013) and their severity ranking⁴ - the “ecological impact”.
The end-Permian mass extinction (252 million years ago)

“Out of the frying pan and into the fire”
The Permian-Triassic World

Enchanted Organ

Intriguing Idaho
Victims on land

Pareiasaurs
“cheek lizards”

Large, herbivorous Permian reptiles

Gorgonopsids: top Permian therapsids

Most gymnosperms ("naked seeds" that formed coals)

Glossopteris

Insects
...and in the oceans

Goniatites

Trilobites

Brachiopods

Rugose corals

Tabulate corals

Crinoids

Radiolarian

Bivalves

As many as 96% of species globally became extinct
How fast was this greatest of all catastrophes?

Since “challenged” by Wang et al. 2014 based on statistical treatment of sites in China / Pakistan – they argue for much more abrupt extinction.
How nasty did it get?

Global warming due to increased CO₂

Extreme Global Warming May Have Caused Largest Extinction Ever

Burning coal may have caused Earth’s worst mass extinction

New geological research from Utah suggests the end-Permian extinction was mainly caused by burning coal, ignited by magma.
What else was around? Acid oceans, toxic metals...

Ocean acidification drove Earth’s largest mass extinction

By Deanna Conners in EARTH | April 20, 2015

New evidence suggests that ocean acidification played a key role in the Permian-Triassic mass extinction event 252 million years ago that killed most life on Earth.

During the Permian-Triassic mass extinction event 252 million years ago, most life on Earth perished. Scientists have now obtained evidence that ocean acidification played a key role in the die-off. The new research was published in the journal Science on April 10, 2015.

Ocean of Acid Blamed for Earth's 'Great Dying'

Mercury May Have Caused End-Permian Mass Extinction
Ozone depletion caused by volcanic gases?

Mass extinction the result of acid rain and ozone loss

Vinegar-Like Acid Rain May Have Fallen During Earth’s Worst Extinction

'The Great Dying': World's worst-ever extinction event 'caused by UV radiation'
Or in contrast, a deadly ice age?

Timing of global regression and microbial bloom linked with the Permian-Triassic boundary mass extinction: implications for driving mechanisms

Björn Barresi², Hugo Bucher², Borhan Bagherpour³, Morgane Brossa¹, Kuang Guodun³ & Urs Schaltegger²

hinges on the synchronicity of the hiatus with the onset of the Siberian Traps volcanism. This early eruptive phase released sulfur-rich volatiles into the stratosphere, thus simultaneously eliciting a short-lived ice age responsible for the global regression and a brief but intense acidification. Abrupt cooling, shrunk habitats on shelves and acidification may all have synergistically triggered the PTBME.
The culprit for all this nastiness?
The Siberian Traps - 6 million km$^3$ of lava

Enough to bury the whole of Austria in 71.5km lava!
Total CO$_2$ released: 30,000 Gt (10 x today's atmosphere)
Volcanism and mass extinction

How fossil fuel burning nearly wiped out life on Earth

George Monbiot

Proceedings of the National Academy of Sciences of the United States of America

Catastrophic dispersion of coal fly ash into oceans during the latest Permian extinction

Stephen E. Grasby, Hamed Sanei & Benoit Beauchamp
The Permian-Triassic boundary

Volcanism and mass extinction

SIBERIAN TRAPS ERUPTIONS

SO₂ emissions
- Volcanic darkness, cooling and photosynthetic shutdown

Cl, F, NOx emissions
- Acid rain
- Increased oceanic Sr/Sr
- Increased continental weathering

Toxic metal emissions
- Toxic metal poisoning

CO₂ emissions
- Dissociation of gas hydrates
- Global warming
- Ocean anoxia
- Ocean acidification
- Negative δ¹³C excursion

Thermogenic gas emissions

TERRESTRIAL MASS EXTINCTION

MARINE MASS EXTINCTION

Ozone depletion, increased UV-B
The Triassic aftermath: coal gaps, reef gaps, and other gaps in life’s record

*Lystrosaurus* looking out over a barren Antarctica

*(from a painting by William Stout)*
The delayed recovery took unusually long (10 Myr) but ultimately paved the way for the dinosaurs.

Find out more in the next talk!

_Eoraptor_ – the earliest dinosaur, 231 Myr old
What are the effects of massive volcanic eruptions and how might they drive a mass extinction?

- thermal stress: cooling, long-term global warming;
- marine anoxia as a result of warming;
- ocean acidification due to elevated pCO$_2$;
- ozone damage by halogens, increased UV-B radiation;
- acid rain;
- toxic metal poisoning;
- darkness and photosynthetic shutdown.

The atmosphere provides the link between terrestrial and marine biospheres
Speaking of today’s atmosphere…

Latest CO$_2$ reading
April 03, 2018
409.20 ppm

Let’s examine what three CO$_2$-induced stresses do: warming, anoxia, and ocean acidification.
Thermal stress

The IPCC predict global ocean warming of 1.1 °C to 6.4 °C by 2100 (compare with an estimated ~15 °C end-Permian warming)

Warming increases aerobic metabolism in animals ($Q_{10}$ law, $10 ^\circ \text{C} = x2$) and stress occurs when $O_2$ demand exceeds an animal’s aerobic scope

Active organisms can elevate their metabolic rate compared to less active organisms, making them more likely to survive extinctions (Clapham, 2016)

Modest temperature rises are unlikely to be the only killer in mass extinction scenarios but extreme end-Permian warming took life past a survival threshold (e.g. 37-40 °C, Sun et al., 2012)
Marine anoxia

Warm water holds less oxygen and increases metabolism and demand. Prolonged exposure to anoxia causes non-selective death by asphyxia. At no point have the world’s oceans become simultaneously anoxic everywhere: anoxia is also therefore unlikely to be the only killer.
>CO₂ / Reduced pH (“ocean acidification”)

IPCC predict ocean pH down by ~0.5 by 2090

b. Surface pH in 2090s (RCP8.5, changes from 1990s)

From IPCC 2013
> CO$_2$ decreases capacity of respiratory pigments to oxygenate tissues (hypercapnia), leading to death.

< pH makes it more costly to build a carbonate skeleton – a big problem for corals and calcareous plankton.
< pH interferes with fish neurotransmitters and chemical signalling leading to failure to detect predators and mates, even at a modest pH drop from 8.1 to 7.7 (Roggatz et al., 2016) well within IPCC predictions…
Is this really what drives extinction? Losing 1% of individuals per generation can drive a species to extinction in little over a century (Knoll, 2007).

Theoretically, \(<pH\) could be the lone killer.
So is life on Earth doomed?

Total mass $\text{CO}_2$ in atmosphere: $2.996 \times 10^{12}$ tonnes \hspace{1cm} (3000 Gt)

Siberian Traps $\text{CO}_2$ release = 30,000 Gt

$30,000 / 3,000 = 10\ldots$ \hspace{1cm} the Traps emitted 10 x modern budget
When might we reach end-Permian CO$_2$ levels?

In 50 years CO$_2$ has increased by 86 ppm (that’s 1.72 ppm/yr)

How long would it take to reach 10 x present (i.e. 4090 ppm)?

We’d need to add $[4090 - 409 \text{ ppm}] = 3681 \text{ ppm}$

That would take $[3681 / 1.72] = 2140.116 \text{ years}$

Which means catastrophe could strike in May 4158
But is this realistic and could it happen?
and also...

Time of Pangaea

Volcanism and mass extinction
Perhaps Earth can take solace in the absence of a supercontinent
And maybe these things...

The calcareous nannoplankton evolved in the aftermath of the Permian crisis. They have been buffering our oceans against the threat of acidification since.

But for how long?