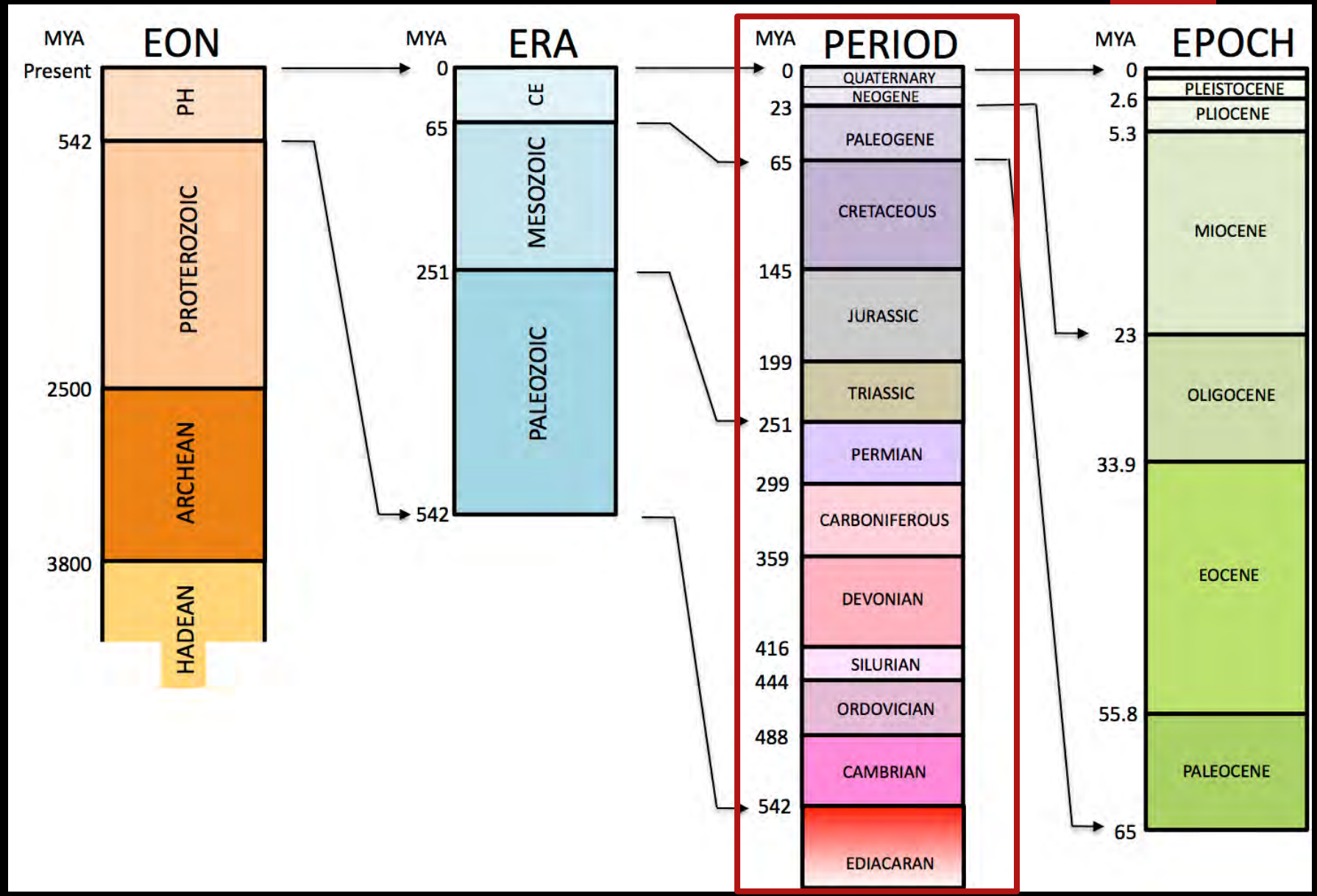
The Ends of the Earth

The Five Events that Almost Ended Life on Earth Forever

THERE HAVE BEEN AT LEAST FIVE MAJOR EXTINCTION EVENTS IN EARTH'S HISTORY. *ALL* HAVE BEEN RELATED IN ONE WAY OR ANOTHER TO CLIMATE.

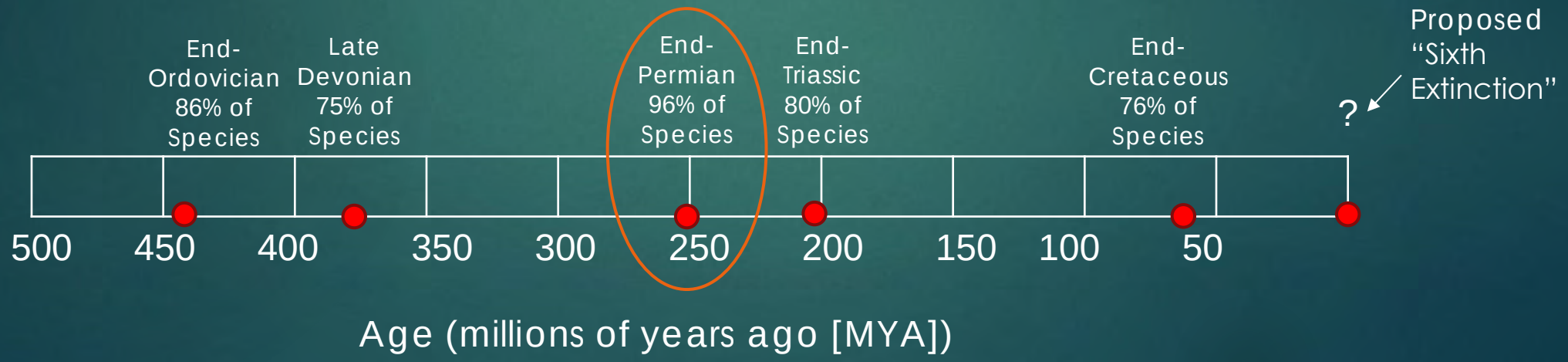
A quick primer on geologic history:



Ph: Phaneozoic Eon
CE: Cenozoic Era

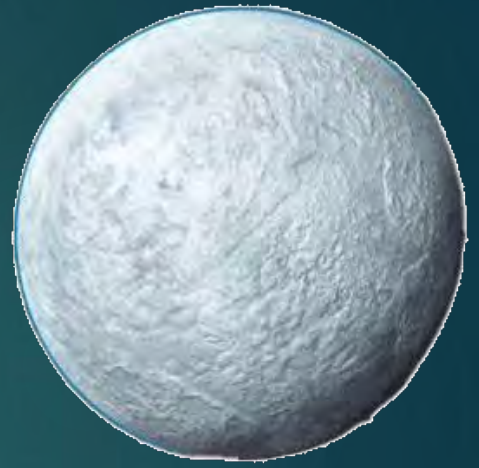
What is an "Extinction Event"

- Mass extinctions—when at least half of all species die out in a relatively short time—have occurred only a handful of times over the course of our planet's history.
- The largest mass extinction event happened around 250 million years ago, when perhaps *96 percent of all species of both plants and animals went extinct*, leaving an exhausted and nearly dead, silent world. It would take almost ten million years to recover, and the world would never be the same.



The "Big Five" Extinction Events

- Ordovician-Silurian Extinction: 440 million years ago
  - Small marine organisms died out.
- Devonian Extinction: 374 million years ago
  - Many tropical marine species went extinct.
- Permian-Triassic Extinction: 250 million years ago
  - The largest mass extinction event in Earth's history
  - affected a wide range of species, including many vertebrates.
- Triassic-Jurassic Extinction: 210 million years ago
  - The extinction of other vertebrate species on land allowed dinosaurs to flourish.
- Cretaceous-tertiary Extinction: 65 Million Years Ago
  - Also called the "K-T" Extinction
  - Asteroid strike in Chicxulub wipes out non-avian dinosaurs and many other species.



"Snowball Earth"

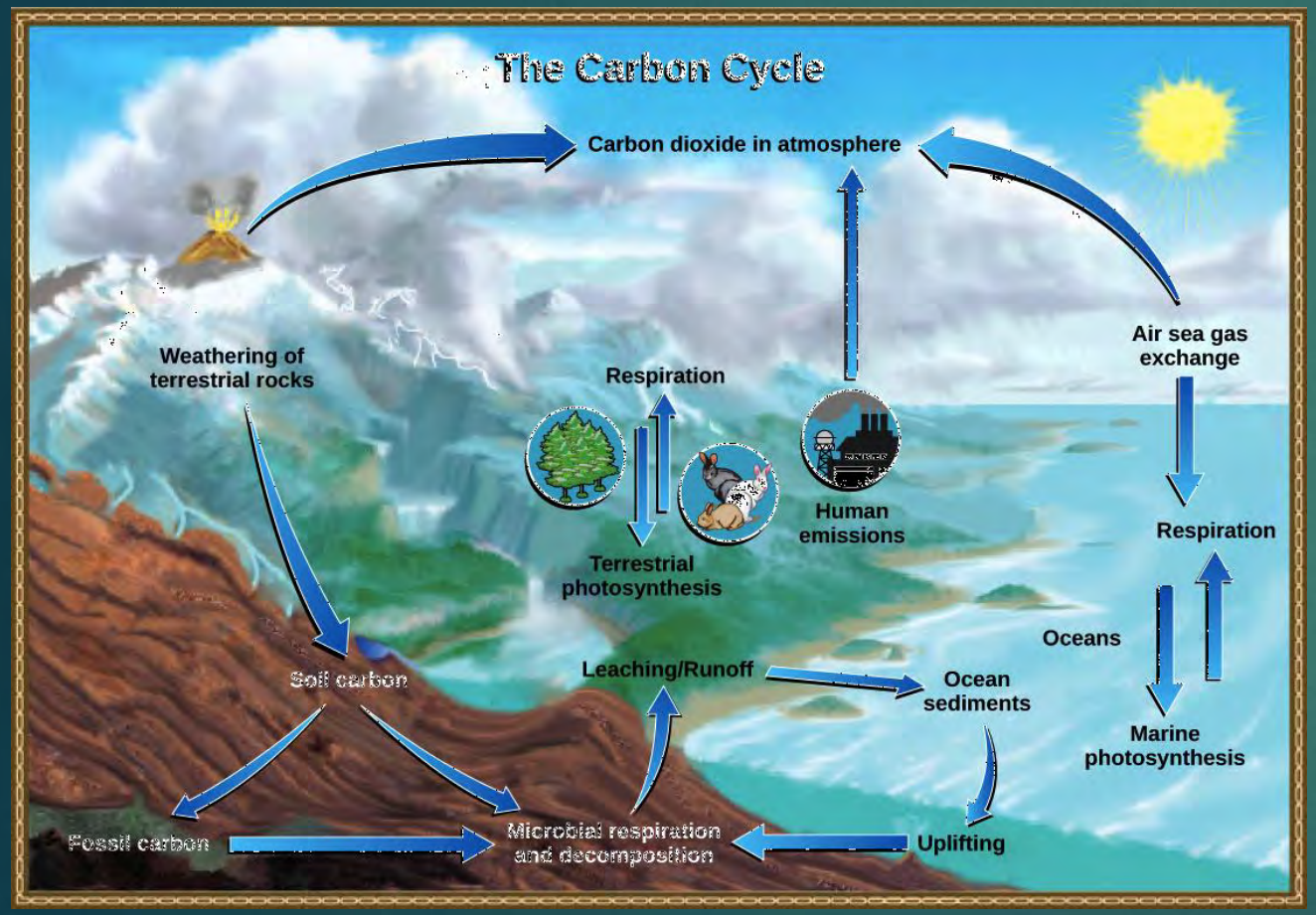
What Might Cause an Extinction Event??

- Extraterrestrial Events:
  - Asteroid Strike
  - Cosmic Radiation
    - E.g., a nearby star falls into a black hole or becomes a supernova. The resulting burst of high-energy gamma rays bombards the earth.
- Climate-related Events:
  - Changes in the Earth's orbit and inclination (Milankovitch cycles)
  - Volcanoes
  - Humans

Extinction Events Have Multiple Causes

- No one single event, even an asteroid strike, can cause global extinction of the majority of plants and animals.
- There need to be pre-existing conditions that stress the entire ecosystem.
- Under these conditions a single event can launch a cascade of events leading to a worldwide extinction event.
- Most, if not all, extinction events in the past have been to some extent climate-related, primarily related to CO_2 concentration in the atmosphere.
- Variations in atmospheric CO_2 are generally due to an imbalance in the short- or long-term carbon cycle.

The Carbon Cycle



The short-term carbon cycle:

Photosynthesis takes up CO_2 to produce energy, releasing O_2; respiration uses O_2 and releases CO_2.

The long-term carbon cycle:

- Volcanoes release CO_2
- Weathering of rocks binds the CO_2 as carbonates. Runoff takes it to the oceans.
- Oceans absorb CO_2
- Marine organisms bind the dissolved CO_2 and carbonate into shells and skeletons.
- The organisms die and the shells and skeletons sink to the ocean floor.
- The ocean floor sinks into the earth in subduction zones.
- Volcanoes release the subducted CO_2
- Orogeny and uplift provides new rocks which weather and absorb CO_2

The First of the Big Five : The End-Ordovician Extinction

44 MYA

86% OF SPECIES EXTINCT.

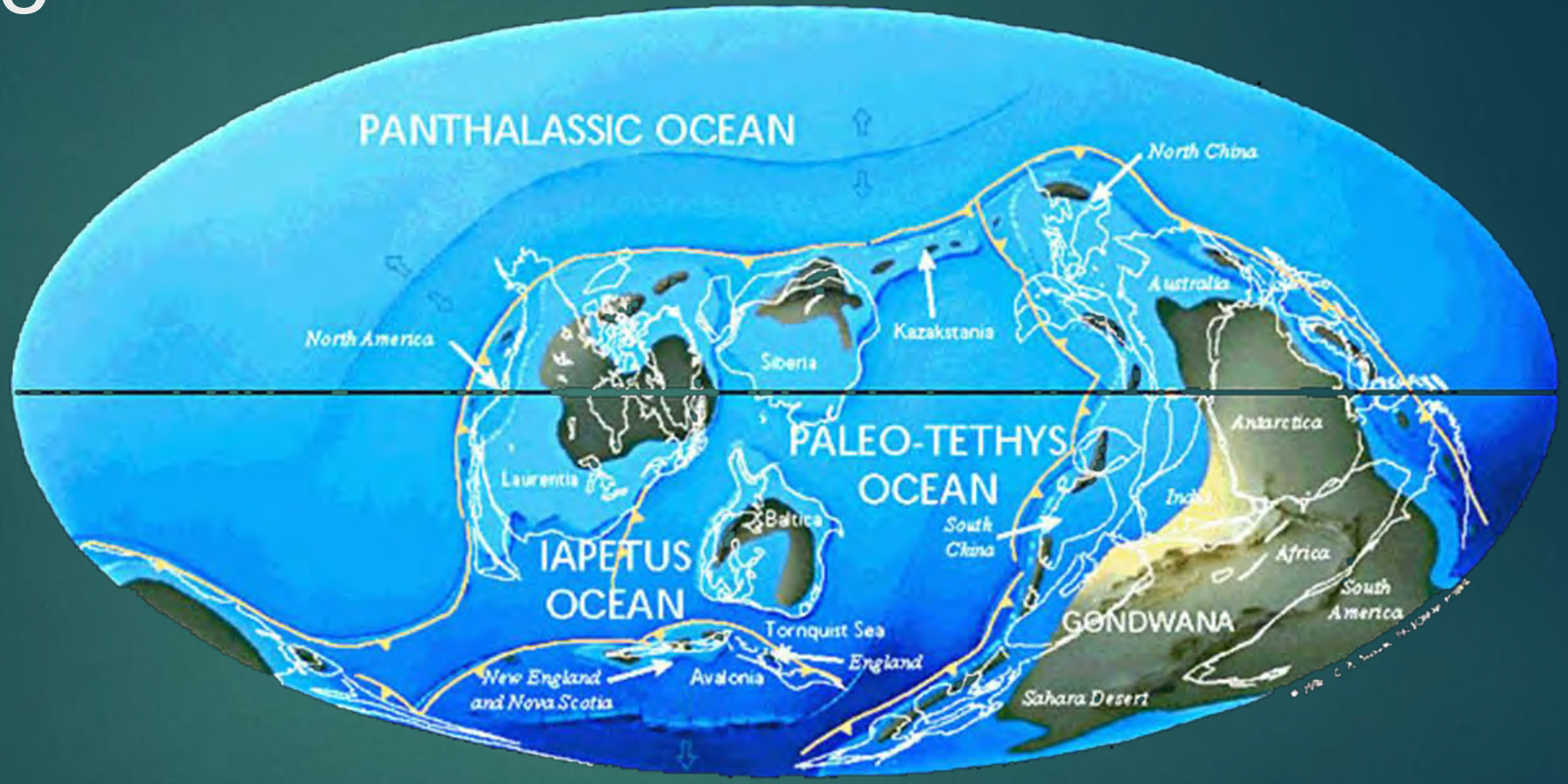
The Ordovician Period 489-444MYA

- 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 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

- 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.

Orthoceras

Cause of the End-Ordovician Extinction: A climate-related disaster.

- Most evidence points to glaciation:
  - Vast glaciers formed at the poles and moved toward the equator, locking up a huge quantity of seawater and drastically lowering sea levels. The shallow seas covering the continents were drained, killing all their occupants. Then too, oxygen levels fell as photosynthesis declined.

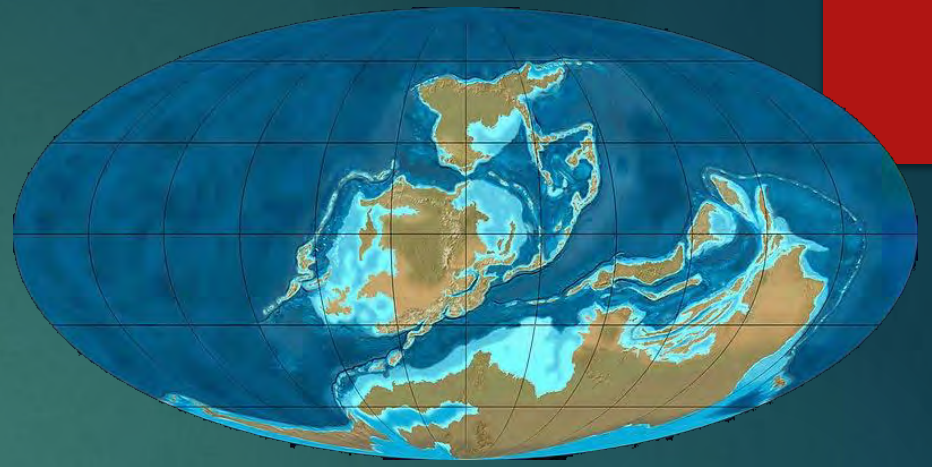
- What caused the glaciation?
  - Cooling due to CO_2 removal through weathering, particularly in the recently uplifted Appalachian mountains. Also, Gondwana had drifted over the south pole, becoming glaciated, increasing the Earth's albedo and incidentally killing life on that continent.

#2: The Late Devonian Extinction:

374 MILLION YEARS AGO

75% OF SPECIES EXTINCT.

The Devonian Period



- Lasted from 416 to 358 MYA
- Began with a high-oxygen peak; ended with a low of 12% (which then rose during the Carboniferous to greater than 30%)
- Most of the land mass was in the supercontinent Gondwana in the southern hemisphere, with Euramerica equatorial.
- Known as "The Age of Fish" due to a great diversification of fish. Bony fish (teleosts) with swim bladders and fins arose, and cartilaginous fish (sharks and rays) became common. By the end of the Devonian vertebrates appeared on land. The first fossil footprints of a terrestrial tetrapod date from 400 MYA.

Plants of the Devonian

- Plants continued to make evolutionary progress during the Devonian. Lycophytes, horsetails and ferns grew to large sizes and formed Earth's first forests. By the end of the Devonian, progymnosperms were the first successful trees, growing up to 98 feet tall with a trunk diameter of more than 3 feet. They did not have true leaves, but fern-like structures connected directly to the branches. There is evidence that they were deciduous, as the most common fossils are shed branches. Reproduction was by male and female spores that are accepted as being the precursors to seed-bearing plants.

In the Devonian fish diversified into two groups: lobe-finned (Sarcopterygii) and ray-finned (Actinopterygii). The Sarcopterygii gave rise to the Ripidistia, the ancestors of all tetrapods and lungfish (Dipnoi).

Latimeria, a crossopterygian living fossil

Trout, an actinopterygian

(Crossopterygii = Sarcopterygii)

Causes of the Late-Devonian Extinction

- The true cause(s) are still a matter of debate.
- The "event" lasted some 20 to 25 million years, and occurred in two waves, with the greatest destruction occurring at 374 and 359 MYA.
- The second event seems to be due to oxygen depletion of the oceans (which led to today's oil-rich shales).
  - The appearance of more sophisticated land plants with root systems may have led to enhanced rock breakup and subsequent eutrophication of the seas.
- The first event is more controversial. Some ascribe it to global *warming* due to volcanic eruptions raising the CO_2 levels, while some ascribe it to global *cooling* due to depletion of CO_2 by all the new land plants. Some even say it was *both*, and the rapid changes themselves are the cause, with most organisms unable to adapt to the swings.

#3 The Granddaddy of Them All: The End-Permian Extinction

250 MILLION YEARS AGO

96% OF ALL SPECIES EXTINCT.

The Permian Period

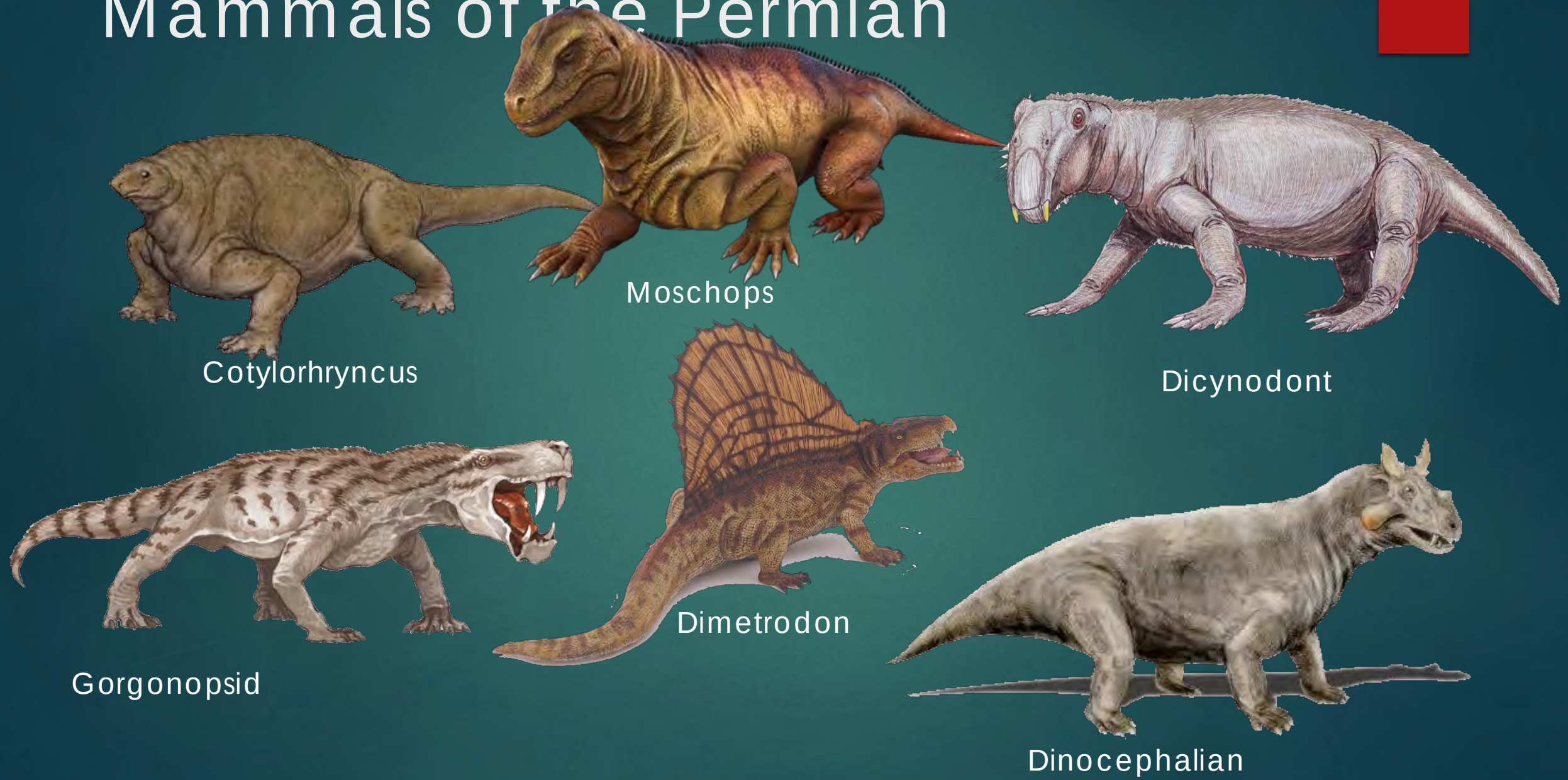
- Named for the Perm region of Russia, because its limits were found in strata in the Ural Mountains.
- Last period of the Paleozoic era, beginning of the Neoproterozoic era.
- Lasted 47 million years, from the end of the Carboniferous 299 MYA to the beginning of the Triassic, 252 MYA.
- Dominated by the giant supercontinent Pangea.
- Saw several glacial periods, beginning at the end of the Carboniferous with much of the southern hemisphere covered in ice.
- By the late Permian the ice had disappeared, leaving a temperate climate, but rather dry.
- Saw the diversification of the early amniotes into the ancestral groups of the mammals, turtles, lepidosaurs, and archosaurs.
- Ended in the Permian-Triassic Extinction, the largest mass extinction in Earth's history, in which nearly 96% of marine species and 70% of terrestrial species died out. It is the only extinction that affected insects. It marked the end for the trilobites, a run of some 300 million years.

The Permian Sea, 270 Million years ago

The world at the time was dominated by two continents known as Pangaea and Siberia, surrounded by a global ocean called Panthalassa. The Carboniferous rainforest collapse left behind vast regions of desert within the continental interior. Amniotes, who could better cope with these drier conditions, rose to dominance in place of their amphibian ancestors*.

*AMNH exhibit text

Mammals of the Permian



The Permian Extinction: Multiple Causes

- Magma from a massive volcanic eruption poured for thousands of years onto the surface in what is now called the Siberian Traps. From the amount of magma released (2 million square miles of it, in places two and a half *miles* deep) it has been calculated that enough CO_2 was released to raise the global temperature by 5°C.
- That same magma ignited vast underground deposits of coal and shale oil left from the Carboniferous, releasing millions of tons of CO_2 and other gasses, including methane, halogenated butane, methyl bromide and methyl chloride, in an unimaginable explosion.
- Hydrogen sulfide levels increased dramatically over a few hundred years. A mass release of H_2S would react with and destroy atmospheric O_2 and ozone in the upper atmosphere allowing ultraviolet radiation to kill off species that had survived the toxic gas.
- CO_2 released by vulcanism could raise ocean temperatures releasing frozen methane (clathrate) reservoirs, expelling enough methane into the atmosphere to raise world temperatures an additional 5°C.
- The CO_2 would also acidify the oceans which, among other effects, would prevent shell production.
- More likely, the Permian–Triassic extinction event was caused by a combination of some or all of the above and other factors; for example, the formation of Pangaea decreased the number of coastal habitats and may have contributed to the extinction of many clades.

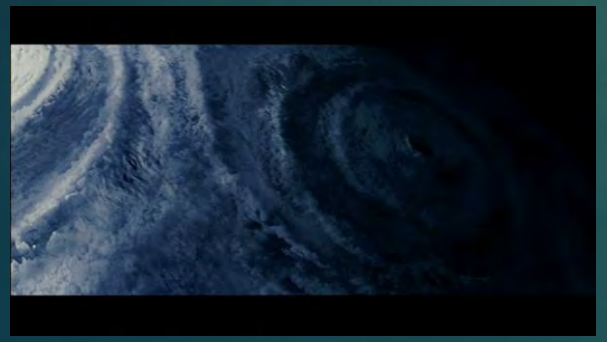
CO_2 and the End-Permian Extinction

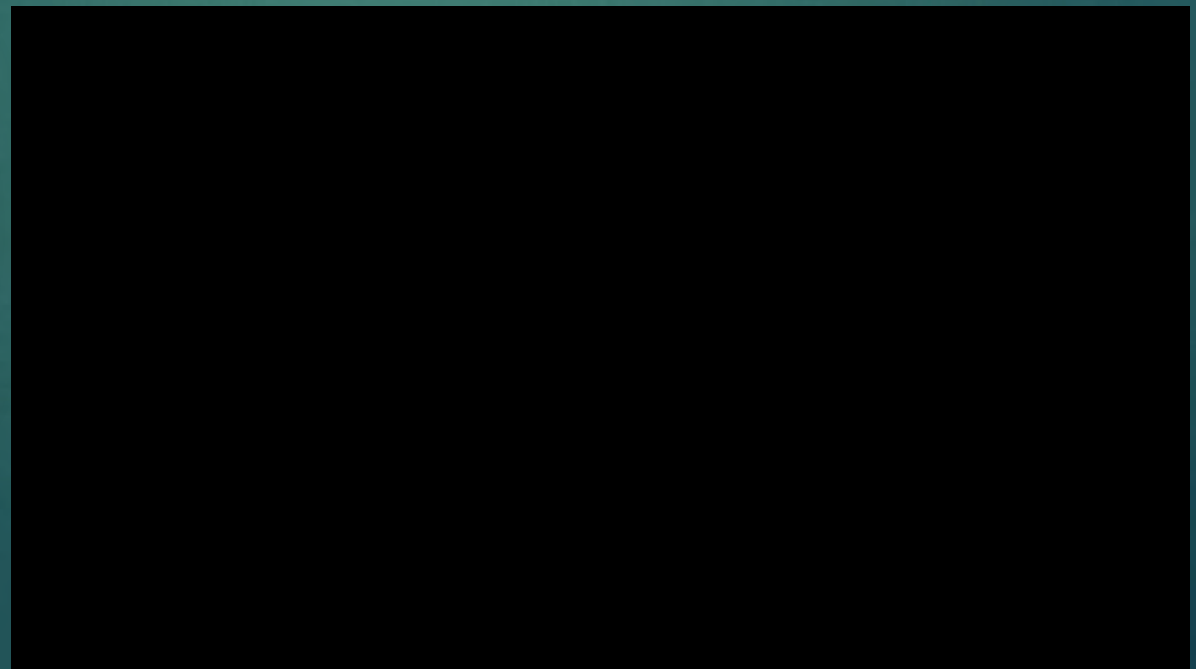
- Modern estimates place the concentration of CO_2 at the end-Permian around 8,000 ppm, although some estimates are as high as 30,000 ppm. The Siberian Traps alone might have released from 10,000 to as much as 40,000 gigatons (thousand million tons) of CO_2 into the atmosphere.
- This resulted in catastrophic global warming and acidic seas.
  - For comparison, today we humans release about 40 gigatons of CO_2 per year, and currently the concentration is 417.9* ppm.
  - Burning all known reserves of oil, gas and coal would inject about 5,000 gigatons of CO2 into the atmosphere.

*on April 28th it was 419.75 ppm)

And let's not forget the hypercanes.

- The National Center for Atmospheric Research (NCAR) has developed weather models based on the end-Permian conditions.
- They propose that in addition to all the other effects there were "hypercanes": continent-wide hurricanes packing 500 mile-an-hour winds, loaded with poisonous hydrogen sulfide picked up from the ocean, along with carbon dioxide.





What could the world be like during the End-Permian Extinction

- Here's a reading from Peter Brannen's book, "The Ends of the World"

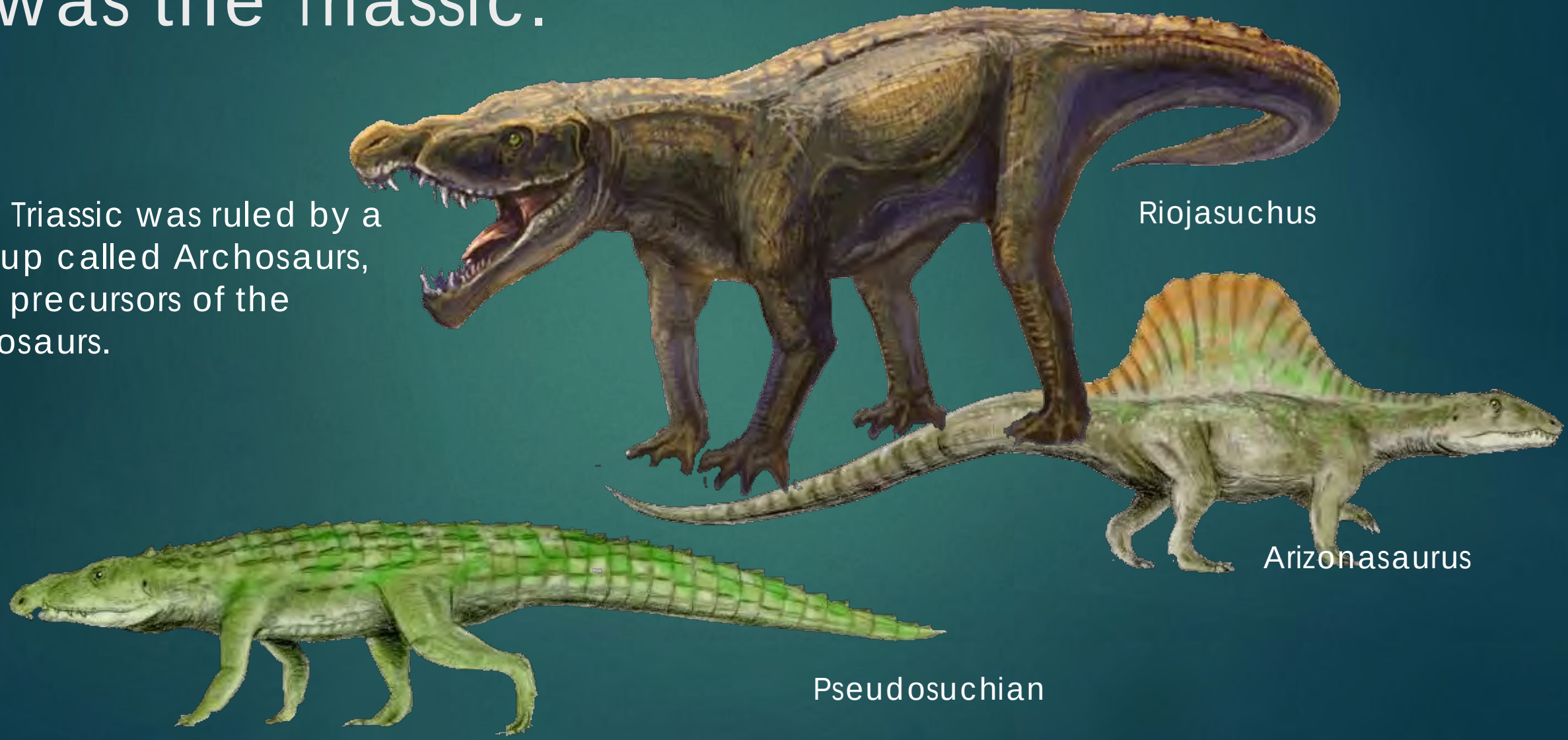
"There was an ocean that was rapidly acidifying---one that, over huge swaths of the planet, was as hot as a Jacuzzi and completely bereft of oxygen. There were sickly tides suffused with so much carbon dioxide and hydrogen sulfide that either poison would have sufficed as a killer in its own right. There was a Russian landscape detonating and being smothered in lava several miles deep. There was a fog of neurotoxins and lethal smog streaming from these volcanoes and, high above, an ozone layer blasted apart by halocarbons, inviting a bath of lethal radiation at the planet's surface. There was forest-destroying acid rain and a landscape so barren that rivers had stopped winding. There were carbon dioxide levels so high, and global warming so intense, that much of the earth had become too hot even for insects. And now there were unearthly mega-hurricanes, made of poison swamp gas, that would have towered into the heavens and obliterated whole continents."

What ended the End-Permian Extinction?

- It took about ten million years for the Earth's biota to recover from the Hell of the end-Permian world.
- Most of the recovery was due to the absorption of the CO_2 out of the atmosphere, returning it (and the global temperature) to 'sane' levels.
  - Factors at work were weathering and sequestration of CO_2 by coral-reef building and shell-building animals.
  - Plant life was not much help, most of it, including trees, having been killed off in the extinction.
  - Weathering was helped by the high CO_2 which produced acid rain but hindered by the fact that most of the Earth's landmass was concentrated in Pangaea, leading to dry interior.

The Age that followed the Permian was the Triassic.

- The Triassic was ruled by a group called Archosaurs, the precursors of the dinosaurs.

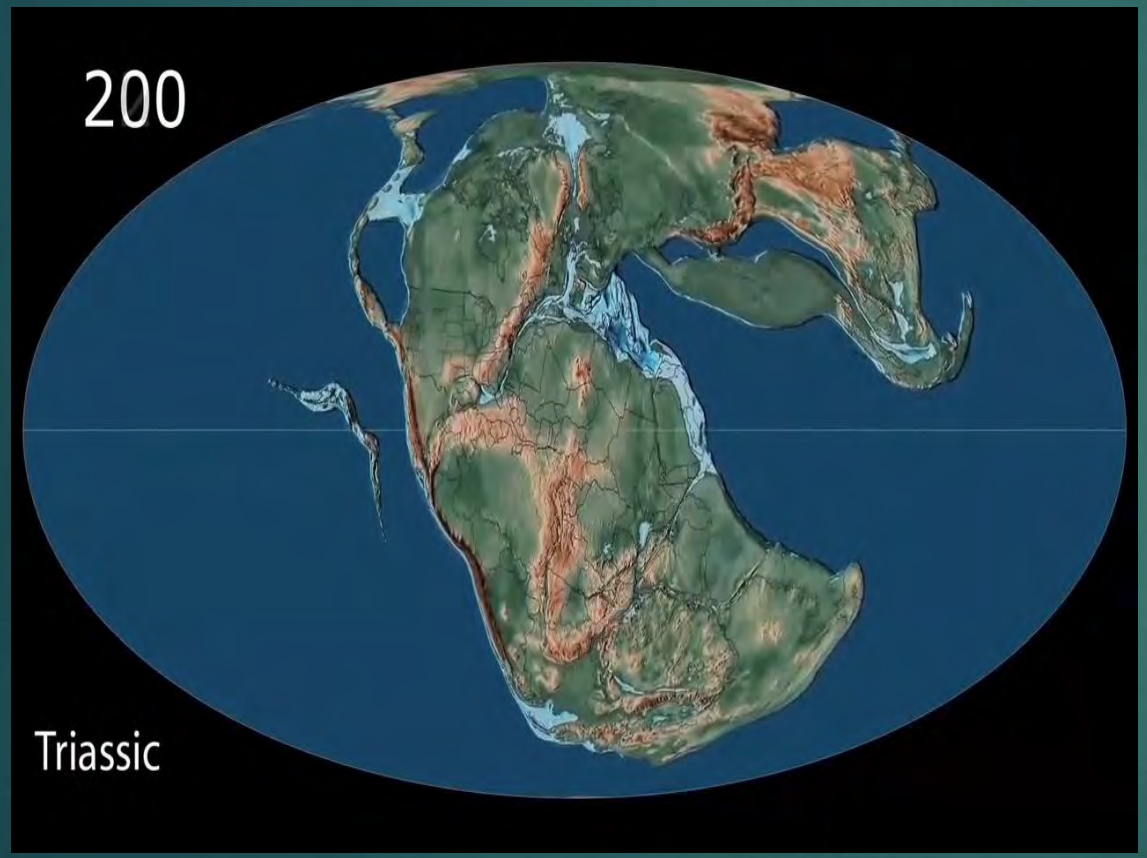


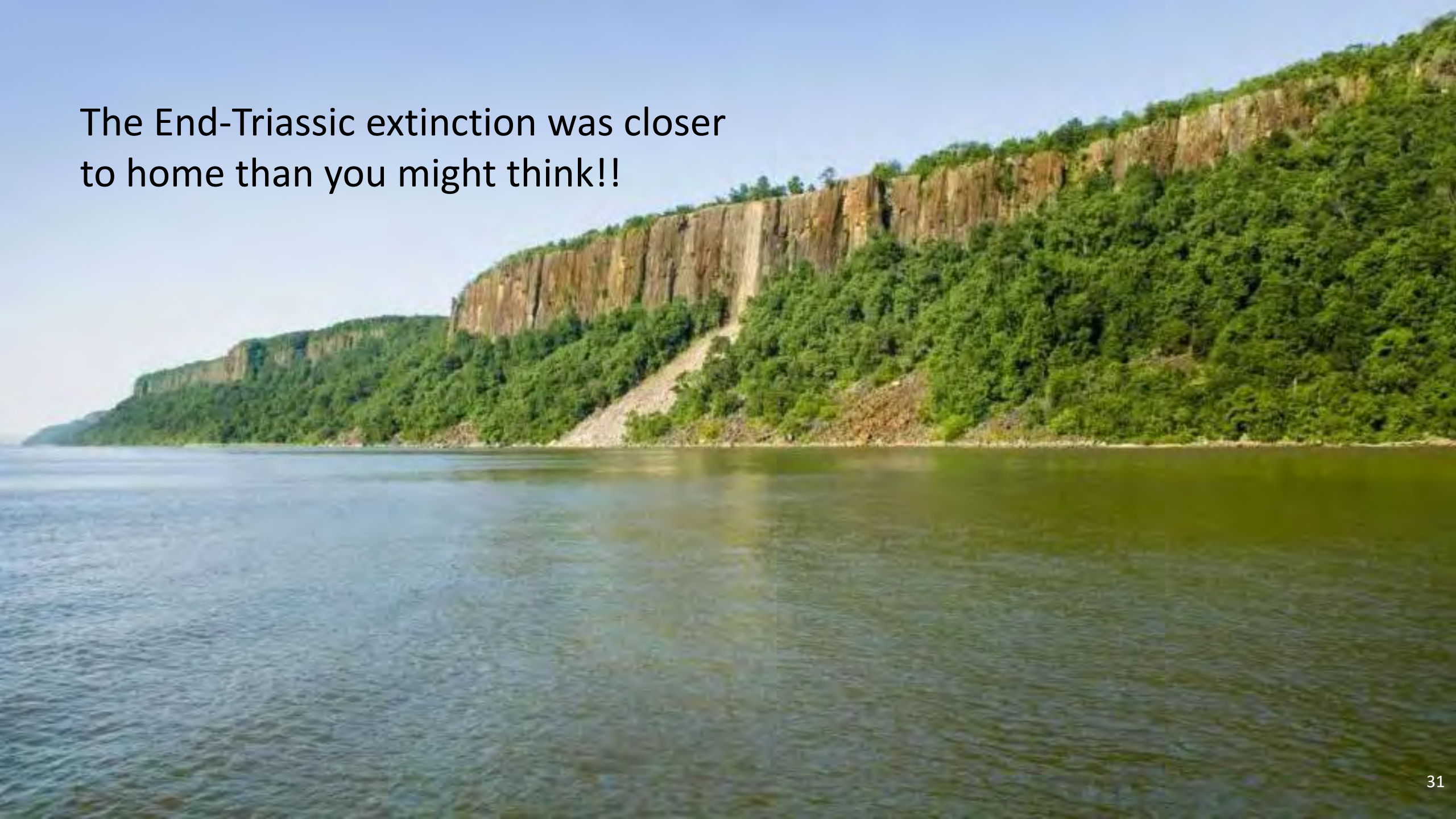
#4 The End-Triassic Extinction

201 MILLION YEARS AGO

80% OF SPECIES EXTINCT

The world of the dinosaurs: Pangaea




The End-Triassic extinction was closer
to home than you might think!!

What caused the end-Triassic extinction?

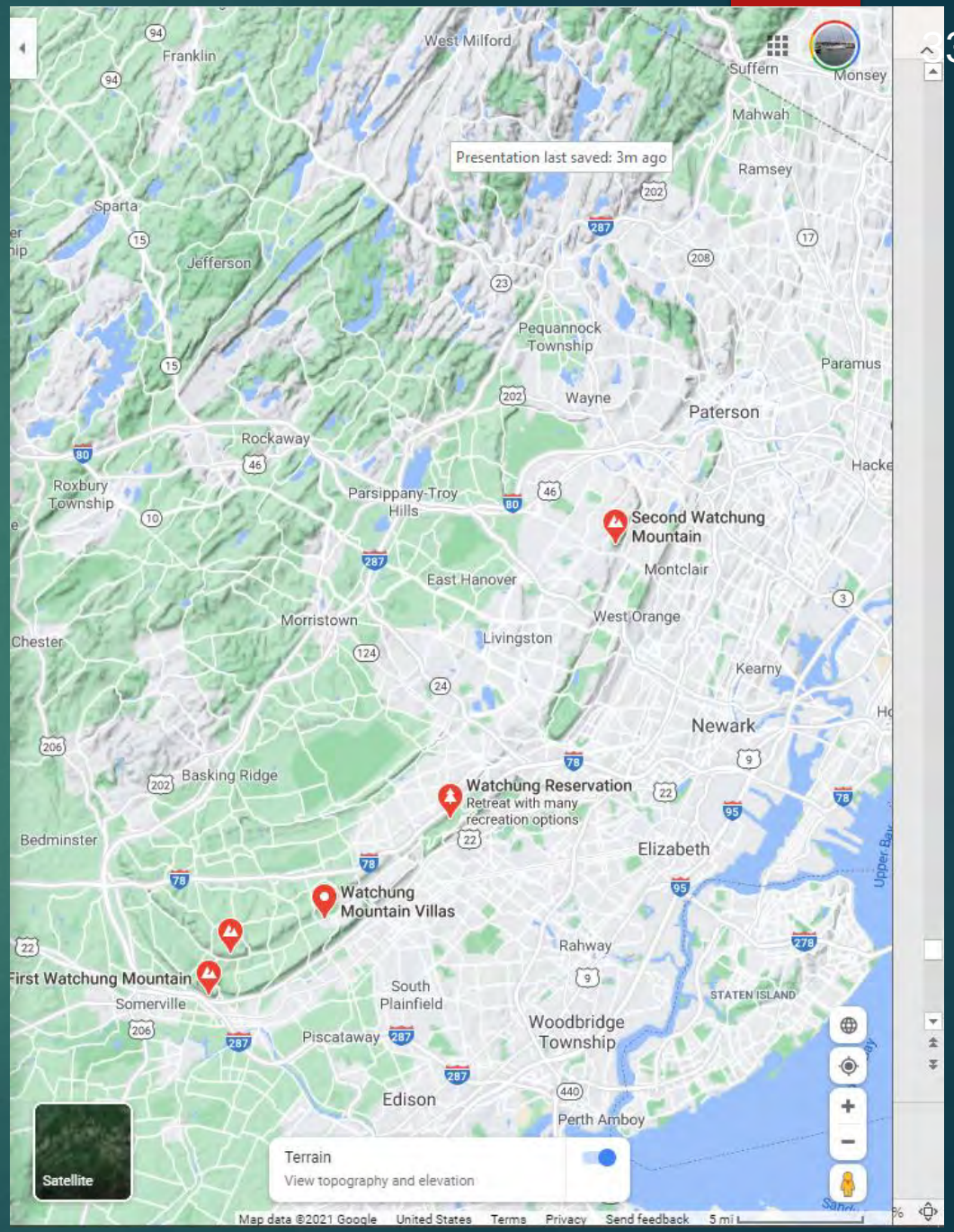
- Pangaea had been slowly breaking up for nearly 30 million years.

But beneath what is now the East Coast of North America a vast blob of the Earth's mantle was rising, kept in check by the thinning floor of the rift valley between the separating plates.

201 million years ago that floor broke, and enormous sheets of magma were released and spread across the land. This was the "Central Atlantic Magmatic Province" (CAMP)

Today you can see this in the Palisades as well as near the Bay of Fundy and even Gettysburg PA where it formed Cemetery Ridge and Little Roundtop, so important in the Civil War Battle of Gettysburg.

A topographic map of northeastern New Jersey shows the waves of magma spreading out, leaving enormous ripples such as the Watchung Mountains.
Remnants remain in France, Brazil and Morocco which were then contiguous.



Grand Manan Island, Bay of Fundy, off Nova Scotia

Global Warming and the End-Triassic Extinction

- The release of such vast amounts of magma would have been accompanied by an equally vast amount of CO_2.
- CO_2 from deep ice cores and the near-disappearance of stomata in fossils of contemporaneous plants, among other things, point to as much as a doubling of CO_2 in the atmosphere
- This led to warming an already warm world and the extinction of many species, including many of the archosaurs, leading to the rapid radiation and ultimate dominance of ….

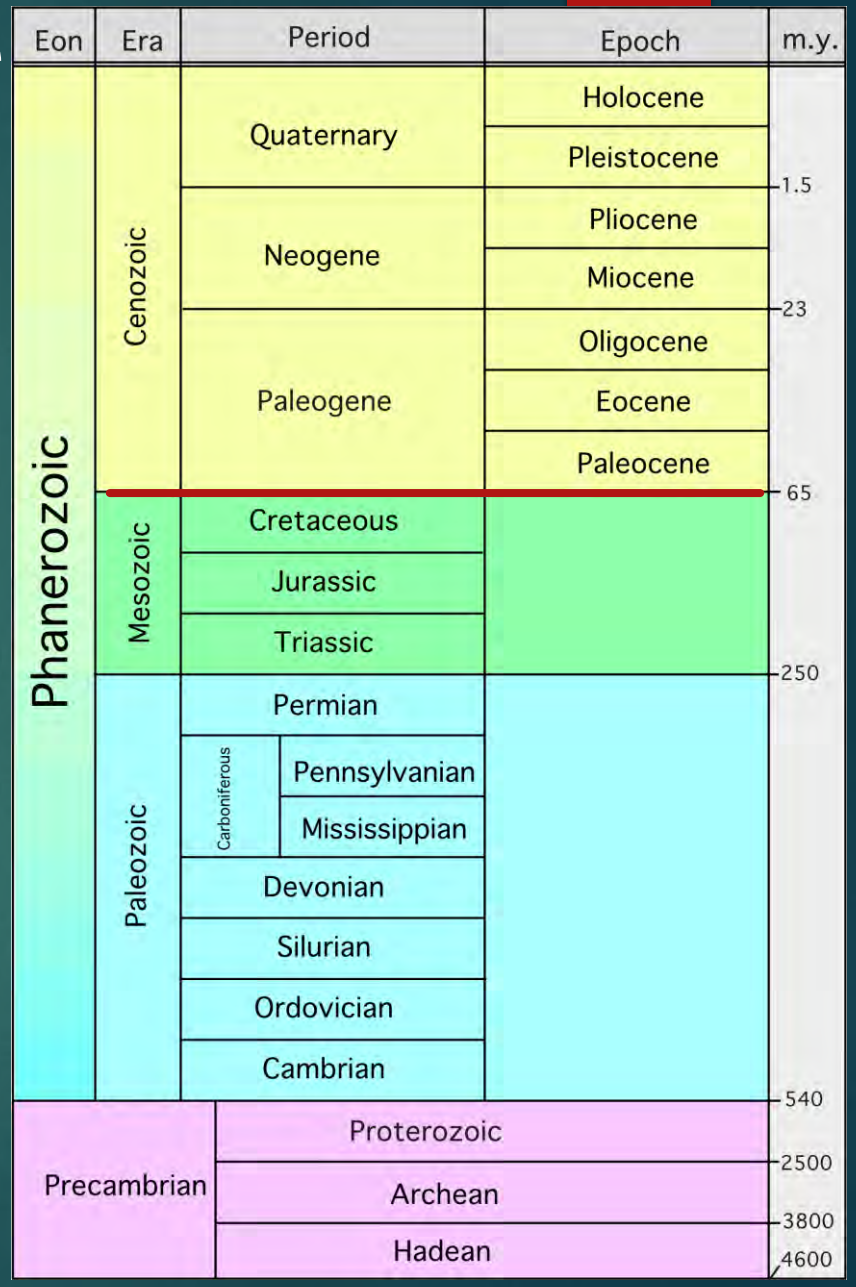
…the most charismatic megafauna of all time: dinosaurs!

- The Permian had seen a proliferation of sprawling reptiles.
- Following the catastrophic End-Permian extinction the beginning of the Triassic saw the appearance of reptiles that rose from the ground, first on four and then on two legs. These were the Archosaurs.
- In the early Triassic the Archosaurs thrived, and soon branched into two lineages which survive today:
  - Pseudosuchians, crocodile-like archosaurs
    - Survive today as crocodiles.
  - Avimetatarsalians
    - Developed into pterosaurs, dinosaurs and today's birds.

When did dinosaurs "rule the earth"?

- Dinosaurs first appeared in the early Triassic period, about 230MYA.
- Dinosaurs remained fairly minor through the Triassic
- They rapidly radiated in the Jurassic and eventually dominated during the Cretaceous.
- Non-avian dinosaurs disappeared at the Cretaceous-Paleogene (K-Pg)* extinction, some 66MYA
- Thus, the era of the dinosaurs is the Mesozoic era, some 160 million years in duration. Not bad, eh?

*Often called the Cretaceous-Tertiary (K-T) extinction



#5 The End-Cretaceous Extinction

66 MILLION YEARS AGO

76% OF SPECIES DIE.

THE END OF THE DINOSAURS*

(ALSO CALLED THE "K-T" [CRETACEOUS-TERTIARY] OR "K-PG" [CRETACEOUS-PALEOGENE] EXTINCTION)

*Non-avian dinosaurs, that is.

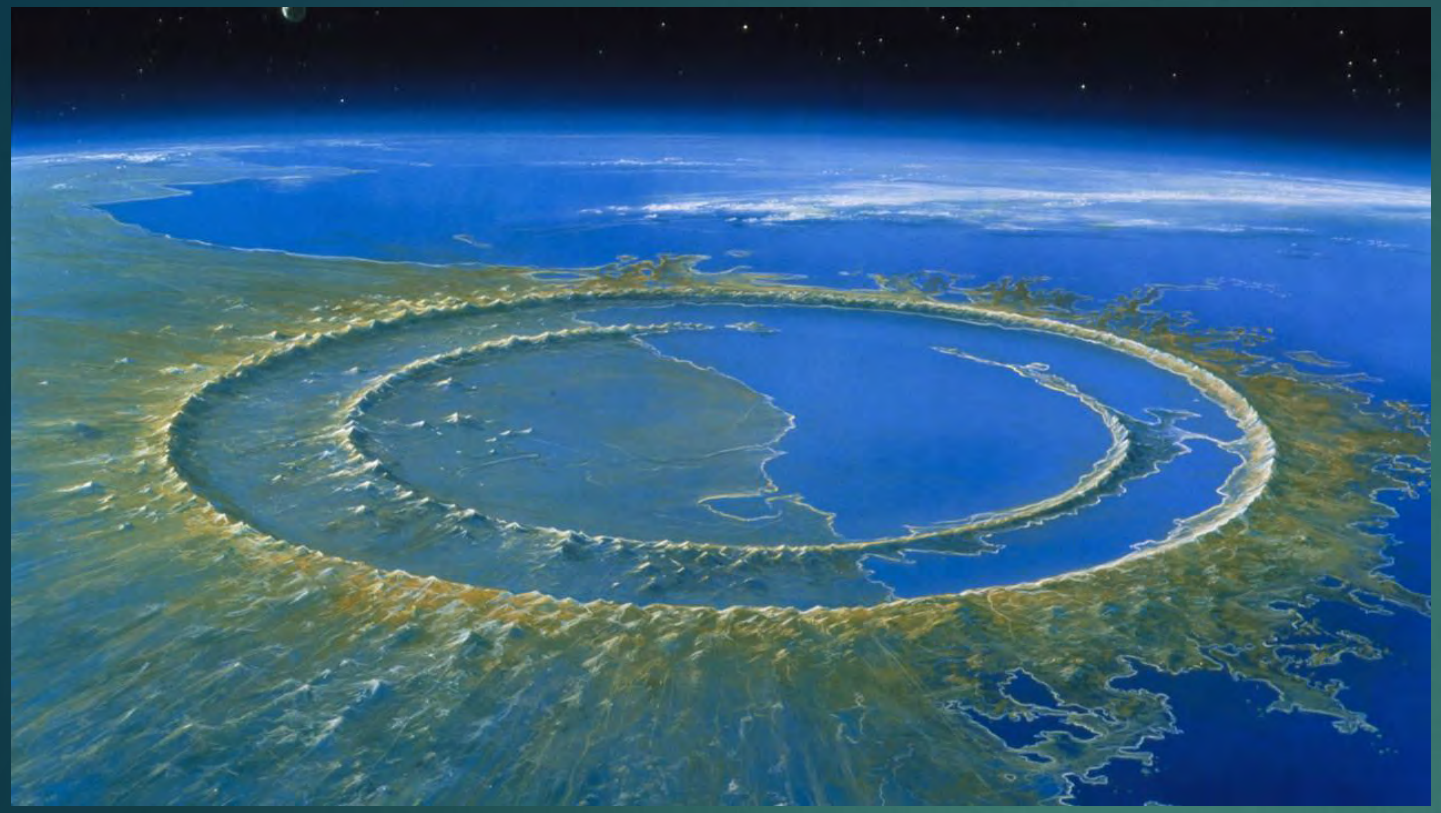
The End of the Dinosaurs: Version 1

The Chicxulub Impact Theory

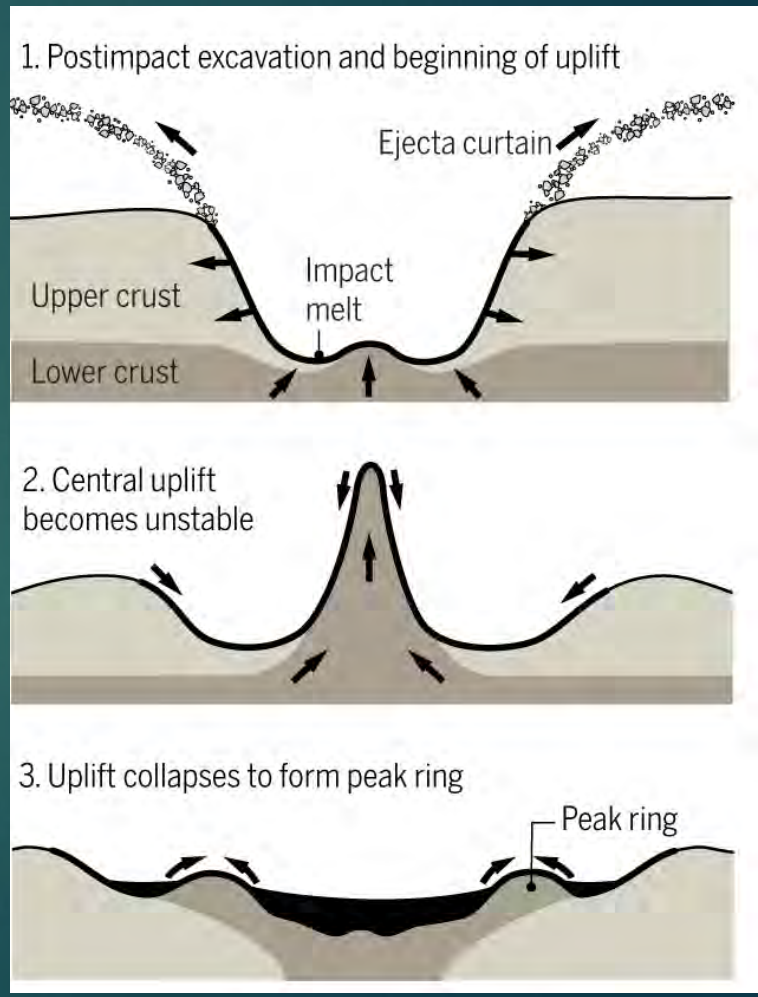
In the 1980s, father-son team Luis and Walter Alvarez, a physicist and planetary scientist respectively, presented a bold new theory.

- They showed that a layer of clay found throughout the world is enriched in iridium—an element rare on Earth but common in space rocks. That layer was deposited at the time of the KT extinction.
- They proposed that a meteorite wiped out the dinosaurs.

The impact theory gained further momentum in the 1990s, when scientists discovered a 110-mile (180-kilometer) wide impact crater in the Yucatán Peninsula that dated to the KT (K-Pg) boundary



Recent findings



Recently scientists were able to bore into the peak ring (offshore) of the Chixculub crater. The ring formed within minutes of the impact and contains material from the lower crust of the earth layered *on top of* sedimentary rock. The findings validate the dynamic collapse theory of the crater's formation.

But, could an asteroid strike really lead to a world-wide extinction including marine organisms?

- Since the publication of Alvarez' theory, there have been doubts about it:
  - Fossil evidence shows a decline in dinosaur diversity in the million or so years preceding the Chicxulub impact, at least outside of Europe and Asia.
  - There has been a lingering uncertainty about the exact date of the Chicxulub impact and thus its contemporaneity with the extinction of nonavian dinosaurs.
  - There are doubts that a localized impact, however large, could lead to world-wide extinction which included marine as well as terrestrial organisms.

Recent findings

- February 2013: Scientists arrived at extremely accurate dating of the Chixculub event.*
  - They dated the event to 66.038±0.049 MYA, and the K-Pg boundary to 66.043±0.043 MYA
  - Thus the impact was within 33,000 years of the boundary, making them essentially indistinguishable.
- But was the impact the cause of nonavian dinosaur extinction?

*Renne et al, “Time Scales of Critical Events Around the Cretaceous-Paleogene Boundary”. *Science* **339** (6120), 684-687, 2013

Dinosaur woes preceded Chixculub

- Throughout most of the Cretaceous the climate had been warm and benevolent ("hothouse"). There were no if any glaciers and sea-levels were at an all-time high.
- Beginning about one million years before the K-Pg boundary the climate became unstable and went through a number of cooling and warming cycles of as much as 6 to 8^{o}C.
- Glaciers formed and melted, vegetation changed, and sea levels rose and fell by up to 40 meters (131 feet)!
- What caused this change?

Deccan Traps and Volcanism*

The Deccan Traps are a large igneous province located on the Deccan Plateau of west-central India and one of the largest volcanic features on Earth. They consist of multiple layers of solidified flood basalt that together are more than 2,000 m (6,562 ft) thick, cover an area of 500,000 km^2 (193,051 sq mi) and have a volume of 512,000 km^3 (123,000 cu mi).

The Deccan Traps began forming 66.25 million years ago, at the end of the Cretaceous period. The bulk of the volcanic eruption occurred some 66 million years ago. This series of eruptions may have lasted less than 30,000 years in total. The original area covered by the lava flows is estimated to have been as large as 1.5 million km^2, approximately half the size of modern India.

*Source: Wikkipedia

Volcanism and climate

- The volcanoes that formed the Deccan Traps poured vast amounts of carbon dioxide, ash, and sulfur dioxide into the atmosphere.
- These periodic pulses would lead to climate instability and acidification of ocean waters.
- Such effects on the global climate must have been stressors on all populations, including the dinosaurs, leading to the decline in diversity seen in the million years preceding the Chixculub event.

The End of the Nonavian Dinosaurs

- The period of climate instability preceding the Chixculub event led to a decline in dinosaur diversity and numbers. Low-diversity populations are less resilient and more vulnerable to external forces.
- The Chixculub event led to a global winter, and, combined with the changes in climate produced by Deccan (and other) volcanic events, produced a profound and permanent change in the global climate.
- Large dinosaurs were unable to adapt, leaving only the smaller and better-adapted dinosaurs (birds) to survive.
- Following the K-Pg boundary events, once the climate re-stabilized, non-dinosaur fauna recovered rapidly, showing restoration of pre-event diversity within about 20,000 years, probably through immigration from refugia. However, the large nonavian dinosaurs were gone forever.


CARTOONSTOCK
.com
"SO, NO MATTER HOW BAD THINGS MAY LOOK, YOU JUST HAVE TO SAY TO YOURSELF, 'HEY, IT'S NOT THE END OF THE WORLD!'"

#6?? The End-Pleistocene "Extinction"

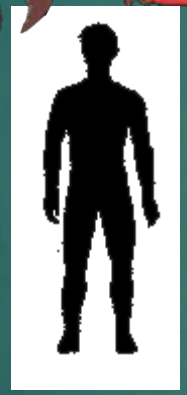
ICE AGES AND THE ANTHROPOCENE ERA

The World after the Dinosaurs

The Early Paleocene: a world without dinosaurs.

- Following the Chixculub and Deccan Traps extinction the world was unsettled, and new forms of plants and animals arose and vied for a place in the ruins.
- Climate was hot but swung through extremes lasting a few hundred to thousands of years at a time.
- The "hothouse" hit its maximum about 56 MYA, caused by a CO_2 release, over some 20,000 years, equivalent to all of today's fossil fuel reserves.
- Temperatures climbed 5 to 8°C, with average inland temperatures near 55°C [131°F]. The temperature of the Arctic Ocean was 76°F and Antarctica (then part of Gondwana) was a lush forested land. Arctic Canada abounded with lemurs, hippos and alligators. Coral reefs were devastated, and early mammals shrank in size to adapt to the heat.
- The was the Paleocene-Eocene Thermal Maximum (PETM)

Animals of the Early Paleocene



Titanboa (50’ long)

Terror Birds

Megalodon (60’ shark)

CO_2 and the Paleocene-Eocene Thermal Maximum (PETM): possible cause

- India and the Deccan Traps
  - As India collided with Asia, sea-bed carbonates from ages of sea life was subducted and then released as CO_2 in volcanoes and magma eruptions, starting before the End-Cretaceous Extinction and continuing into the early Paleocene.
  - But as the collision pushed up the Himalayas it exposed vast amounts of rock whose subsequent weathering drew down the CO_2, and the slow decline to the modern Ice Ages began.

The Cenozoic: The Age of Mammals

- The Cenozoic began in a "nuclear winter" following the K-T extinction, barren and devastated, with only 5% of species left alive to repopulate a dark and cold earth.
- By the Paleogene the temperature had warmed to 55°C, with tropical forests and deserts inland.
- Later in the Neogene the climate cooled, leading to large furry mammals like the wooly mammoth.
- The Quaternary (present period) has been characterized by a series of glaciations.

The Cenozoic: The Age of Mammals

Eon	Era	Period	Epoch	m.y.
Phanerozoic	Cenozoic	Quaternary	Holocene	
			Pleistocene	1.5
		Neogene	Pliocene	
			Miocene	23
		Paleogene	Oligocene	
			Eocene	
			Paleocene	65
	Mesozoic	Cretaceous		
		Jurassic		
		Triassic		250
	Paleozoic	Permian		
		Carboniferous: Pennsylvanian		
		Carboniferous: Mississippian		
		Devonian		
		Silurian		
		Ordovician		
		Cambrian		540
Precambrian		Proterozoic		2500
		Archean		3800
		Hadean		4600

Mammals of the Paleogene, 65 to 23 MYA

coryphodon

uintatherium

Andrewsarchus

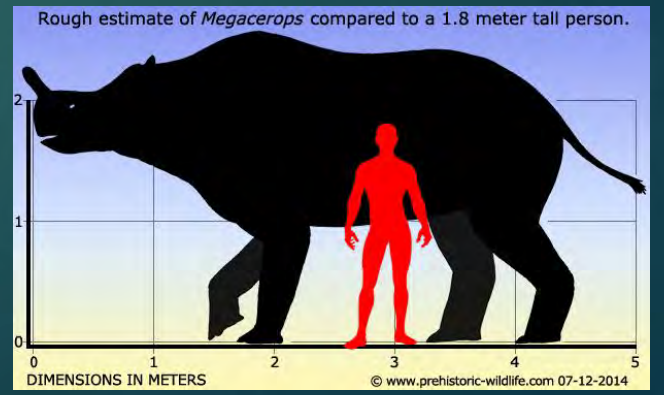
arsinoitherium

Mammals of the Paleogene

Magistotherium

megacerops

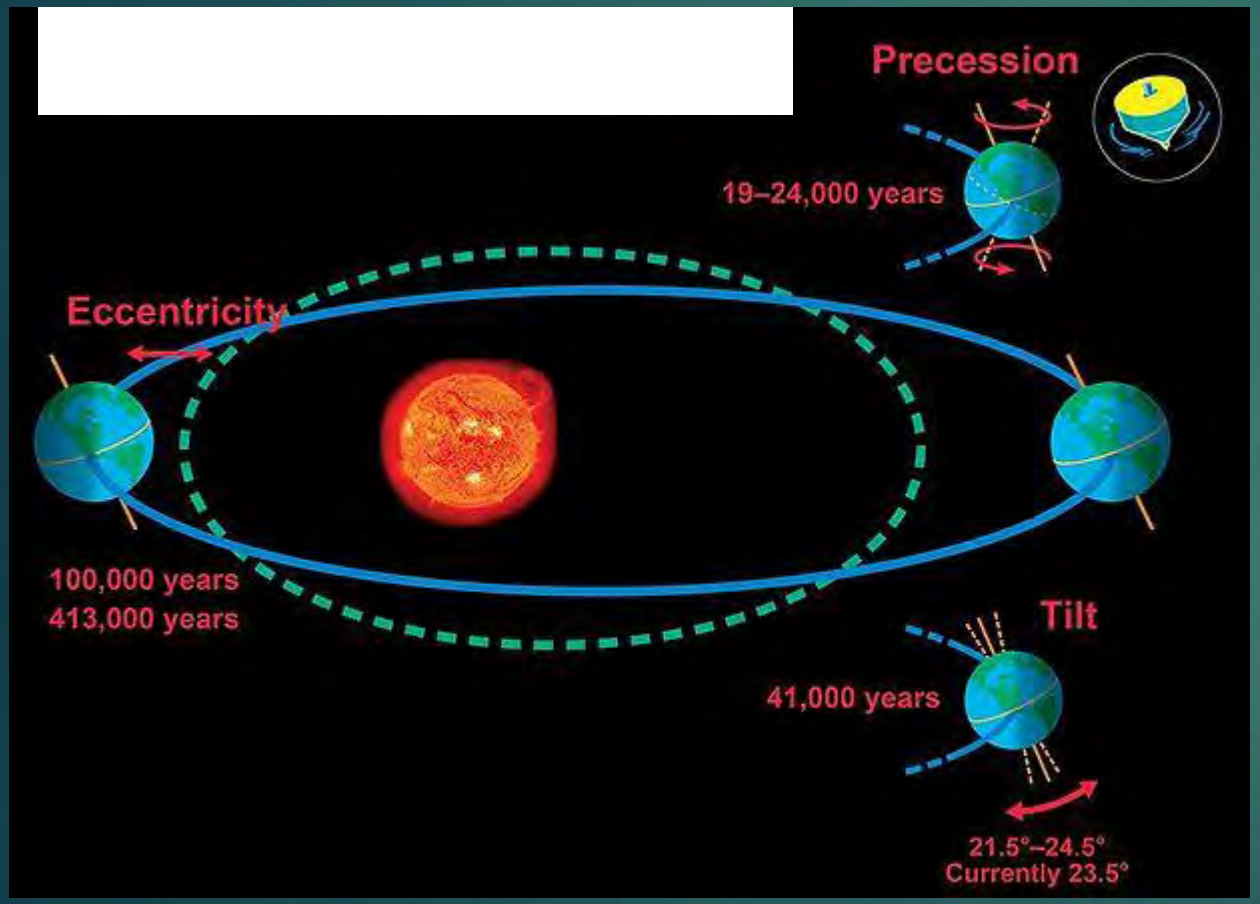
megatherium



The Modern Age (Neogene and Quaternary Periods) Begins

- By about 3 MYA the earth had cooled to recognizable temperatures. Sea levels fell as polar ice began to re-form, and the land-bridge between North and South America (Panama) emerged, drastically changing ocean currents.
- From about 2.6 MYA until recent times (i.e., the industrial age) the earth's climate has been mostly driven by astronomical shifts known as Milankovitch cycles.
- These shifts resulted in periodic ice ages of the Pleistocene Epoch, which continues today.

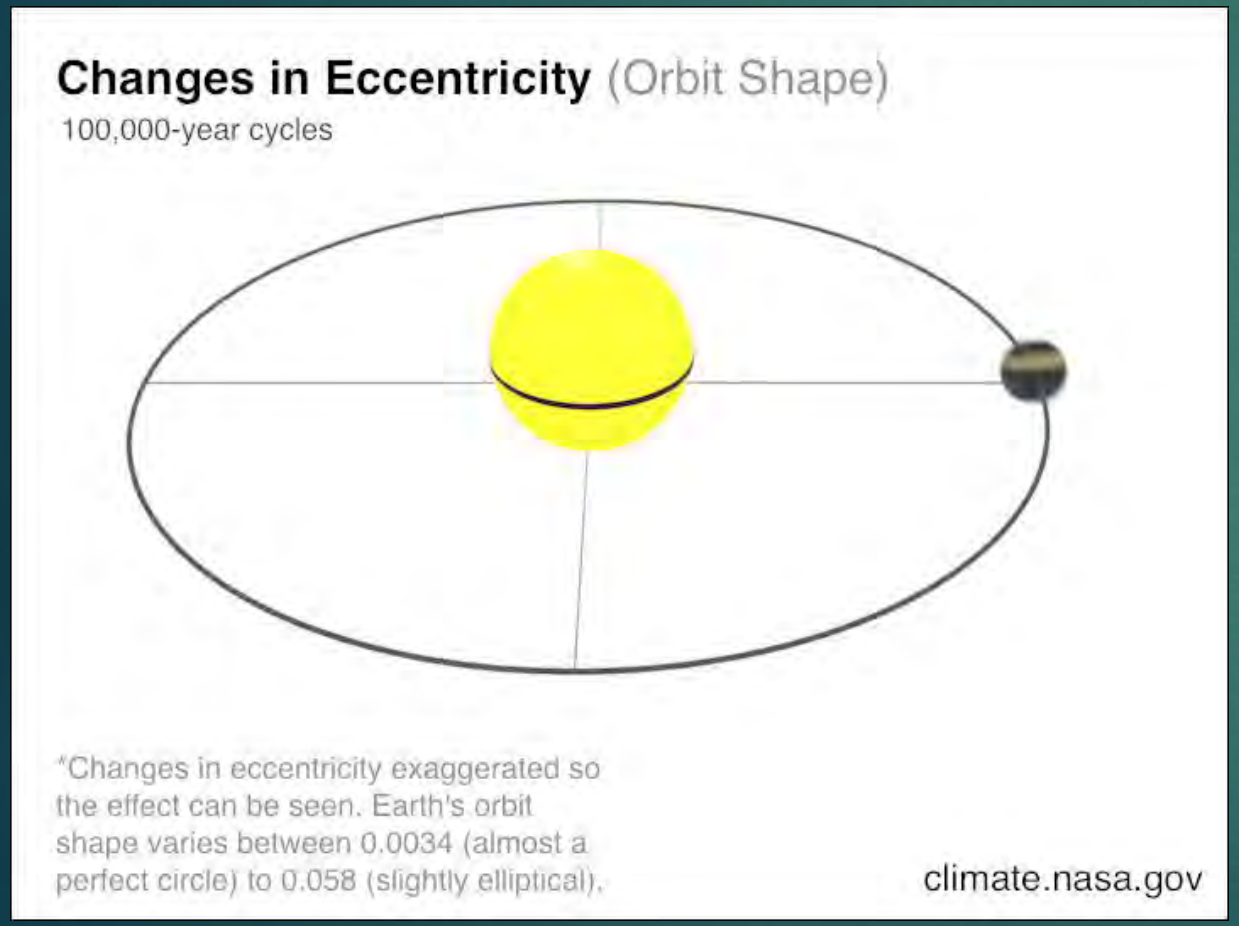
Milankovitch Cycles



Eccentricity (*ca* 100,000-year cycle) influences overall insolation.

Precession (26,000-year cycle) and ***Tilt*** (41,000-year cycle) both influence the extremes of summer and winter in the northern and southern hemispheres.

Orbit Eccentricity

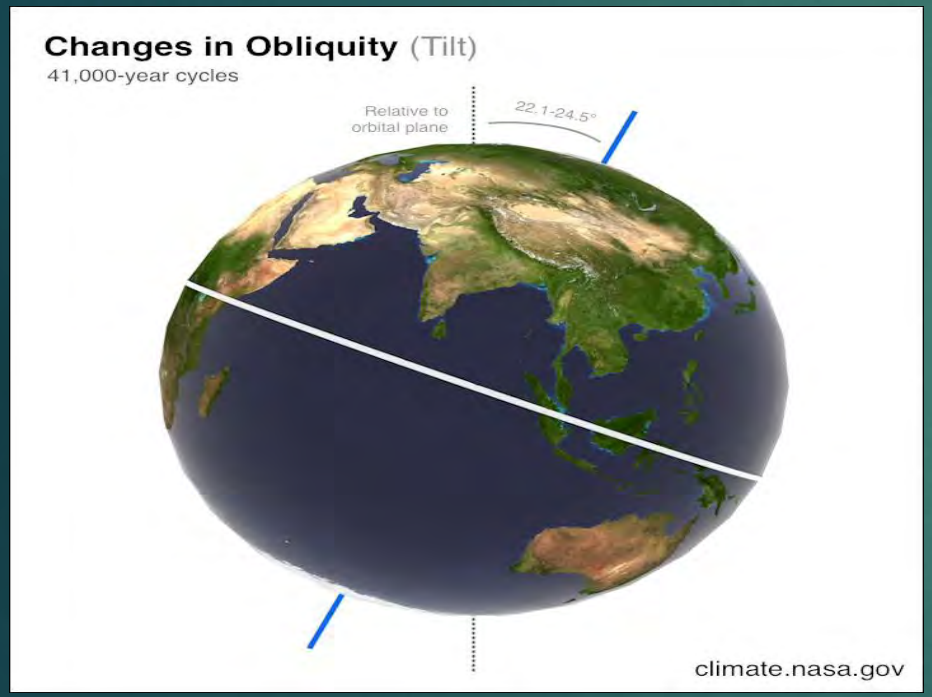


Earth's orbit is not circular; instead, it is elliptical, or "eccentric". Gravitational effects of Jupiter and Saturn periodically alter the orbital eccentricity. When the orbit is most elliptical, solar radiation varies by 23% from aphelion to perihelion.

Due to eccentricity seasons vary in length. The more eccentricity the more discrepancy in seasonal duration.

Currently the Earth's orbit is near its most circular, and Northern Hemisphere summers are about 2.5 days longer than winters.

Effects of Obliquity and Precession



Obliquity is the tilt of the Earth's axis relative to its orbital plane.

- The greater the obliquity the greater the difference in temperature between summer and winter.
- Obliquity varies between 22.1° and 24.5°, and is currently at 23.4°.

Precession is the "wobble" in the axis (relative to the fixed stars), much like a spinning top.

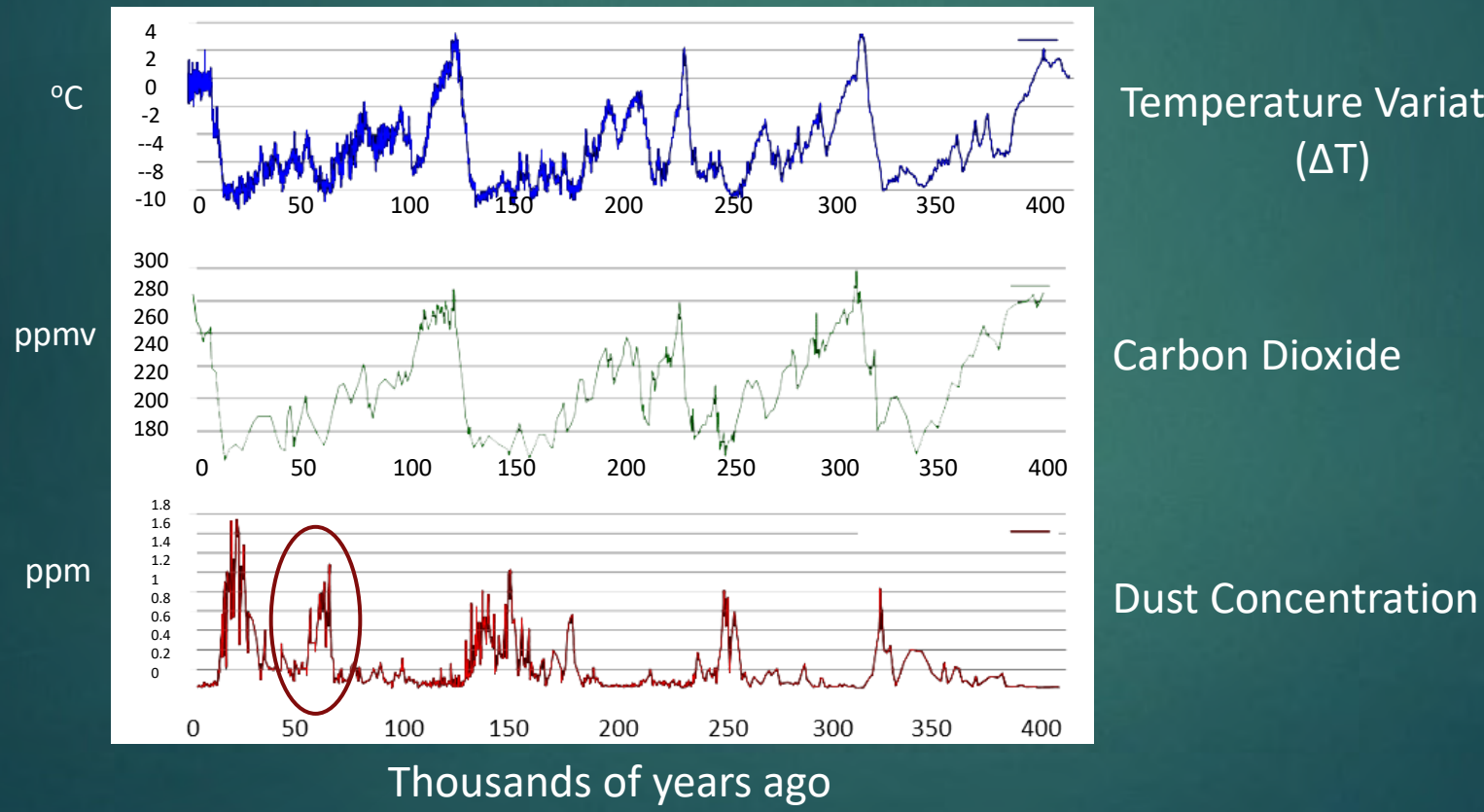
- Precession makes seasons more extreme in one hemisphere and less so in the other.
- Currently perihelion occurs during the Northern Hemisphere winter, moderating the extremes in the Northern Hemisphere and making Southern Hemisphere summers hotter.

Milankovitch Cycles and the Pleistocene

- Milankovitch cycles are considered to be the driving force behind the glacial-interglacial cycles of the last 450,000 years, the end of the Pleistocene Epoch (2.6 MYA – 11,700 YA), AKA "the Ice Age".
- Milankovitch predicted glacial cycles lasting 41,000 years
- This seems to hold to a degree between 1 and 3 MYA, but since then the cycles seem to be around 1-3 million years.
- We are currently in an interglacial period, but according to Milankovitch, overdue for the next glaciation.

The Vostok Ice Core*

- Antarctic drilling of the ice over Lake Vostok in Antarctica provided the longest ice core to date, revealing climate changes over the last 420,000 years. (Late Pleistocene [2.6MYA-11,700 YA] and Holocene [11,700 YA-Present]



*Petit J.R. et. al. "Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature **399**, 1999

Lost Megafauna of the Pleistocene

Some 74,000 years ago Mount Toba in modern Indonesia erupted.

- The eruption was the equivalent of a million tons of TNT, 1,000 times the power of Krakatoa, and 3,000 times the power of Mt. Saint Helens.
- Ash fell as far away as India, leaving a 6-inch deposit there.
- It spewed out 11 billion tons of sulfur dioxide
- It injected 720 cubic miles of dust into the stratosphere, where it circled the earth and led to a sudden and drastic drop in global temperature that would have lasted ten years or more.
- Much as with Krakatoa, the sonic boom would have circled the earth and been deafening to the small tribe of migrants in Africa.
- Traces of Toba ash are found in Greenland ice cores.

Where are we today?

- Based on the past 2.6 million years of climate changes we are in an interglacial period and have been for the last 12,000 years.
  - *This "Edenic" period encompasses all of civilization, from agriculture to industrial development.*
- Most previous interglacial periods of the Pleistocene lasted just about 10,000 years.
- Thus, we should be overdue for another onslaught of glaciers covering North America, with sea levels dropping 400 feet, connecting Alaska and Australia once again to Asia and England to the Continent.
- That we are not is likely due to humanity's release of vast amounts of CO_2 into the atmosphere, 100 times more than volcanoes do naturally, and at a rate far outstripping the ability of weathering to compensate for.
- Instead, we face not another Ice Age, but global warming to levels not seen since the End-Triassic extinction 200 million years ago.

Are we in the "Sixth Extinction Event"?

- Since the dawn and spread of humanity natural ecosystems have been dramatically altered, driven by hunting, agriculture, and, more recently by industrial levels of resource extraction, industrialized fishing, etc.
- Today only 3% of mammals are considered "wildlife"; the other 97% is composed of humans and our domesticated animals.
- Trawlers have devastated coral reefs and removed some 90% of the top predators from the oceans.
- Much of the Pleistocene megafauna of North America is gone, including indigenous camels, tigers, giant sloths, etc.

Are we in the "Sixth Extinction Event"?

- Consider these facts:
  - In the past 400 years there have been only 800 documented species driven to extinction.
  - Given some 1.9 million species known, this is 0.042%. Compare this to the End-Permian Extinction of 96%
  - Extinction events are not due to one cause only. They are the result of the Earth's environment being stressed by multiple factors and then pushed over some tipping point by one trigger, leading to a cascade of events.
  - We haven't reached that yet. But we seem to be on our way. The environment is stressed, and it wouldn't take much of an event to drive it over any one of many tipping points.
    - For one example, if we burn all our carbon reserves in the next hundred years or so we'd raise the temperature by 12 degrees, quite similar to the trigger for the End-Permian event.

What does the future hold?

- Cheer up! No matter what we do short of sterilizing the Earth, in 10,000 years or so dead sea life with $CaCO_3$ on the ocean floor will dissolve and like an antacid tablet restore the ocean pH and allow more CO_2 to dissolve into the seas.
- Erosion will take up most of the remaining extra CO_2, though this will take about 100,000 years.
- According to Milankovitch cycles we're due for another ice age in 50,000 years, if enough CO_2 has been removed by then. If not, the next chance for an ice age would be 400,000 years from now.

The Last Extinction: The End of Life on Earth

- The ever-brightening sun will continue to increase the hydrological cycle and increase weathering. Millions of years from today, Binding of CO_2 by weathering will draw down the atmospheric CO_2 to levels below where plants can survive.
- Without plants, O_2 levels will decline, and animals will die off. Without life in the seas the binding of CO_2 into sea-floor carbonates will cease, and the source of renewed CO_2 from volcanism will fail.
- The sun will continue to get hotter and hotter, eventually leading to a barren planet populated only by prokaryotes, as it was in the beginning.
- Ultimately it will become too hot even for the prokaryotes, and the final extinction will have ended, leaving a lifeless planet to eventually be consumed by the sun as it expands, in perhaps a billion years.