Climate Tipping Points (CTPs)

- A CTP is defined as a threshold in a control parameter (e.g., heat) at which a small additional perturbation causes a self-perpetuating change leading to substantial and widespread Earth system impacts.*

- Many of these changes can take place over decades or less and may be irreversible in terms of human lifetimes.

*Armstrong McKay et al, “Exceeding 1.5oC global warming could trigger multiple climate tipping points”, Science 377 (6611), p1171,9 September 2022

GAIA, DAISYWORLD AND TIPPING POINTS

GAIA and Daisyworld

- James Lovelock proposed in 1972 that the Earth and the organisms living on it form a self-regulating system which maintains optimal conditions for life in the face of changing factors like the increasing warmth of the sun or increasing CO_2 via various feedback mechanisms: the Gaia hypothesis.
- For example, imagine a planet populated only by daisies, some white and some black.
  - In the beginning, the planet's sun is too cool for the daisies. This favors the black ones who can best absorb what light there is.
  - Black daisies begin to predominate.
  - The black daisies thus warm the planet, producing favorable conditions for daisies.
  - But the sun begins to warm.

Daisyworld, continued

- As the sun warms, the black daisies absorb too much heat, and the planet begins to get too warm.
- Because of their high albedo, white daisies are favored.
- The white daisies reflect the excess sunlight, cooling the planet
- Thus, the varying mix of daisies keeps the world's temperature ideal for daisies.
- A feedback mechanism has maintained an optimal temperature in the face of a changing environment.

Example of GAIA In Action: Biota and weathering

- Increased CO_2 warms the atmosphere
- Weathering of rocks (silicates) removes CO_2
- Biota (e.g. plants, microorganisms, lichen, etc.) enhances weathering.
- THUS: as the earth warms, biota increase weathering
- Weathering reduces CO_2
- The earth cools.

Tipping points

- The idea of a tipping point refers to some drastic change in the environment which can occur over a short time (tens to hundreds of years) which is irreversible except over a geologic timescale.
- Tipping points have occurred a number of times in the past, resulting in such large-scale changes as glaciation.
- An example is the AMOC (Atlantic Meridional Overturning Circulation

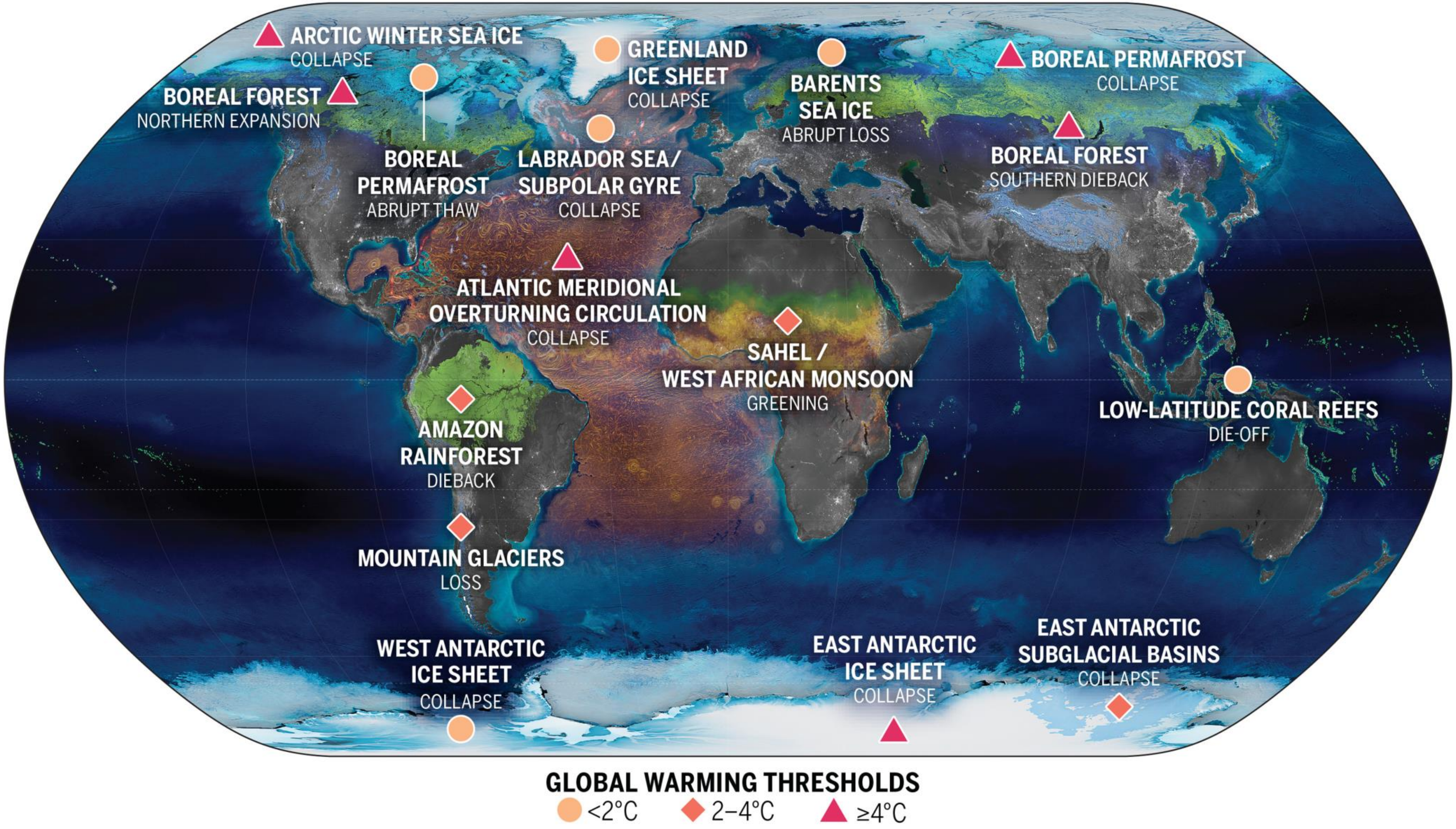
AMOC

- Driven by winds, the warm water of the mid- and southern Atlantic flow northward, bringing heat to the Nordic areas of Europe.
- As the warm water flows it loses heat and undergoes evaporation.
- Thus, it becomes saltier and denser.
- In the northern regions this denser water sinks and returns southward along the ocean floor to upwell again in the south, replacing the water that has moved north.

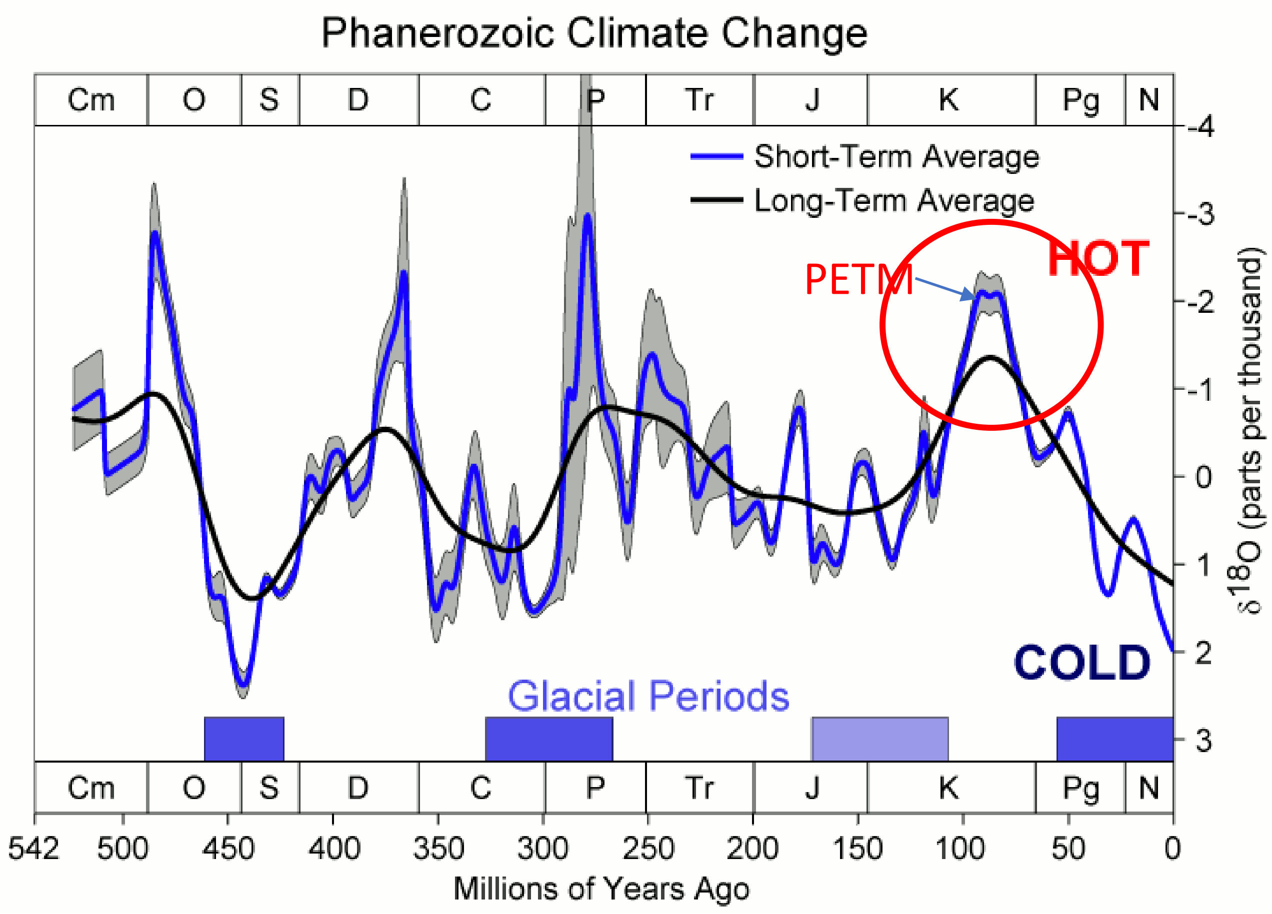
AMOC and climate

- The AMOC represents a tipping point:
- In a cooling environment the sea ice in the north expands its coverage, diminishing evaporation.
- This slows the downwelling in the north.
- This slows the transport of heat from the south, making the north colder.
- This increases the sea ice cover
- This mechanism has contributed to glaciation in the past few thousand years.

Potential tipping points



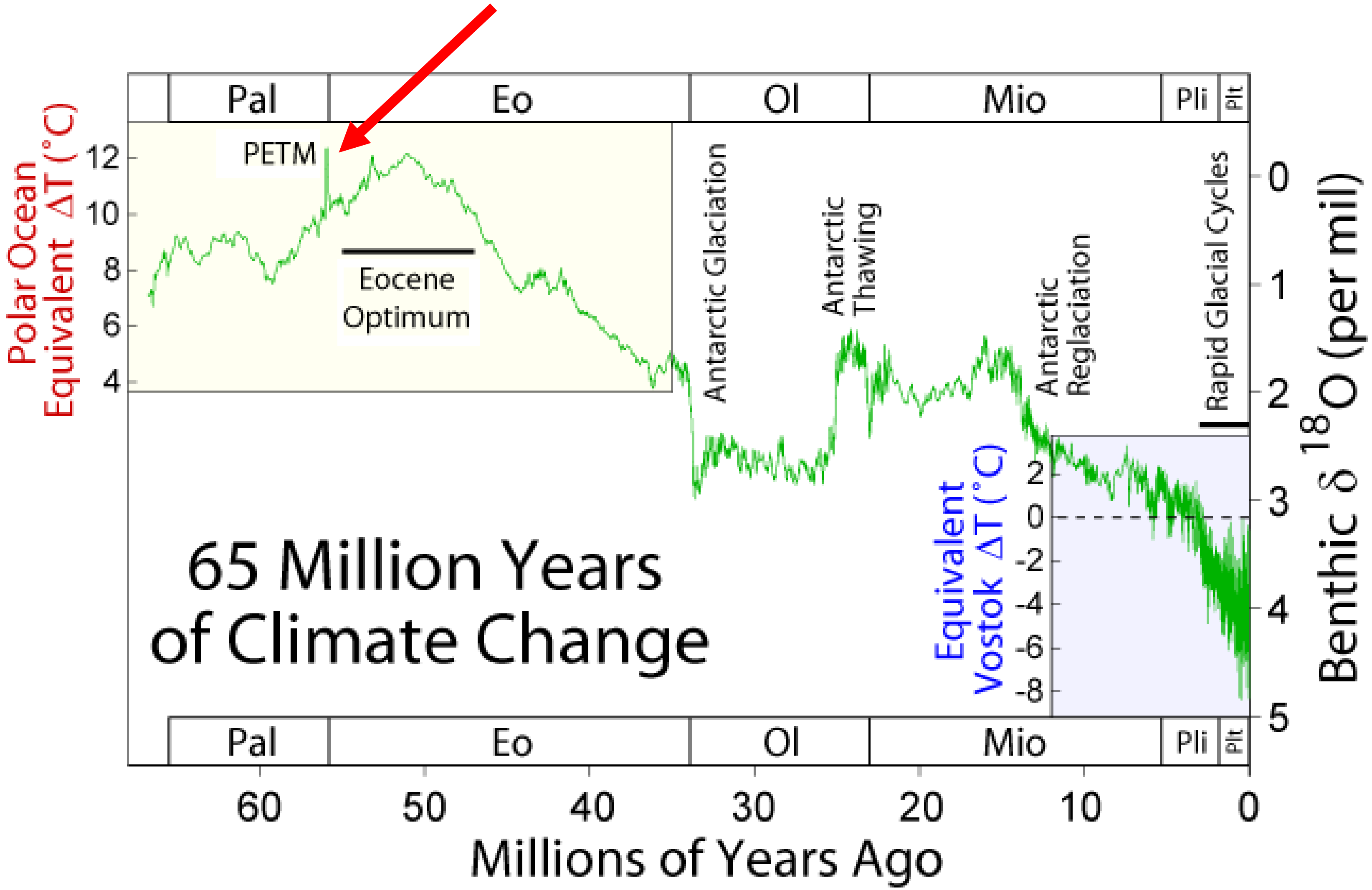
δ^{18}O-derived global temperature



Analysis of oxygen isotopes, along with studies of fossils of temperature-sensitive biota (e.g. corals) show marked fluctuations in global temperature. It was relatively warm between 540-340Ma (Cambrian explosion, 530Ma) and again between 260-40Ma.
It was cold enough for glaciation between 340-260Ma (mid-Carboniferous-Permian). It was warm again between 260Ma and 40Ma (Age of the Dinosaurs, 245-66Ma). It has been cold ever since 40Ma.

$$\delta^{18}O = \left(\frac{\left(\frac{^{18}O}{^{16}O}\right)_{sample}}{\left(\frac{^{18}O}{^{16}O}\right)_{standard}} - 1 \right) \times 1000$$

Paleocene-Eocene Thermal Maximum (PETM)



PETM

- The Late Paleocene (c. 57 Ma) was a warm period, with global temperature 22.3–28.3 °C (72.1–82.9 °F) [2022: 14.8^{o}C/58.6^{o}F]
- PETM (56 Ma) reached 27.2–34.5 °C (81.0–94.1 °F)
- The cause was a period of massive carbon release into the atmosphere, estimated to have lasted from 20,000 to 50,000 years. The entire warm period lasted for about 200,000 years.
- 12,000-15,000 Gt of carbon were released over the 50,000 years, averaging 0.24 Gt per year [2022: 36.8Gt]

The World of the PETM

Antarctica is a temperate forest, with summer temperature around 25°C (97.7°F).
The climate in North America (>30° N) is tropical, with high temperatures and lots of rainfall, and small seasonal differences between summer and winter.
There is no ice at the poles, so sea levels are 100 meters (328 feet) higher than today*.
Antarctica is inhabited by many species of birds, including Klebowski's penguins which reach 6.5' tall and weigh 265lbs.
Island India is a hot, humid equatorial tropic.
Northern hemisphere mammals become smaller
Polar Seas reach temperatures of 12°C (56°F)
Equatorial seas are largely uninhabitable, causing the extinction of many marine animals.

*Poughkeepsie elevation: 180'

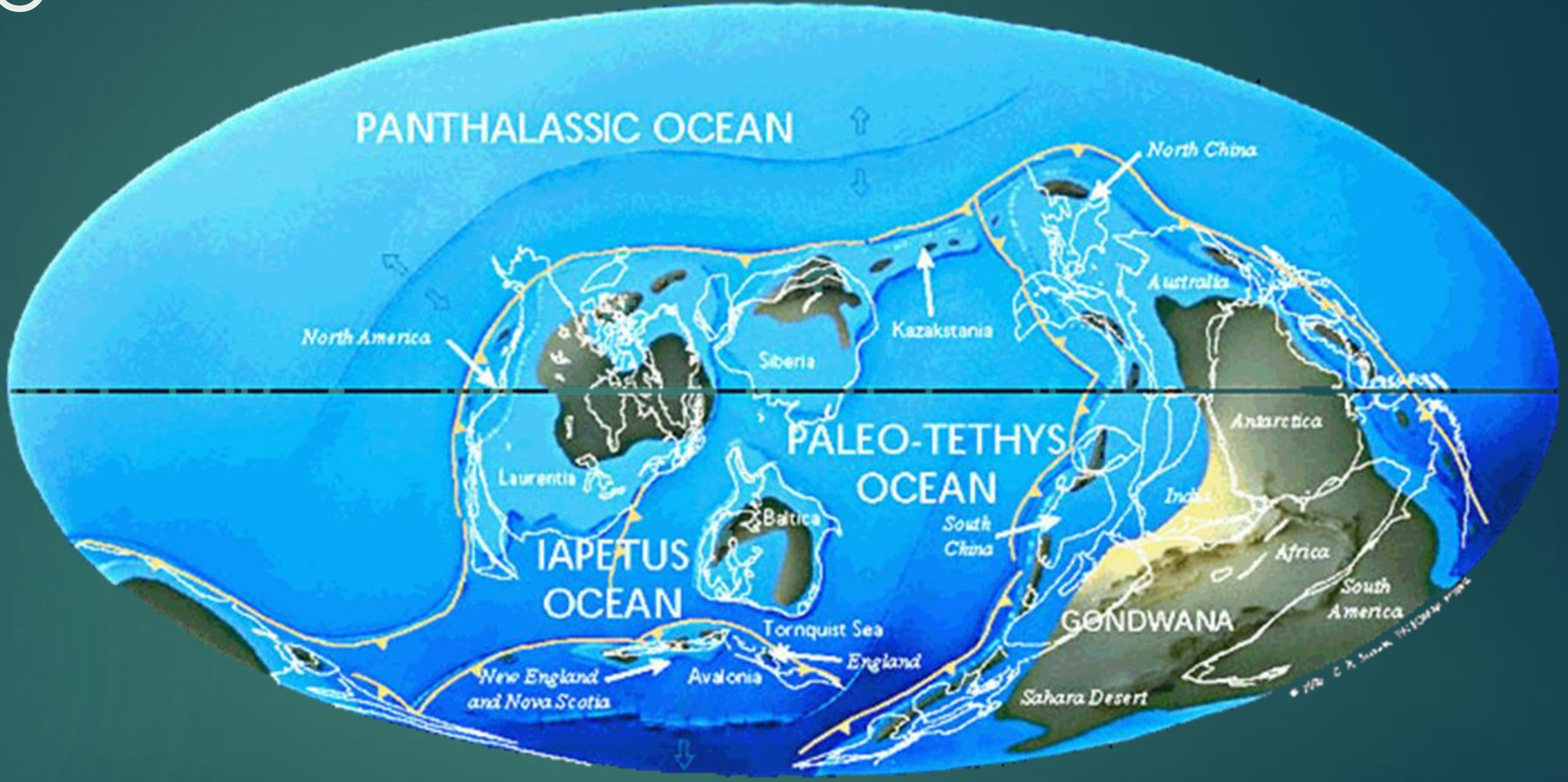
What caused the PETM?

- The PETM might have been caused by a tipping point.
- Volcanism in Greenland was responsible for the initial release of CO_2
- This initial release warmed the oceans
- The warming may have led to the release of methane stored on the ocean floor as clathrates (crystalline methane)
- The warming oceans meant less solubility for dissolved gasses like CO_2 and methane
- This led to the oceans pouring CO_2 and methane into the atmosphere.
- Which led to increased global warming and a positive feedback loop.

Let’s take a look at some major eras in Earth’s history

The Ordovician World, 488 million years ago

The Ordovician Period lasted almost 45 million years, from 489 to 444 MYA. During this period, the area north of the tropics was almost entirely ocean, and most of the world's land was collected into the southern supercontinent Gondwana.



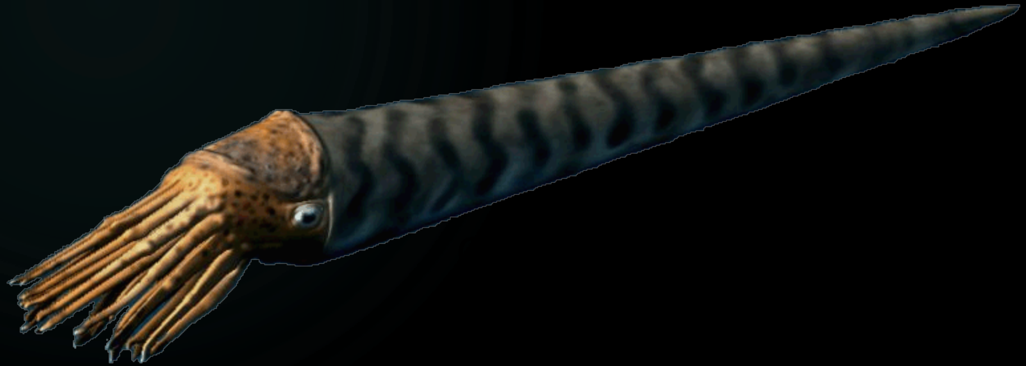
The Ordovician Period 489-444MYA

- The climate was initially very warm (ocean temperature 42°C [108°F]; it slowly cooled, until it was reasonable by the middle Ordovician. Temperature then rapidly declined, leading to intense glaciation and sea-level fall.
- In the beginning, oxygen levels were around 17%*, and CO_2 about 15X today's value.
- Ended around 444MYA with a mass extinction that killed 85% of living species (the second most severe of all extinction events!).

*Equivalent to about 5,000 feet above sea level today

The Ordovician Period

- The early Ordovician climate was warm and wet. Shallow seas covered most of the continents.
- During this period invertebrates diversified
  - Coral reefs appeared (though the corals were *tabulate* corals, not the modern scleractinian corals)
  - Mollusks became apex predators of the oceans, including the cephalopods (nautiloids), clams and snails.
- The first land plants appeared.
- Arthropods became the first animals to invade the new habitat: land.
- The first vertebrates (early fish) appeared.



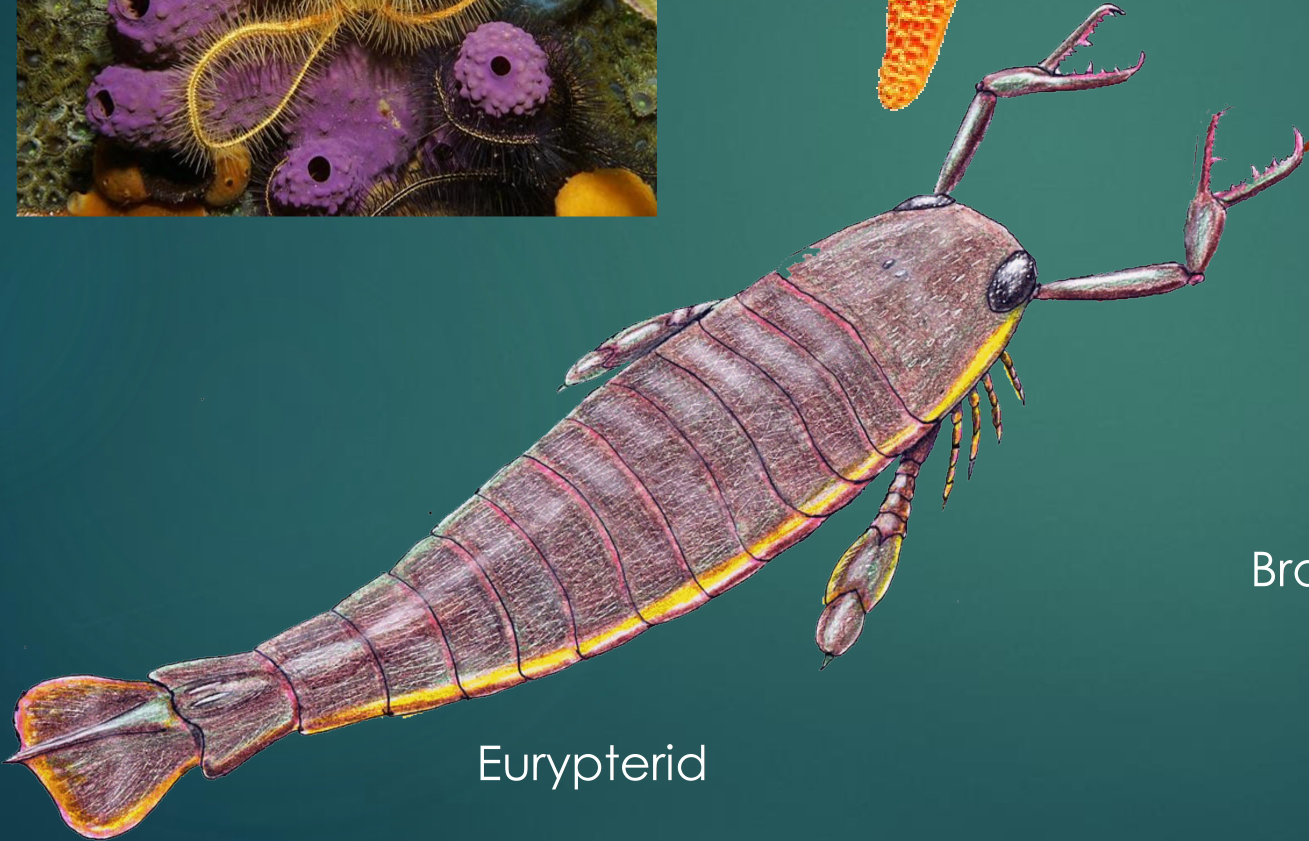
Life in the Ordovician

- Because of the extremely high sea levels, a shallow tropical sea (The Great American Carbonate Bank) covered North America (ankle deep: you could wade from a tropical beach in Wisconsin to Texas).
- Rivers didn't exist; plants had not developed roots, so nothing held banks in place.
- The day was 20 hours long
- Most life was in the shallow seas. Life on land was restricted to patches of liverworts near the shores and lichen further inland.
- Atmospheric CO2 was high, 3,000 to 9,000 ppm (415ppm today), largely due to massive volcanic activity in an island chain in the Iapetus Ocean (the islands eventually collided with North America to form the basis of the Appalachians).

Life in the Ordovician (cont'd)

- It was a good time for life: the biggest expansion (number of new species) in the history of the earth. The numbers tripled in 10 million years.
- Oxygen was at times higher than today (26% vs 21%), good for large animals to develop (some straight-shelled nautiloids reached 12 feet long!) Oxygen would plummet toward the end of the period to as low as 12%.
- In the mid-Ordovician there was a period of meteoric impacts, probably debris from an asteroid collision some millions of years before outside the orbit of Mars.

Invertebrates of the Ordovician



Eurypterid

Brachiopod