Origins and extinctions

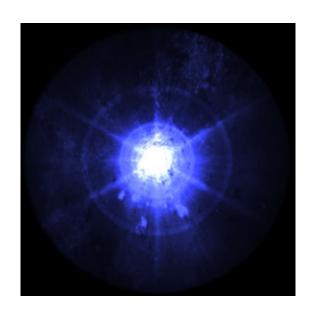
Michael J. Benton (University of Bristol)

Bright Horizons 10

Sunday, October 2nd, 2011

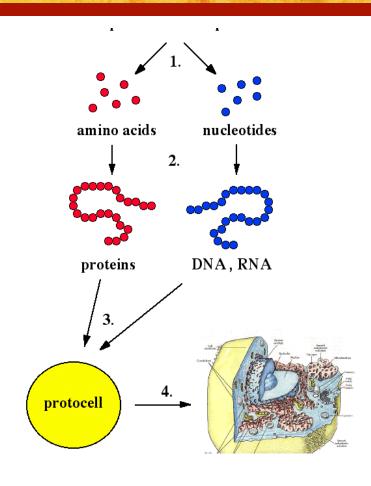
History of Life on Earth

- The origin of life, followed by a whirlwind tour of the past 4.6 billion years of history.
- The Universe came into being about 15 billion years ago, with the sudden appearance of all the matter and energy in the Universe as a single very hot and dense point: the Big Bang.
- What came before is a matter of complete speculation.
- Can we identify 10 key stages from nonlife to modern life?



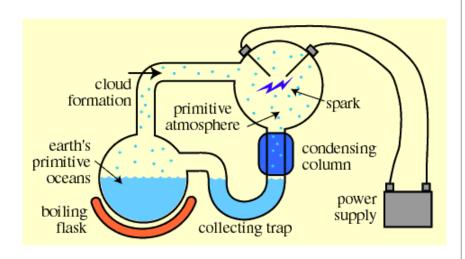
Origin of Life

- We don't know how life originated.
- Probably arose on Earth, but an alternate theory (panspermia) suggests it arose elsewhere and drifted through space to seed the Earth – little evidence
- What does life need? A way of harnessing energy to do useful work, a way of storing and reproducing genetic information, a way to keep the inside separated from the outside.
- Which of these arose first is a matter of debate.



Formation of Organic Molecules

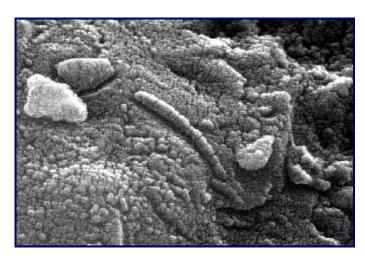
- Fairly complex organic molecules will form spontaneously under conditions that existed on the primitive Earth. Energy input from the Sun, volcanoes, or lightning.
- Can produce amino acids, nitrogenous bases, fatty acids, sugars—all the building blocks of macromolecules. Plus a lot of others.
- Organic molecules are common in comets and certain asteroids does this mean there's life elsewhere in the Universe?



Age of the Bacteria

- Prokaryotes dominated the Earth for most of its history. Multicellular eukaryotes are less than 1 billion years old.
- Prokaryotic fossils are very small, and consist mainly of fossilized cell walls. Some structures formed by mats of bacteria are found today and also fossilized from 2 billion years ago. The cyanobacteria (blue-green algae) form cell walls that fossilize nicely.
- Oldest traces of life: 3.5 3.8 billion years old. Very few rocks available of this age or older.
- Bacteria can live under a much wider variety of conditions than eukaryotes. They use many different sources of energy and carbon, and can grow at very high temperatures, high pressures, acidic conditions, etc. Large eukaryotes need much more stable conditions to survive.





The Onset of Oxygen

- The atmosphere of the primitive Earth was probably like that of Mars today: nitrogen, carbon dioxide, water vapour, but no free oxygen.
- Oxygen comes from photosynthesis, in which hydrogen is removed from water, leaving oxygen gas.
 Cyanobacteria created the oxygen in the atmosphere.
 Today, green plants and the cyanobacteria do this.
- About 2 billion years ago, the oxygen level in the atmosphere started to rise. We can detect this geologically: layers of iron oxide on the bottoms of oceans stopped forming when oxygen appeared.
- Many bacteria are poisoned by oxygen. They died out or found anaerobic niches. Aerobic metabolism, much more efficient than anaerobic, became possible.
- This event marks the onset of the Proterozoic Eon and the end of the Archaean Eon.

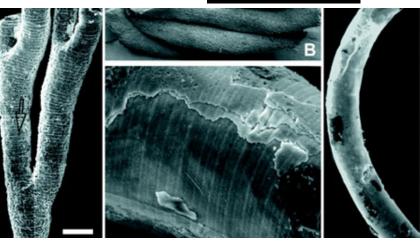


Banded iron formations (BIFs)

Rise of the Eukaryotes

- The Proterozoic Eon, starting with the appearance of an oxygenic atmosphere about 2 billion years ago, and ending with the Cambrian Explosion about 540 million years ago, was dominated by small, soft-bodied eukaryotes. Some were unicellular, others multicellular.
- Bacteria were still very common, and continue to the present.
- Eukaryotic fossil cells are identified by their size and surface appearance—they look like present day cells. Proterozoic fossils include algae (seaweeds), protists (single celled eukaryotes), and simple animals.





Ediacaran Life

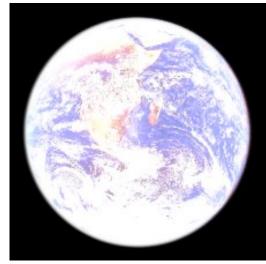
- Also known as the "Vendian". The Ediacaran Period (630-540 Mya) is the last part of the Proterozoic Eon, just before the Cambrian explosion. A worldwide proliferation of multicellular organisms whose form seems unlike anything alive afterwards
- Flat, segmented forms.

 Maybe ancestral to jellyfish and worms? Or soft-bodied arthropods? Or an extinct kingdom of life?
- Few or none survived into the Paleozoic Era.



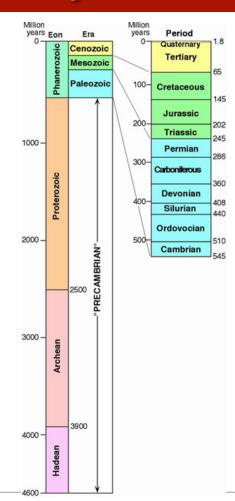
Snowball Earth

- A theory, not accepted by all scientists:
- Near the end of the Proterozoic, 550 million years ago, the Earth suffered a massive Ice Age. Glaciers covered all, or nearly all, the Earth, including tropics.
- The freeze lasted several million years. Ice reflects sunlight, keeping the Earth cold. It ended due to the greenhouse effect: carbon dioxide from volcanoes built up in the atmosphere, trapping the Sun's warmth and slowly raising the Earth's temperature.
- This caused a mass extinction, possibly killing off most Ediacaran forms and leading to the Cambrian explosion of new life forms.
- There is indeed strong evidence for glaciation cross the Equator... but could the whole Earth freeze over?



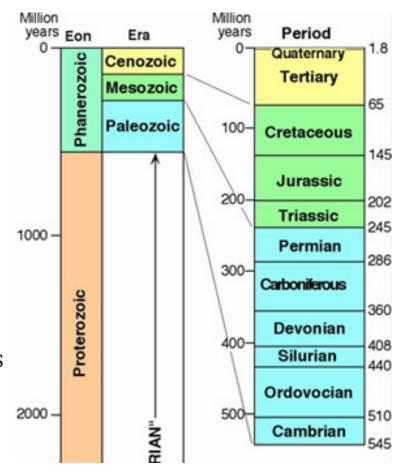
Our Story So Far

- We have come 5/6 of the way through the history of the Earth.
- Earth forms 4.6 billion years ago
- Solid surface forms 4 billion years ago
- Life starts (?) 3.8 billion years ago
- Age of Bacteria
- Oxygen atmosphere develops 2 billion years ago.
- Eukaryotes evolve.
- Ediacaran life: 630 million years ago. First multicellular life, forms unknown today



The Phanerozoic

- The last 545 Myr are the Phanerozoic, the time of 'abundant life'
- The Phanerozoic Eon is subdivided into 11 geological periods, from the Cambrian to the Quaternary
- These periods fall into three eras, Paleozoic, Mesozoic, and Cenozoic, respectively 'ancient', 'middle', and 'recent' life
- The pre-Phanerozoic time had always been seen as mysterious until the last 50 years or so of research into the Precambrian Eon



Cambrian Explosion

- About 540 million years ago, there was a sudden appearance of large numbers of multicellular organisms in the fossil record. Rocks older than this appear devoid of fossils (because they are too small to see, and because the multicellular organisms didn't have hard parts to preserve.
- This sudden appearance of fossils is called the Cambrian explosion. Most of the higher level taxa present today appeared at this time.
- Cause: probably triggered by a mass extinction, and origin of skeletons.

Burgess Shale faunas -->

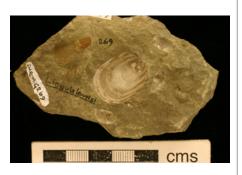


Cambrian Life

- Sea floors dominated by trilobites, sponges, hyolithids, inarticulate brachiopods, and other weird forms
- Total global diversity quite low
- No life on land

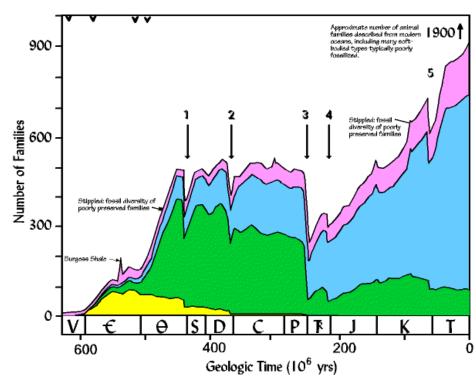






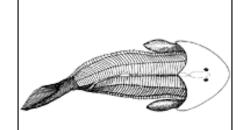
Cambrian/Ordovician

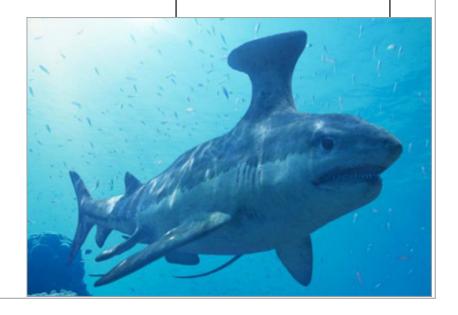
- Jack Sepkoski's famous plot of marine animal diversification over the past 600 Myr (i.e. Ediacaran to present-day)
- Shows Cambrian faunas, then rise to Ordovician faunas, and Paleozoic plateau
- Is this pattern real or an artifact of being a record of families, not species, through time?
- Note the 'big five' mass extinctions



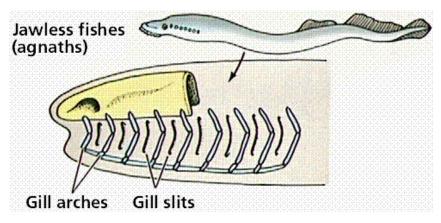
Paleozoic Era

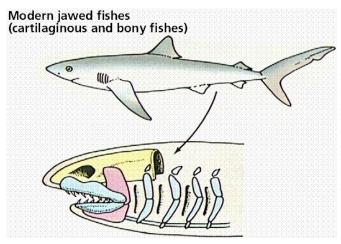
- The Paleozoic starts with the Cambrian explosion 540 million years ago, and ends with the Permian mass extinction, 250 million years ago.
- Several mass extinctions mark boundaries within the Paleozoic.
- Early Paleozoic dominated by marine invertebrates.
- Appearance and evolution of fish during the Silurian and Devonian. Jaws developed, then bones.

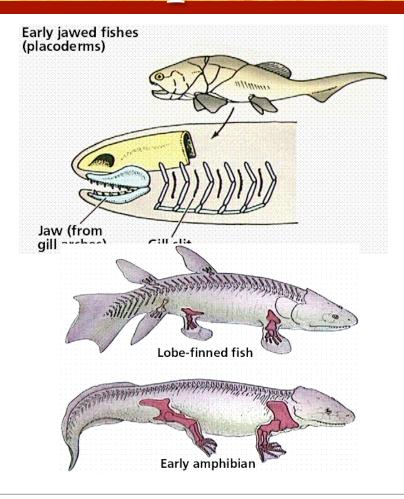




Fish and Amphibians







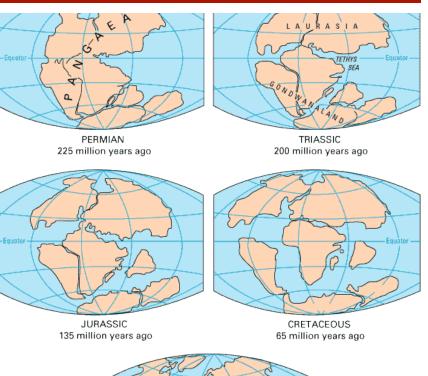
Terrestrialization

- Life invaded the land in the Ordovician and Silurian. First plants (which needed to evolve the ability to stand upright and transport nutrients against gravity), then arthropods (insects, etc.) and vertebrates.
- First amphibians in the Late Devonian, first reptiles in the Mid Carboniferous, and reptiles rose to dominance in the Permian
- At the end of the Paleozoic, the continents were joined into a single land mass, Pangaea.

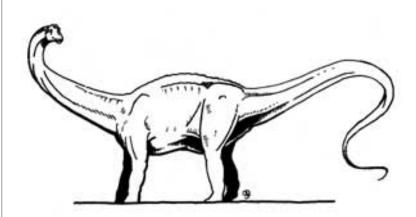


Mesozoic Era

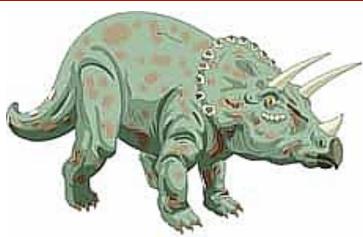
- Lasted from 250 million years ago until 65 million years ago, ending with an asteroid impact in the Yucatan peninsula of Mexico.
- Age of the dinosaurs, reptiles that were the largest animals on land and in the sea during this period.
- Fragmentation of Pangaea into many continents allowed speciation to occur in many different habitats.
- Flowering plants, birds, and mammals appear.



The Age of Dinosaurs



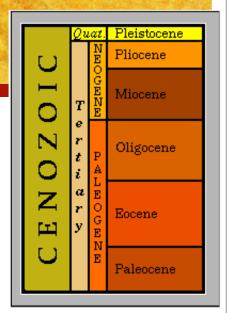


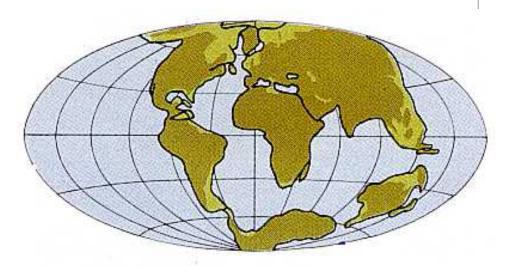




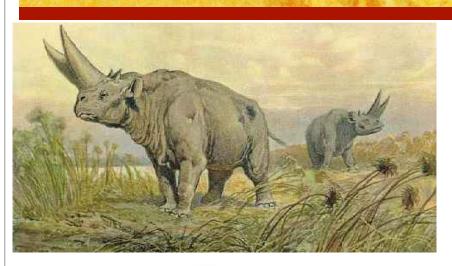
Cenozoic Era

- Started 65 million years ago, continues to present.
- Mammals become the dominant life form on land. An adaptive radiation that took advantage of the sudden loss of dinosaurs.
- Another large group evolves: the grasses.
- Adaptive radiation of birds and flowering plants,
- Geologically, continents that had been separated started to collide: Africa with Europe, North America with South America, India with Asia





Cenozoic Life



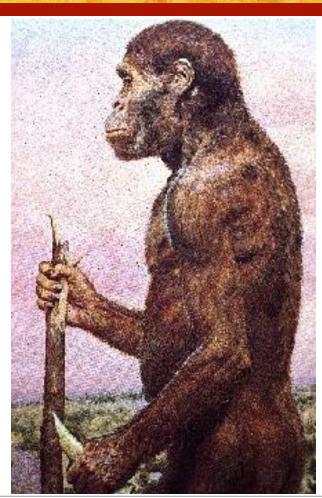




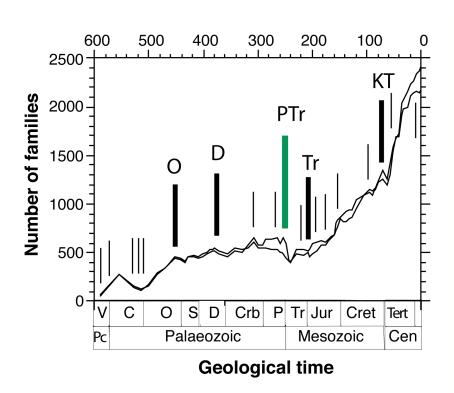


Origin of humans

- Split of humans from chimps maybe 7 Myr ago
- Oldest human is Sahelanthropus from Chad
- First 5-6 Myr of human evolution happened in Africa
- Most famous precursor form is Australopithecus
- Escape out of Africa for *Homo* erectus about 1 Myr ago, and later for *Homo sapiens* about 150,000 years ago

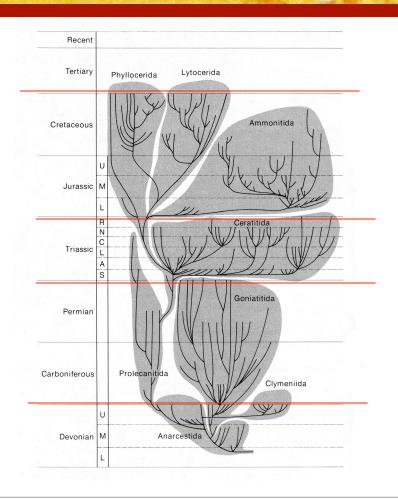


Extinction events



- Many times of high extinction rate through the past 500 Myr of the history of life
- Sometimes show high turnover (high extinction and high origination rates)
- Most such extinctions are regionally or ecologically restricted

Background extinction



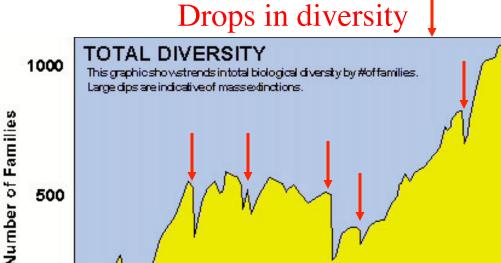
- Extinction is a normal part of evolution
- In the evolution of the ammonites, extinction was happening all the time
- Mass extinctions (red lines) punctuate the overall pattern
- But mass extinctions account for only 10% of extinction through geological time

Defining mass extinctions

600

- 1. Loss of many species;
- 2. Loss of forms of diverse ecology;
- 3. Rapid geologically;
- 4. High extinction rate.

Smaller events are called 'extinction events'



Millions of Years Adapted from Sepkoski, Jr J.J. Paleobiology 19, no.1 (1993)

Geologic Time

Mass extinctions

- 1. Background extinction
- 2. Extinction events
- 3. Mass extinctions

 End-Ordovician 	445 Mya
------------------------------------	---------

- Late Devonian 367 Mya
- End-Permian 252 Mya
- End-Triassic 200 Mya
- KT (Cretaceous/ Tertiary) 65 Mya

Scaling

	famili	es species
•End-Ordovician	-12%	-50%
•Late Devonian	-14%	-50%
•End-Permian	-52%	-80-96%
•End-Triassic	-12%	-50%
•KT (Cretaceous/ Tertiary)	-11%	-50%

•Species extinction rates must be higher than family rates because there are typically 10-100 species per family

The big five/ six (0)



- Possible end Precambrian event loss of Ediacaran
 animals
- At least four major extinctions occurred during the Cambrian (542-488 Myr ago)
- Severely affected trilobites, brachiopods, and conodonts

The big five (1)

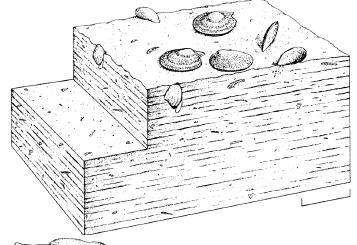


- The **end-Ordovician** mass extinction (445 Myr ago)
- Disappearance of one third of all brachiopod and bryozoan families, as well as numerous groups of conodonts, trilobites, and graptolites
- Much of the reef-building fauna was also decimated.
- Maybe caused by southern glaciation and lowering of sea levels



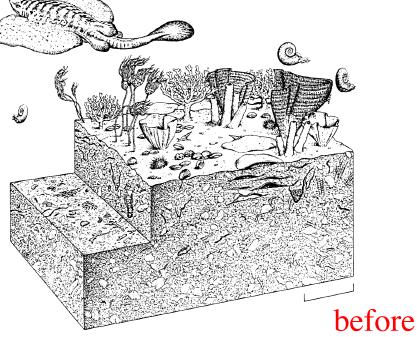
The big five (2)

- The **Late Devonian** mass extinction (367 Myr ago)
- Little impact on life on land
- 70% of marine families died out major reef-builders including stromatoporoids, and rugose and tabulate corals, were devastated
- Other groups severely affected, including armoured fishes
- Maybe related to sea level change/ anoxia



The big five (3)

after



- Permo-Triassic mass extinction, 252 Myr ago
- Massive losses at global and regional scales
- Switch from rich reef faunas before to depauperate fauna after
- Switch from bioclastic limestone to black shale
- Ecological collapse
- Cosmopolitanism

MEISHAN BOUNDARY REDS

ORGANIC-RICH, LAMINATED SHALE. Clarata. COMMON.

MARLY MICRITES ALTERNATING WITH THIN ORGANIC-RICH LAMINATED SHALES

MASSIVE MICRITE WITH OCCASIONAL THIN LAMINAE OF CALCSILTITE, SCATTERED PYRITE.

5CM OF DARK SHALE CAPPED BY A THIN, PYRITIC, PRISMATIC CALCUTE LAYER.

MICRITE/WACKESTONE WITH LOW DENSITY BRACHIOPOD FAUNA AND DIFFUSE Planaties BURROWS.

7 CM BOUNDARY CLAY, DARK MICACEOUS MARI, WITH "Oloceras", Clargia AND PERMIAN BRACHIOPODS.

5 CM BOUNDARY CLAY, PYRIDIC BASAL CONTACT, PERMIA FORAMS AND CONODON'S.

ORGANIC-RICH MARLY MICRITIE GRADES UP TO MASSIVE PACKSTONE OF FINE SHELL HASH OF BRACHIOPODS AND FUSULINIDS. OCCASIONAL CHERT NODULES.

PACKSTONE, ABUNDANT FORAMS (INCLUDING PUSULE BUILDING AND BRACHROPODS,

Wignall et al. 1993, Hist. Biol.

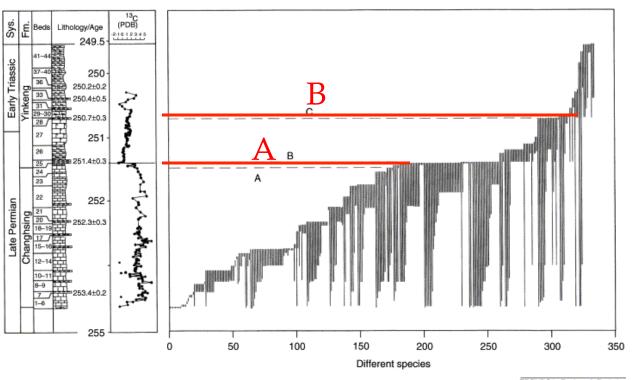
TRIASSIC

The boundary -Meishan

- Fossiliferous marine carbonates in uppermost Permian
- Sudden appearance of dark marls in lowest Triassic; pyrite
- Limited fossils

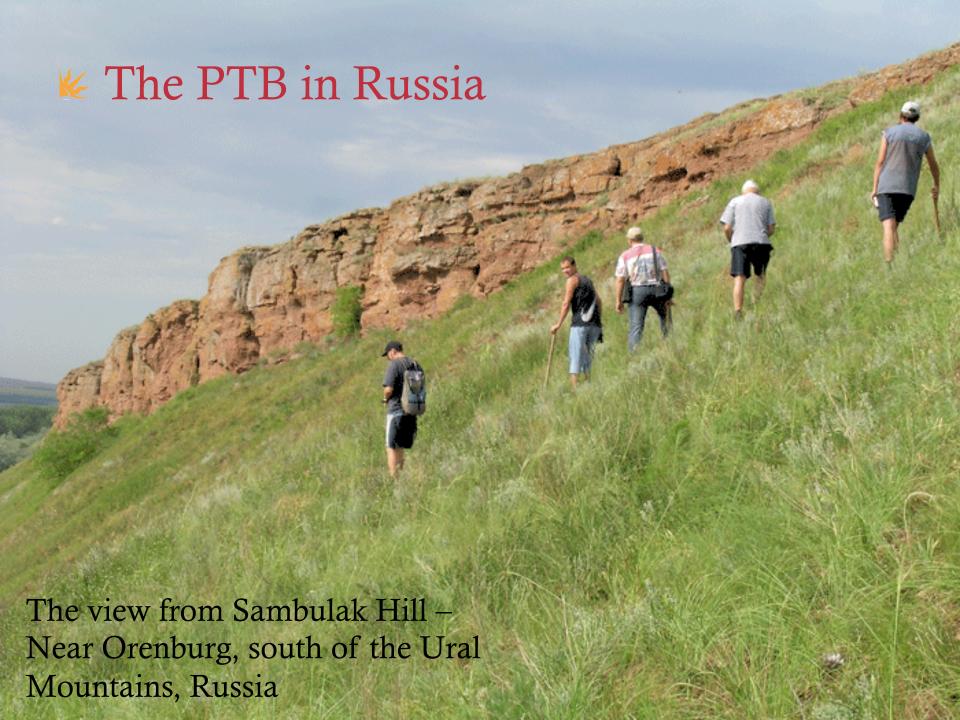


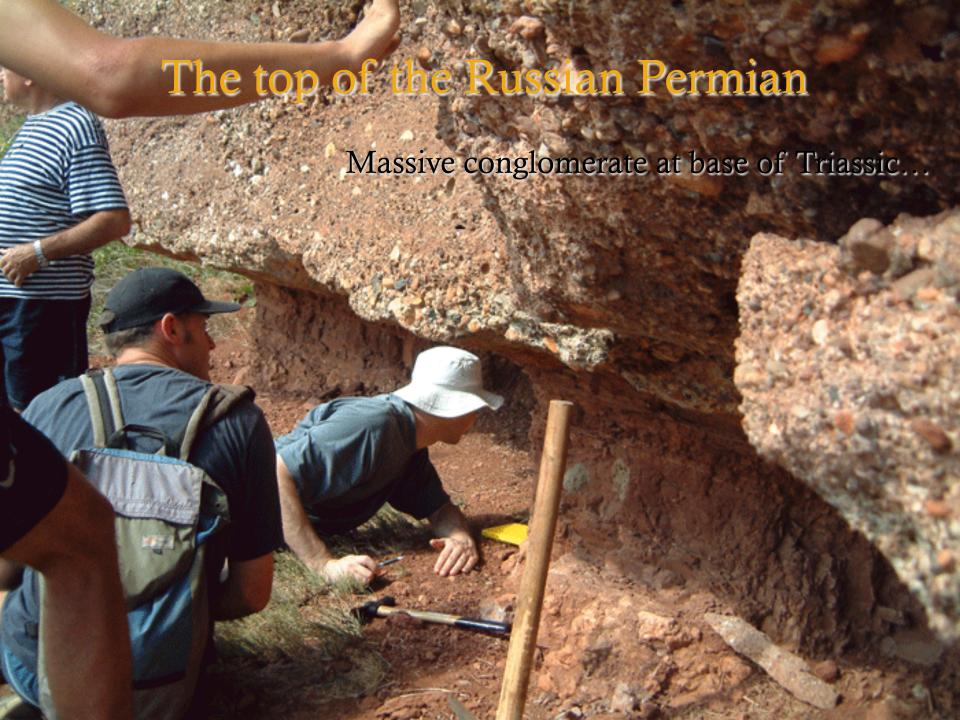
Permo-Triassic mass extinction in China

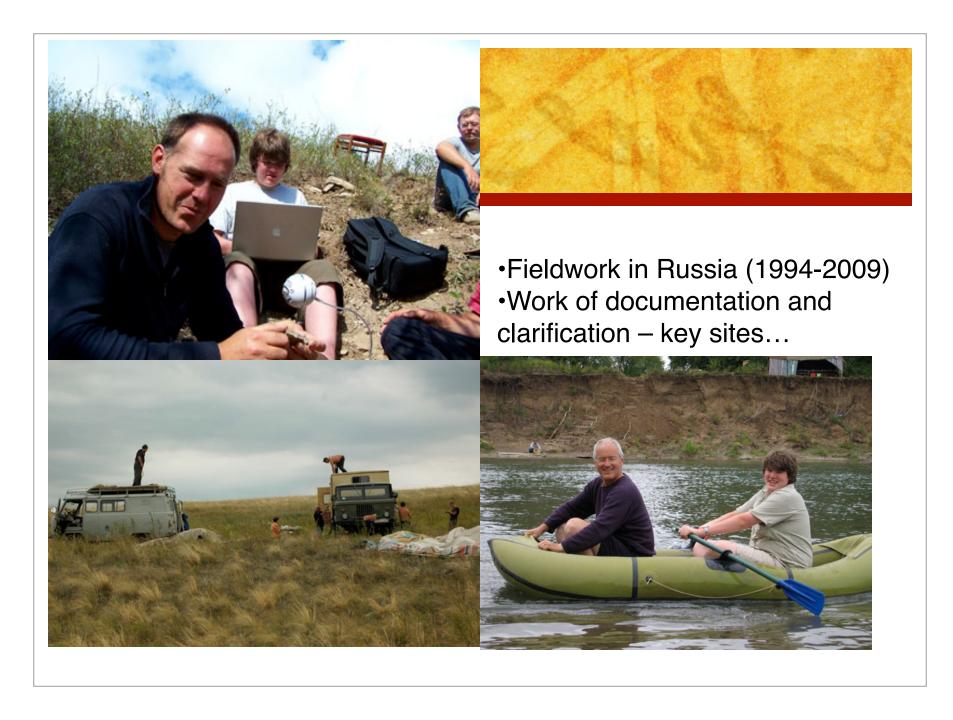


- One major extinction level (A): loss of 90% of species
- Later level (B): loss of 5% of disaster species Jin *et al.* (2000) *Science*
- •Two levels are spaced about 500,000 y apart

TRENDS in Ecology & Evalution







Kotel'nich 1



 Hundreds of complete skeletons of the pareiasaur Deltavjatia have been found, each preserved (upright) in scours on top of a paleosol



Kotel'nich 2

First fossils found in the 1930s, and serious, industrial-scale excavation in the 1950s
The fauna included dicynodonts and other tetrapods, and was equated with the Karoo Cistecephalus Zone on shared taxa

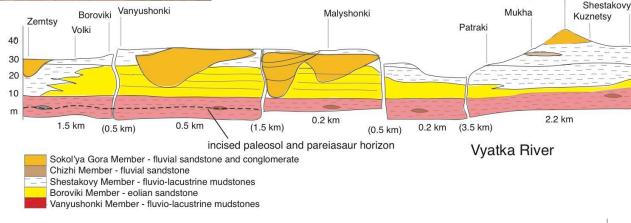


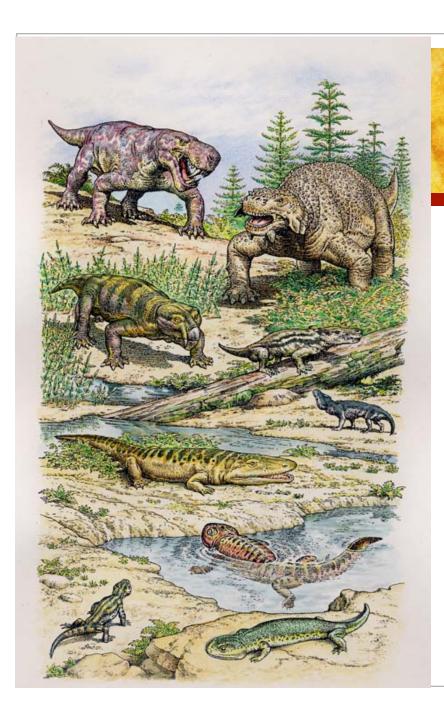


Kotel'nich 3

Agafonovo

Most beautiful outcrops
Rich faunas; clearly not terminal Permian, but what age?

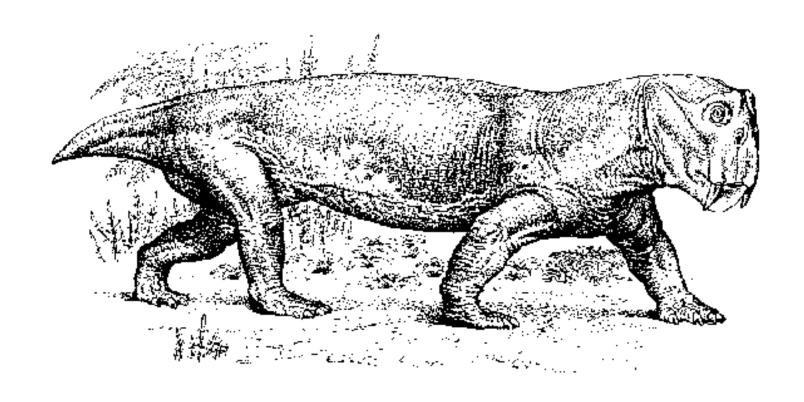


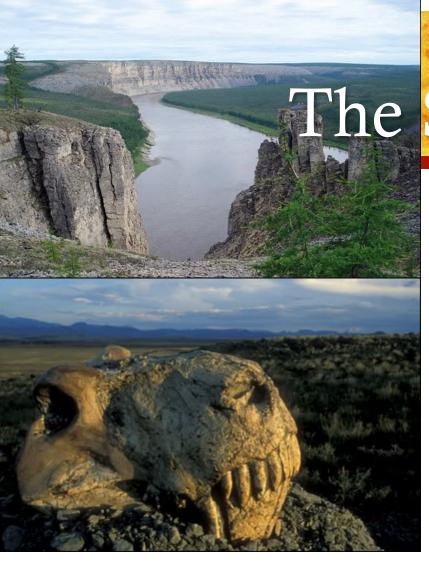


Before: rich faunas on land

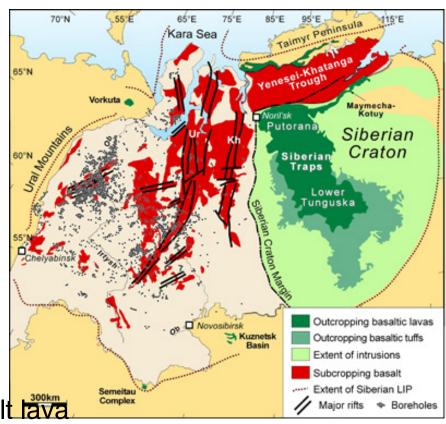
- The scene in the Late Permian of Russia
- Diverse amphibians and reptiles
- Complex food webs
- Top carnivores

After: Lystrosaurus





The Siberian Traps



Up to 1.3 million cubic km of basalt lava

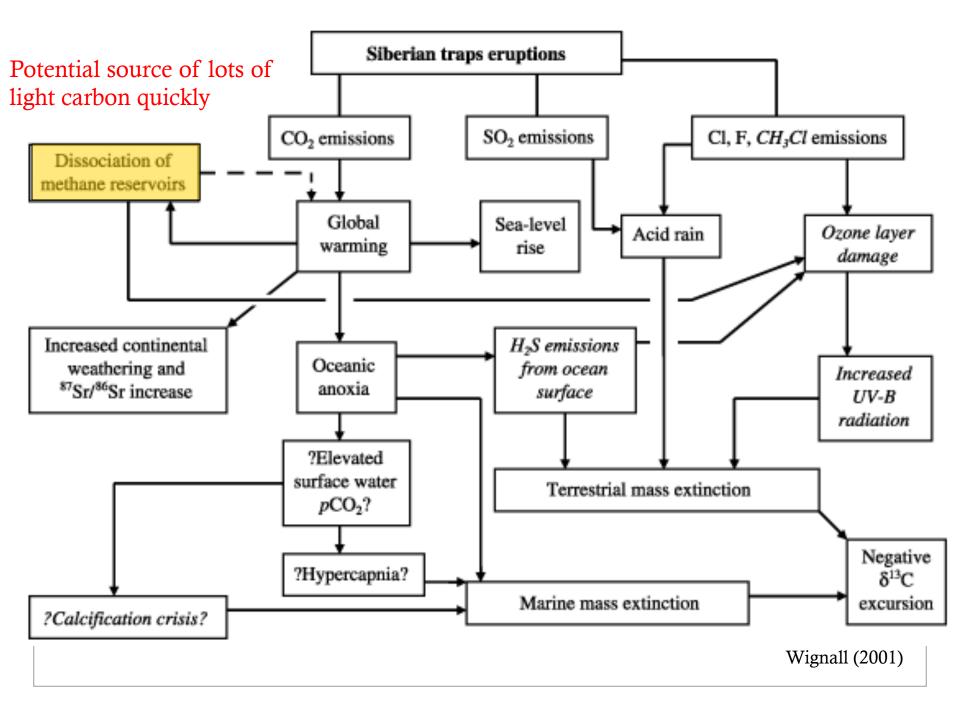
• Erupted for < 2 Myr; source of CO₂, etc.

Reichow et al. 2009, EPSL

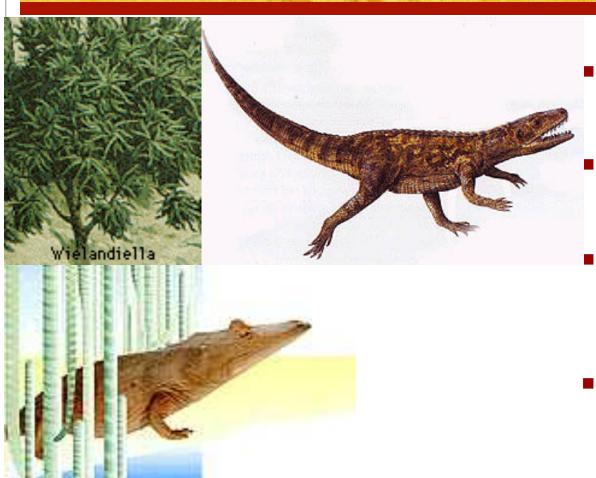
Piecing together the evidence



- 1. Anoxia worldwide = ocean stagnation
- 2. Oxygen isotopes show global warming of 5°C or more
- 3. Huge influx of carbon-12 ('light') isotope
- 4. Terrestrial settings show massive erosion probably from death of plants = aridity, and perhaps acid rain
- 5. Mutated spores indicate ozone hole
- 6. Organisms on land and in the sea suffer a massive extinction over 500,000 y
- 7. This is followed by c. 5 my of grim conditions for life
- 8. Massive basalt eruptions in Siberia
- 9. Limited evidence for impact



The big five (4)



- The **end-Triassic** event (200 Myr) affected life in the sea more than on land
- Loss of conodonts, many families of brachiopods, ammonoids, bivalves
- Earlier event (end-Carnian), some 25 Myr before, saw major turnover on land
- Driven by CAMP volcanism (-> acid rain, ocean stagnation)



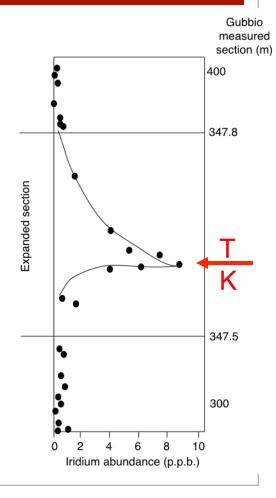


- The Cretaceous-Tertiary (KT) event (65 Myr ago) is the most famous, but not the biggest, mass extinction
- Life in the sea (foraminifera, rudist bivalves, ammonites, belemnites, marine reptiles) suffered...
- ...as did life on land (dinosaurs, pterosaurs, some marsupials)
- Almost certainly linked to the Chicxulub impact

Evidence for impact

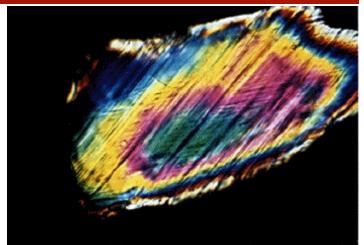


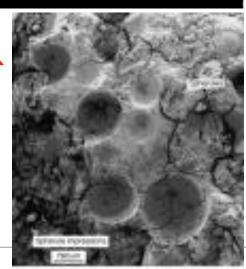
- Alvarez *et al.* (1980) reported KT boundary sections at Gubbio, Italy and Stevns Klint, Denmark
- Iridium spike iridium generally comes from extraterrestrial sources, so can act as geochronometer
- Either unusual concentration, or massive impact



Evidence for impact

- 1. Iridium anomaly
- 2. Shocked quartz
- 3. Stishovite
- 4. Glassy spherules
- 5. Similarity of ratios of elements in boundary clays to chondrites
- 6. Isotopic changes in C and O
- 7. Presence of <u>clays</u> in so many sections
- 8. Abrupt shifts in some pollen ratios
- 9. Abrupt plankton extinctions
- Chicxulub crater, Yucatán Peninsula, Mexico





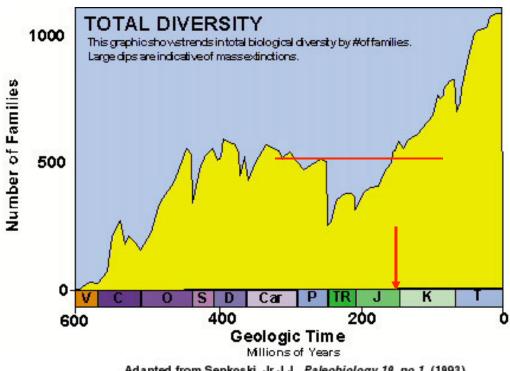


Impact

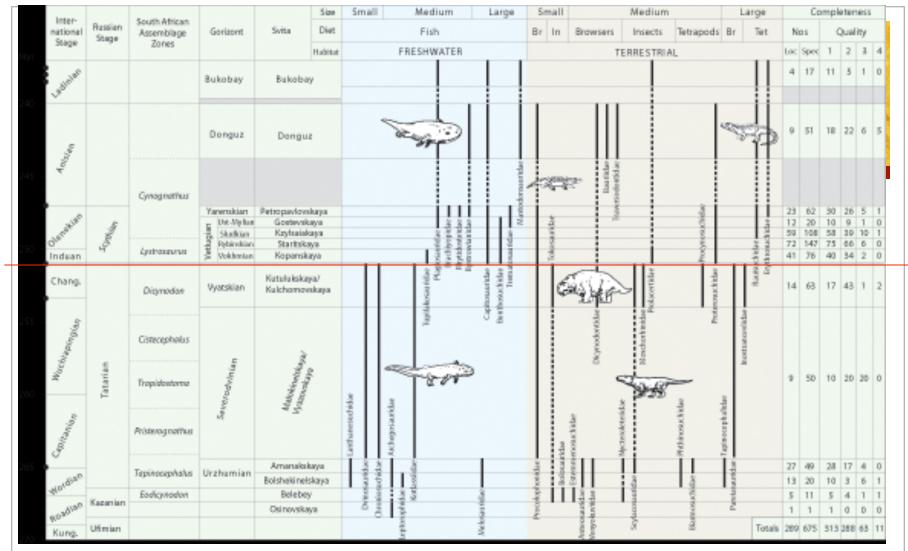
- •There was a massive impact 65 Myr ago
- •This coincided with the extinction of the dinosaurs, and other groups
- •But was this the sole cause? - also the Deccan Traps volcanic eruptions
- •Impact -> masses of dust -> blacking out of Sun -> freezing and end of photosynthesis

Recovery

 At global level, recovery of family diversity took 100 myr, until the end of the Jurassic - a return to some 500 families Very slow because the 50% of families that survived the event had all been hugely depleted



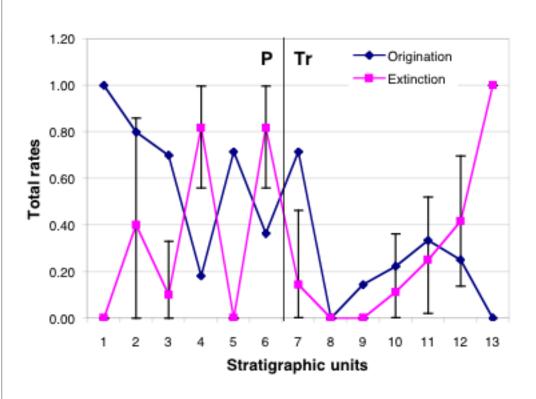
Adapted from Sepkoski, Jr J.J. Paleobiology 19, no.1 (1993)



Turnover of tetrapods across the PTB

(Benton et al., 2004 Nature, 432, 97-100)

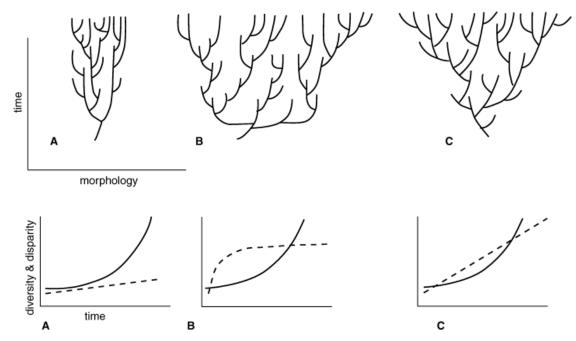
Recovery 3



- Tetrapod diversity in Russia is volatile throughout
- Major change is switch from highly volatile faunas in the Late Permian to low rates of O and E in the Early Triassic
- Origination in particular is depressed after the PTB
- But no full recovery even15-20 myr after the PTB

(Benton et al., 2004 Nature, 432, 97-100)

Diversity and disparity



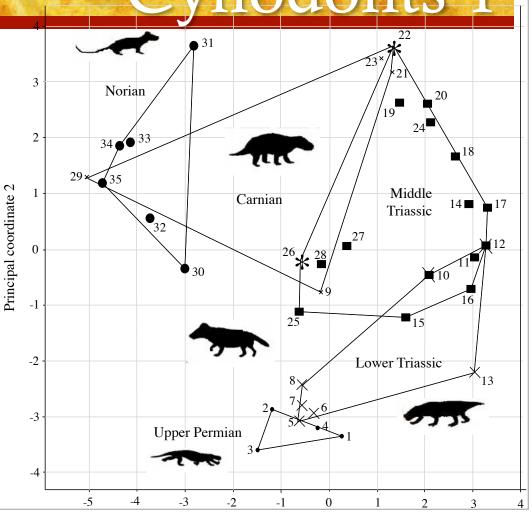
- •Diversity (species richness; solid line) and disparity (morphological variance; dashed line) are generally decoupled
- •Commonly morphospace is explored rapidly (disparity rises) and then lineage diversification occurs (diversity rises) option B

Cynodonts

 Occupation of morphospace (based on discrete morphological characters) is intriguing – shows an expansion, and a migration

 The migration means nothing – cannot be equated to any changes in broad character types

[Mitchell et al. 2011]



Principal coordinate 1

Cynodonts 2

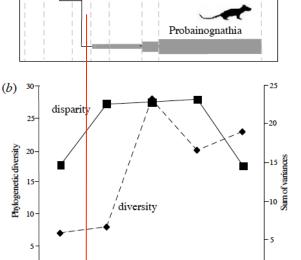
Basal cynodonts

Myr 252.6 245.9

PERMIAN

(a)

- Cynodonts arose in the latest Permian, but expanded only in the Triassic (include ancestors of mammals)
- Slow expansion in the Early Triassic, then rapid expansion afterwards
- Disparity rises first, diversity second



Geological Time

Norian

Cynognathia

Norian

TRIASSIC

Epicynodontia

[Mitchell et al. 2011]

Summary

- Origins and extinctions detected throughout the history of life
- 'Stable' phases in macroevolution punctuated by mass extinctions
- Mass extinctions could be massively catastrophic loss of up to 90% of all life at end of Permian but life recovered each time
- Recovery time was proportional to intensity of extinction, but probably not a linear relationship (1-10 Myr)
- Recovery can mark a complete restructuring of ecosystems, with formerly dominant groups gone
- Order of magnitude improvement in quality of data in the past ten years (i.e. radiometric dating; fossil data)