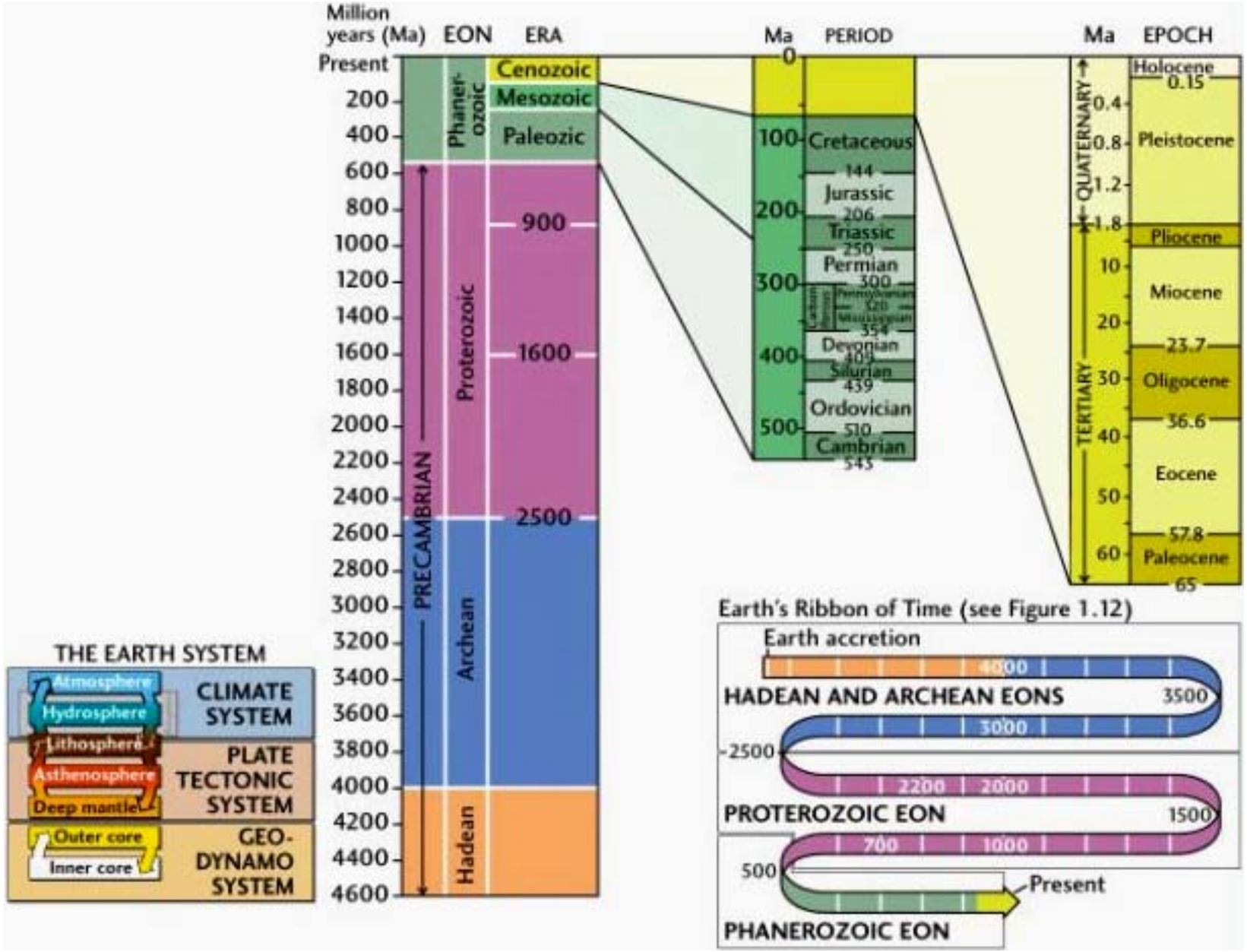
The Big Five:

Mass-extinction events during the Phanerozoic

Bas van de Schootbrugge


Million years (Ma)
EON
ERA
Present
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
4200
4400
4600
Phaner-ozoic
Proterozoic
Archean
Hadean
PRECAMBRIAN
Cenozoic
Mesozoic
Paleozic
900
1600
2500
Ma
PERIOD
0
100
200
300
400
500
Cretaceous
144
Jurassic
206
Triassic
250
Permian
300
Carbon.
Pennsylvanian
320
Mississippian
354
Devonian
409
Silurian
439
Ordovician
510
Cambrian
545
Ma
EPOCH
QUATERNARY
TERTIARY
0.4
0.8
1.2
1.8
10
20
30
40
50
60
Holocene
0.15
Pleistocene
Pliocene
Miocene
23.7
Oligocene
36.6
Eocene
57.8
Paleocene
65
THE EARTH SYSTEM
Atmosphere
Hydrosphere
CLIMATE SYSTEM
Lithosphere
Asthenosphere
Deep mantle
PLATE TECTONIC SYSTEM
Outer core
Inner core
GEO-DYNAMO SYSTEM
Earth's Ribbon of Time (see Figure 1.12)
Earth accretion
4000
HADEAN AND ARCHEAN EONS
3500
3000
2500
2200
2000
PROTEROZOIC EON
1500
700
1000
500
Present
PHANEROZOIC EON

Class outline

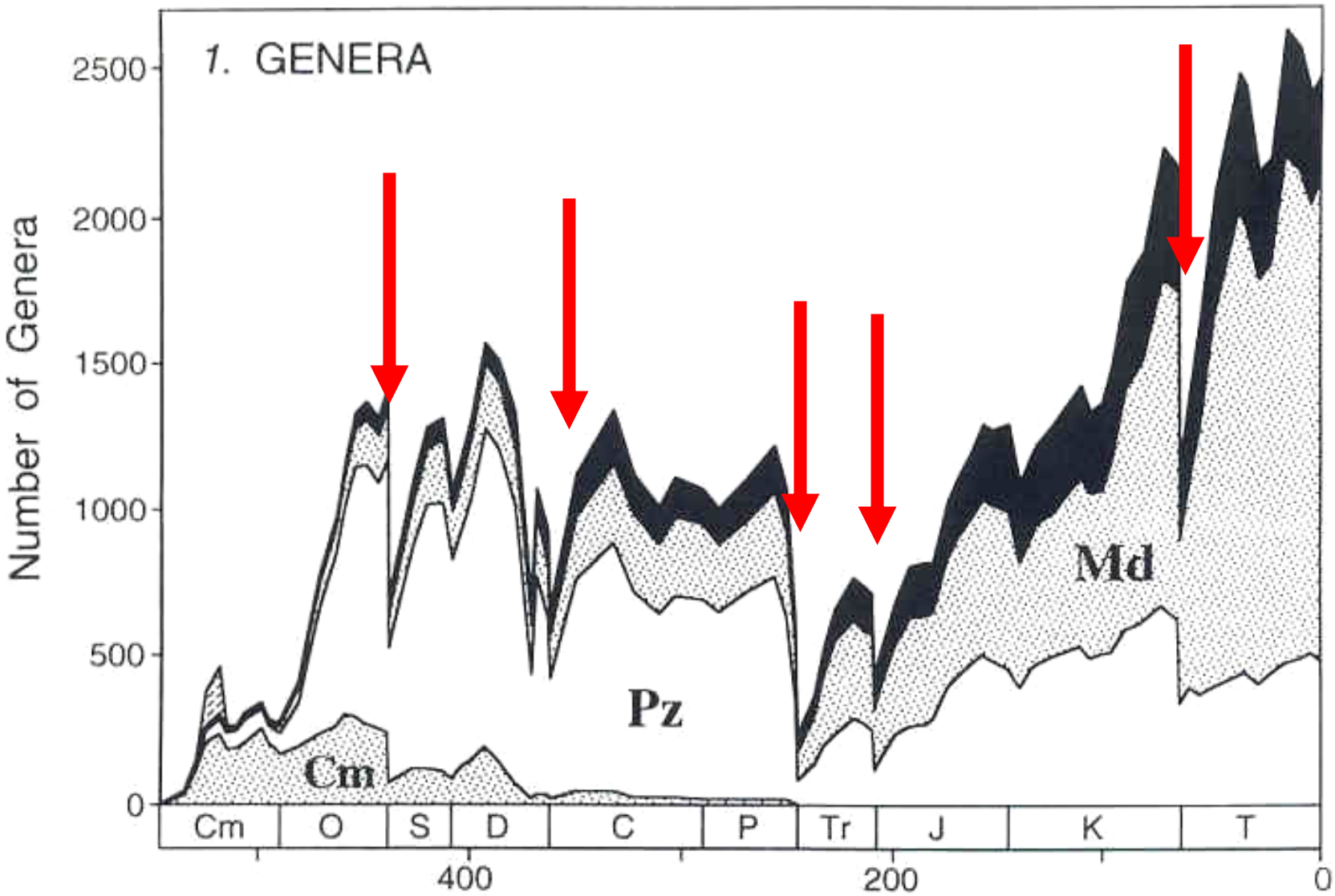
- What are mass-extinction events? - A brief history of catastrophism *vs* gradualism
- Ordovician-Silurian
- The end-Devonian - Anoxia
- Permian-Triassic boundary - Murder on the orient-express
- Triassic-Jurassic boundary - Volcanism
- Cretaceous-Tertiary boundary - Extraterrestrial impacts

The legacy of John Phillips

English paleontologist John Phillips recognized in 1860 that the fossil record of life could be divided in 3 distinct systems each with its own characteristic assemblage of animals and plants. He termed these:

Paleozoic = Old Life
Mesozoic = Middle Life
Kainozoic = Recent Life

Jack Sepkoski and the diversity of marine life



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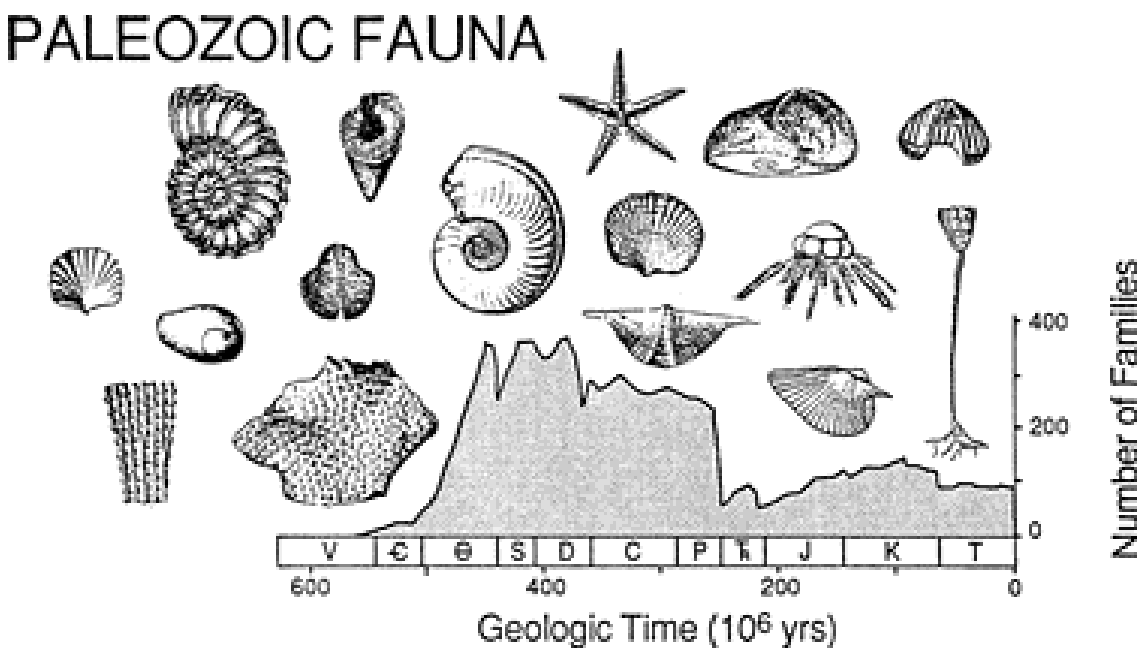
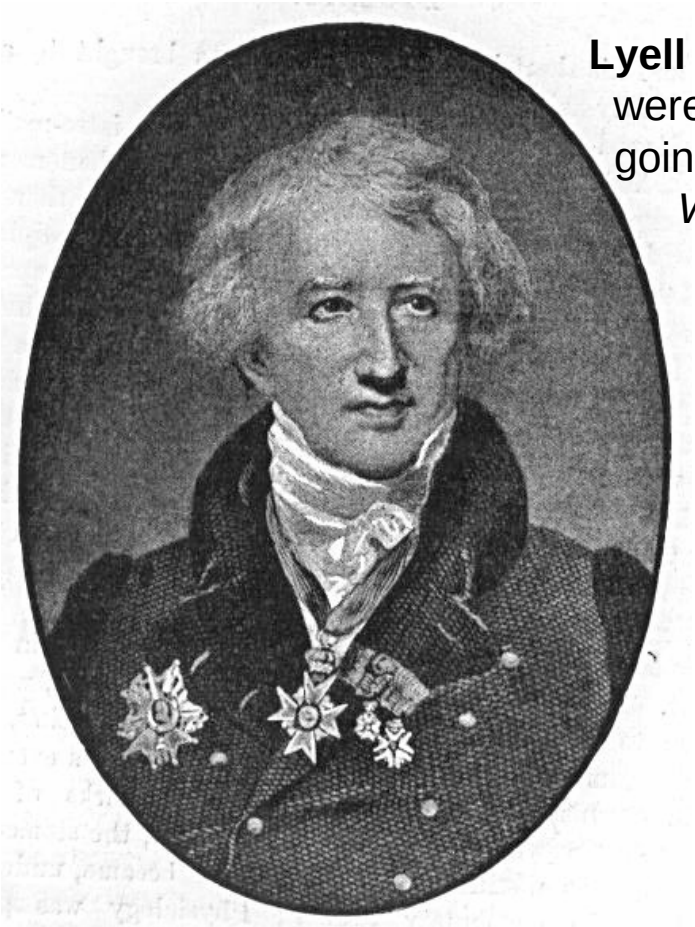


3 basic faunas:

The Cambrian Fauna
The Paleozoic Fauna
The Modern Fauna

Each characterized by a distinct assemblage of organisms

Catastrophism *vs* Uniformitarianism

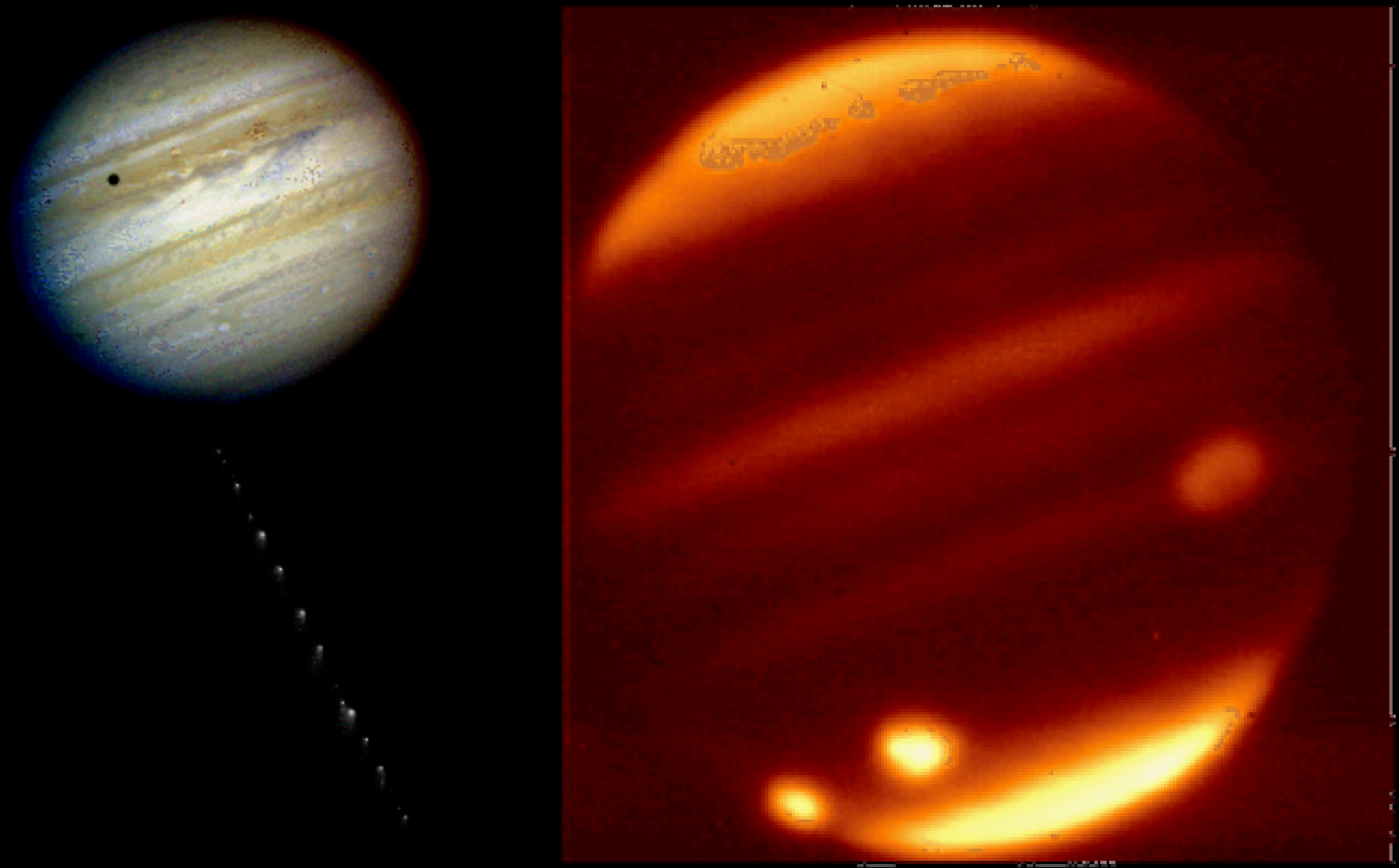


Lyell (and Hutton who wrote down the theory of Uniformitarianism) were convinced that all geological process were slow and cyclic, going on forever and ever, very much in line with Darwins ideas.
We find no vestige of a beginning - no prospect of an end.

Georges Cuvier (1769-1832) was convinced that the evolution of the Earth was dominated by large cataclysmic events

A history of catastrophism

- The big changes came with the advent of space missions and our research on the Moon.
- In 1980 Louis W. Alvarez et al. published a paper on how a meteorite impact was reponsible for the K/T extinxtion.
- In 1994 observations on the impact of the Shoemaker-Levy comet on Jupiter made people realise how devastating these events are.



Impacts of Shoemaker-Levy on Jupiter, 1994.
The biggest circle of the two is as big as the Earth

The end-Ordovician extinction

After the Cambrian radiation and crisis, life thrived during the Ordovician (some 455 million years BP). The continents were widely dispersed and each continent and shelf sea had its own endemic fauna and flora. But something changed towards the end of the stage….

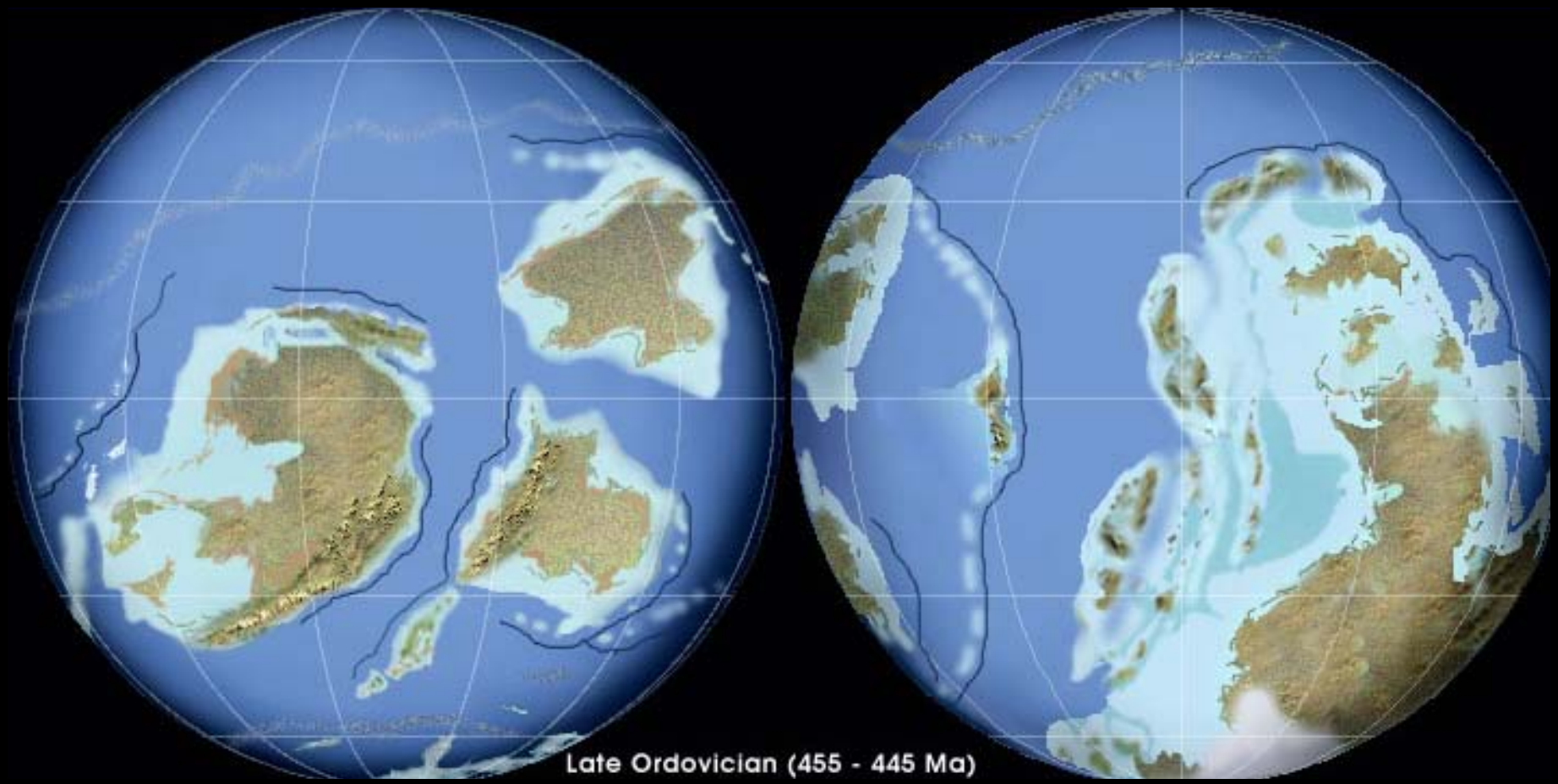


Table 1.1 Extinction intensities at the five major mass extinctions in the fossil record: species-level estimates based on a rarefaction technique

Mass extinction	Families: Observed Extinction (%)	Families: Calculated species loss (%)	Genera: Observed Extinction (%)	Genera: Calculated species loss (%)
End-Ordovician	26	84	60	85
Late Devonian	22	79	57	83
End-Permian	51	95	82	95
End-Triassic	22	79	53	80
End-Cretaceous	16	70	47	76

Source: simplified from Jablonski (1994).

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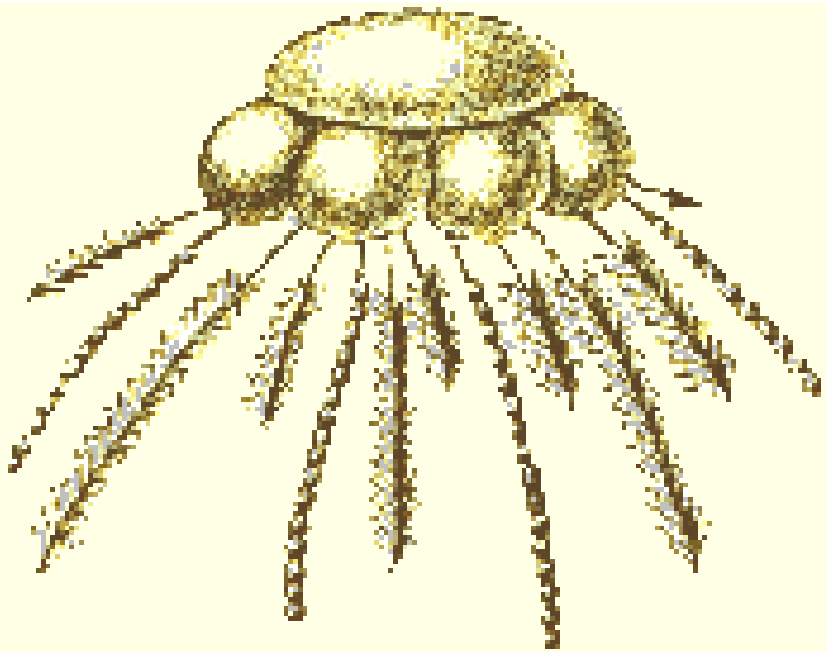
The Big Losers - Graptolites

These very useful biostratigraphic marker fossils suffered a severe extinction at the close of the Ordovician with almost all species disappearing. The extinction was followed by an extremely rapid recovery during the Early Silurian.

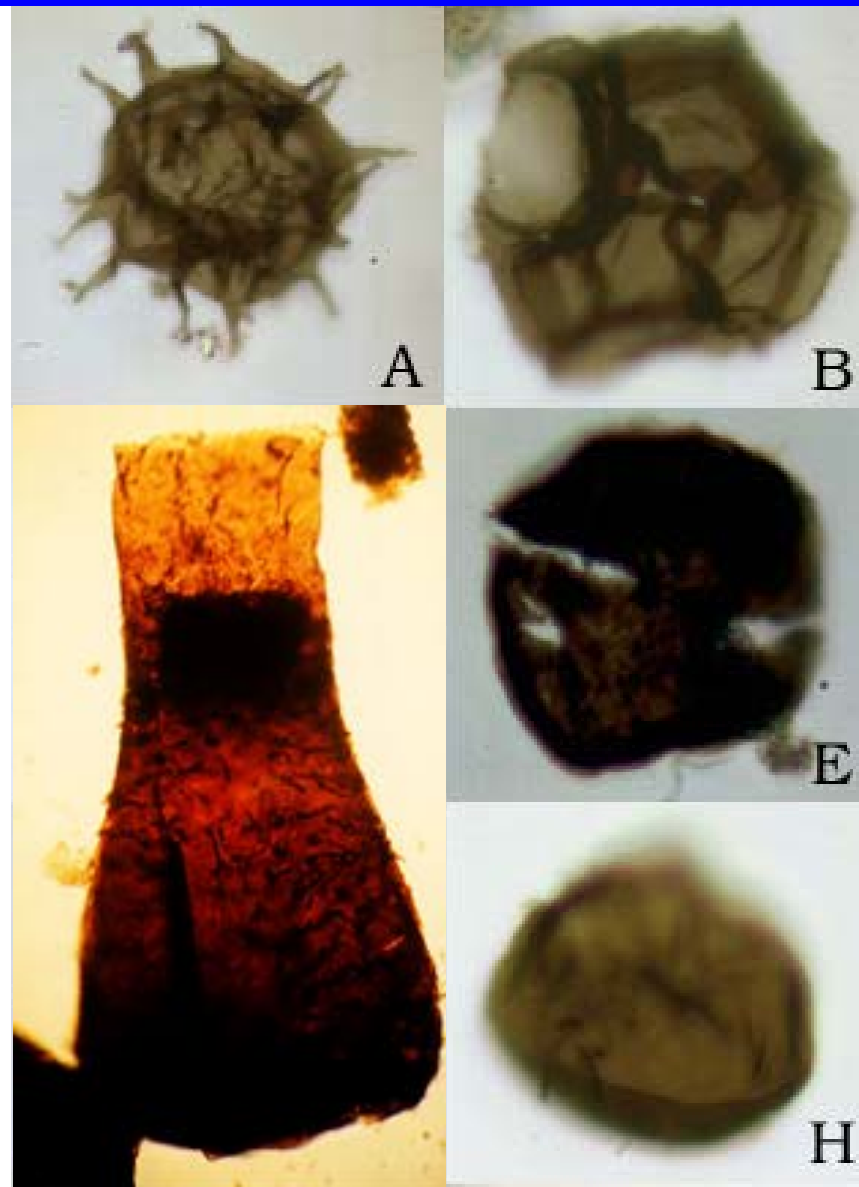


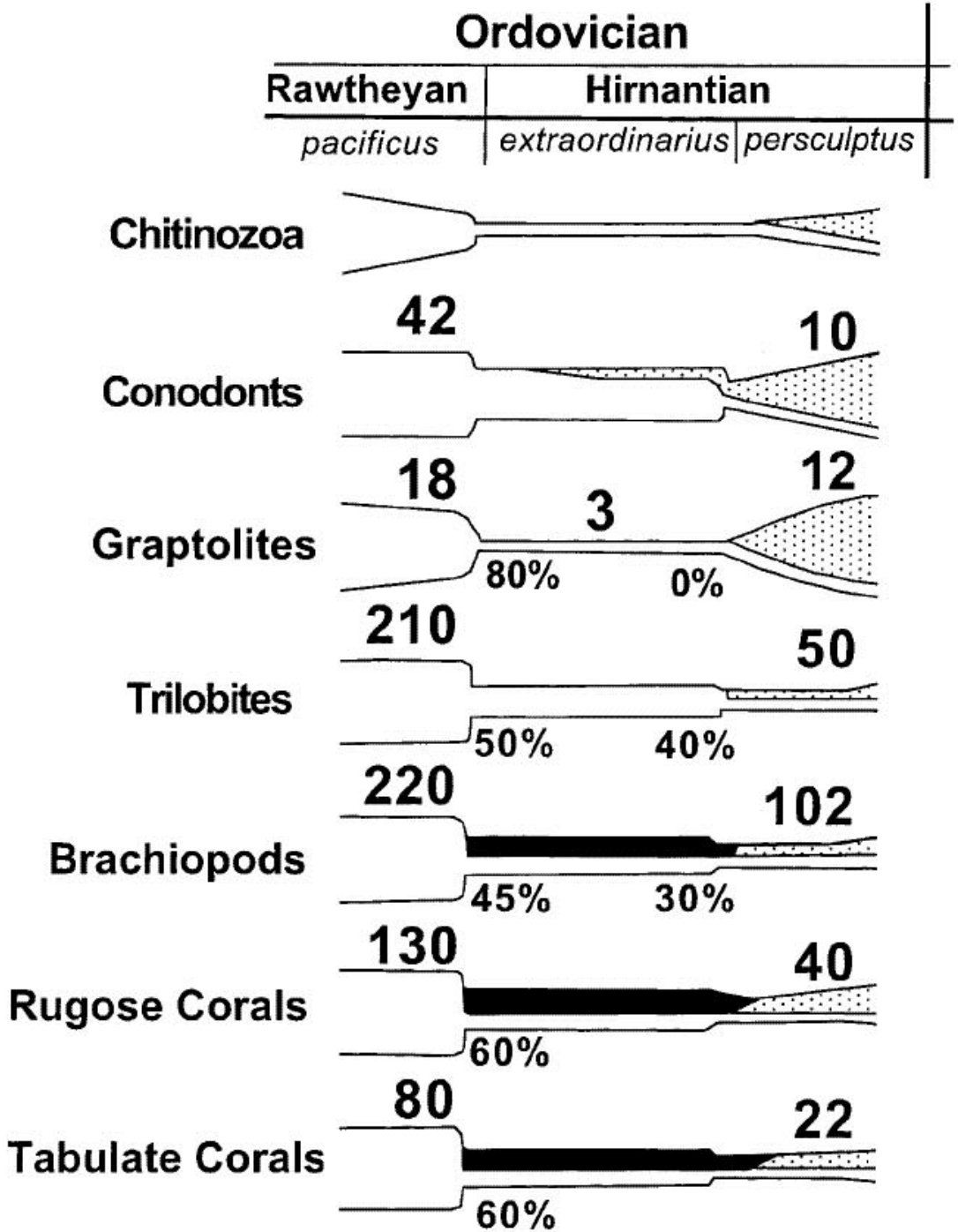
The Big Losers - plankton

The base of the Ordovician food chain was hard hit.

9 out of 11 species of Chitinozoans disappeared.

Acritarchs reached a diversity low point during the Late Ordovician too.




Ordovician
Rawtheyan
Hirnantian
pacificus
extraordinarius
persculptus
Chitinozoa
Conodonts
42
10
Graptolites
18
3
12
80%
0%
Trilobites
210
50
50%
40%
Brachiopods
220
102
45%
30%
Rugose Corals
130
40
60%
Tabulate Corals
80
22
60%

Carbon isotope excursion

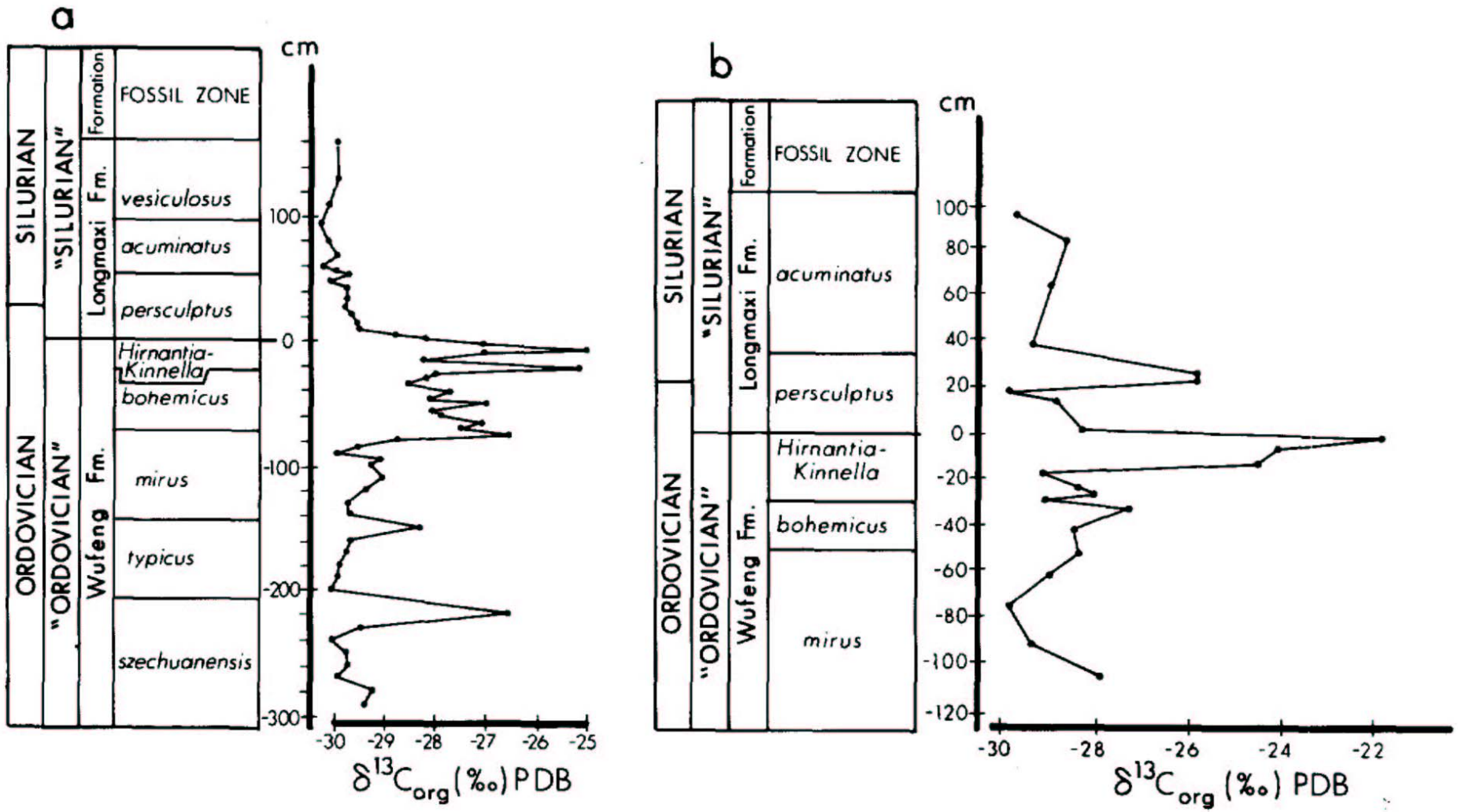


Fig. 4. Stratigraphic plots of $\delta^{13}C_{org}$ in the Wangjiawan Section (a) and Huanghuachang Section (b), Yichang, Hubei Province, South China. Periods/systems recognized in China are shown between *quotation marks*. (After K. Wang et al., 1993b.)

In brief

End-Ordovician marked by two pulses of extinction.

Mainly benthic communities affected

Composite effect of both extinctions greatest in the tropics

Possible causes?

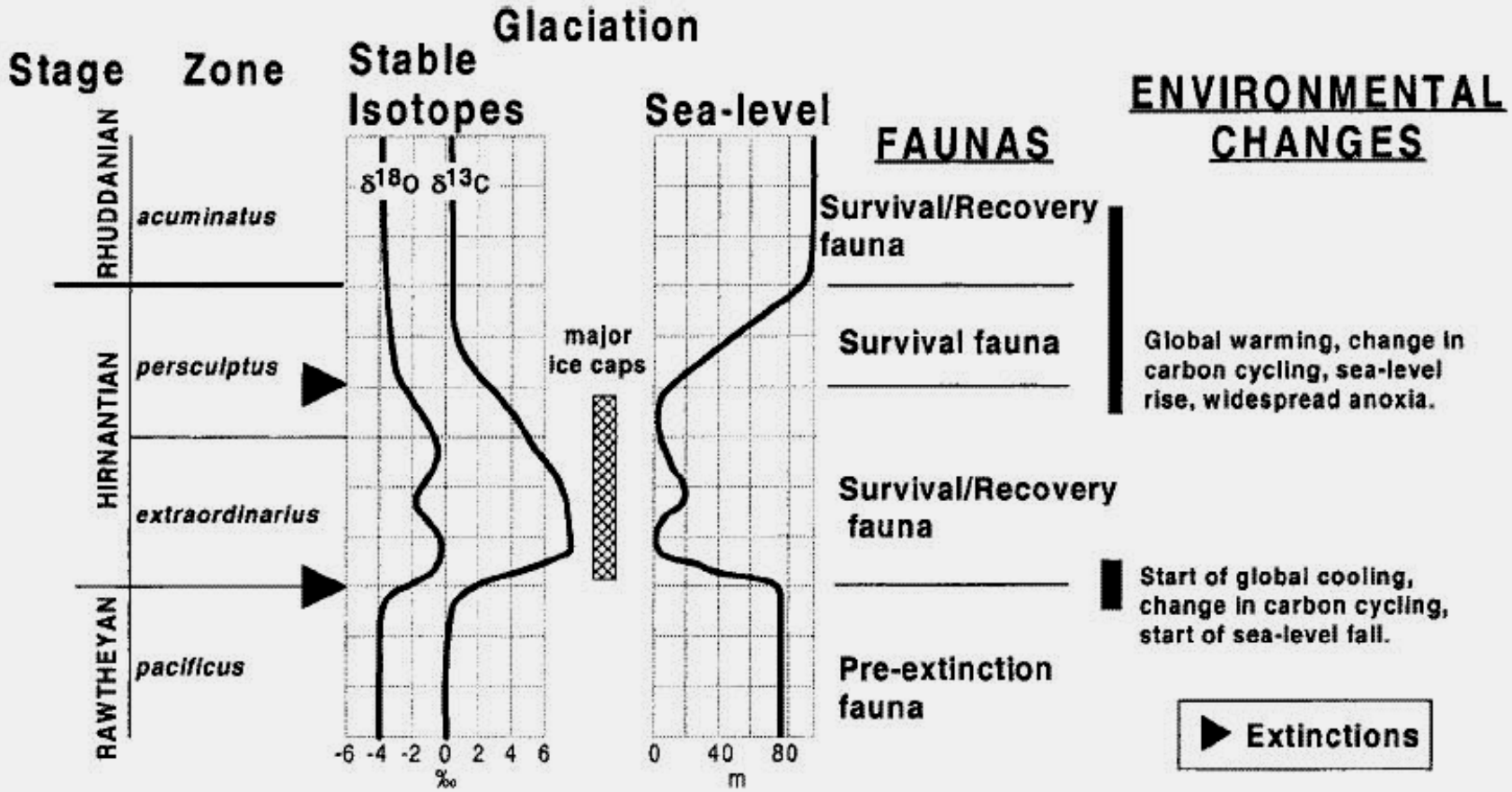


Figure 1. Late Ordovician–Early Silurian stratigraphy, isotope stratigraphy, environmental change and succession of faunas. The base of the Hirnantian is placed data in at the base of the *extraordinarius* Zone after Underwood *et al.* (1997). The carbon isotope profile is modified from Brenchley *et al.* (1994) and the sea-level curve is modified from data in Brenchley *et al.* (1995).

Geol. J. **36**: 329 340 (2001)

The end-Devonian extinction

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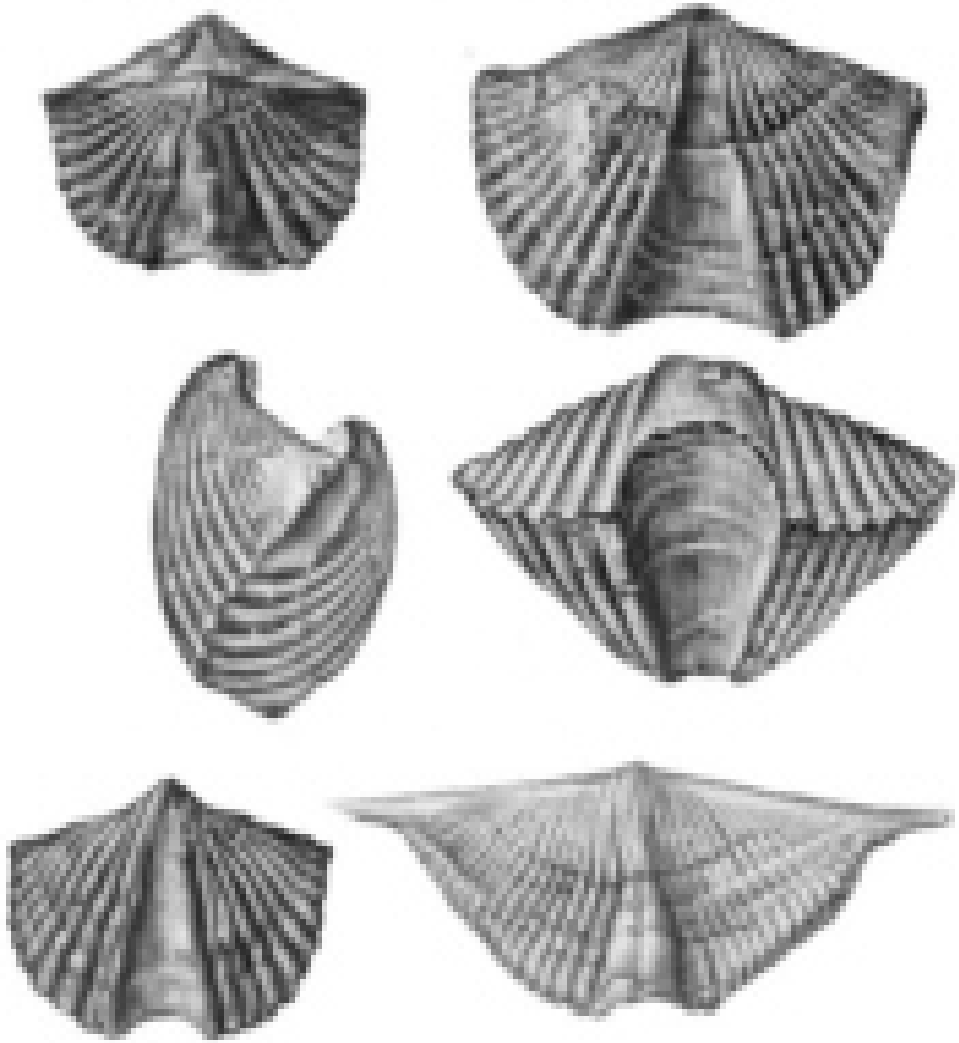
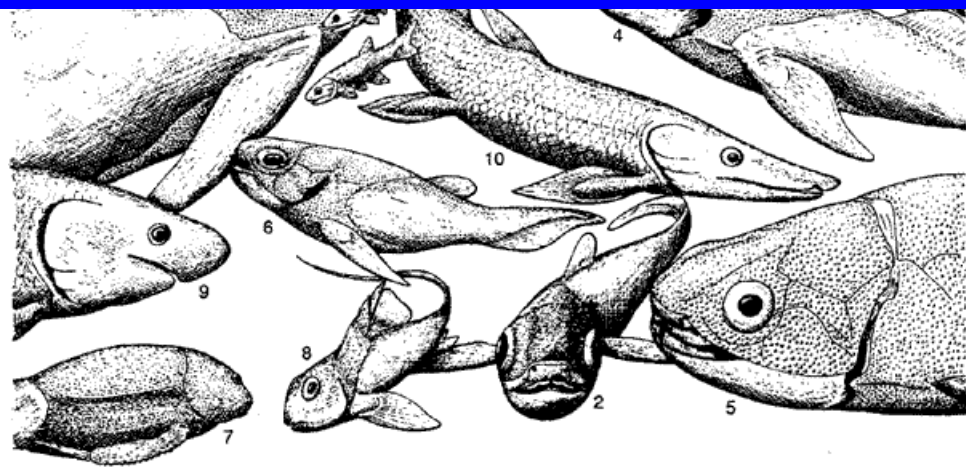
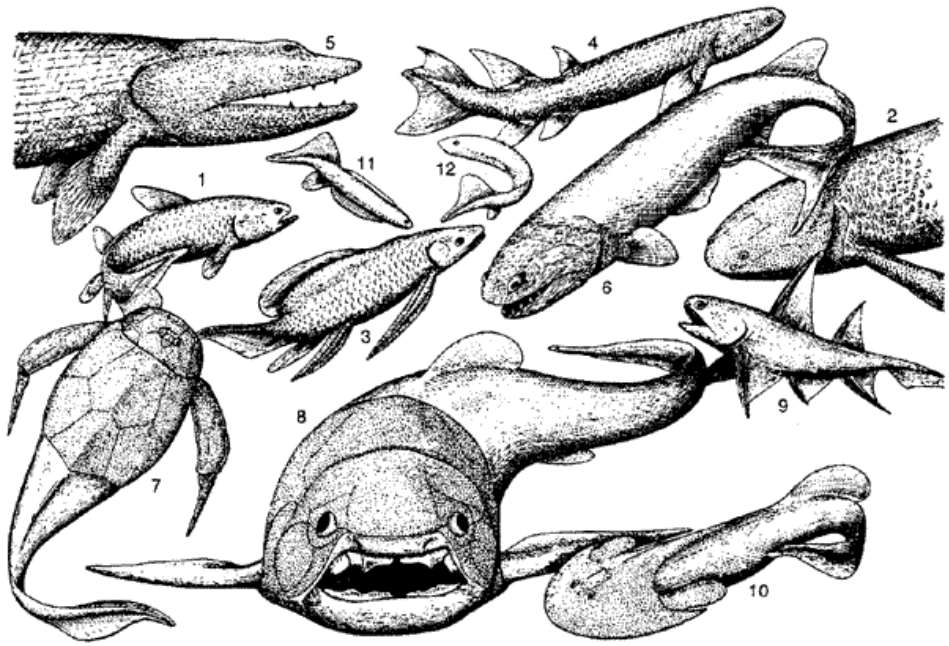
The Big Losers - Brachiopods



The Devonian - The age of fishes

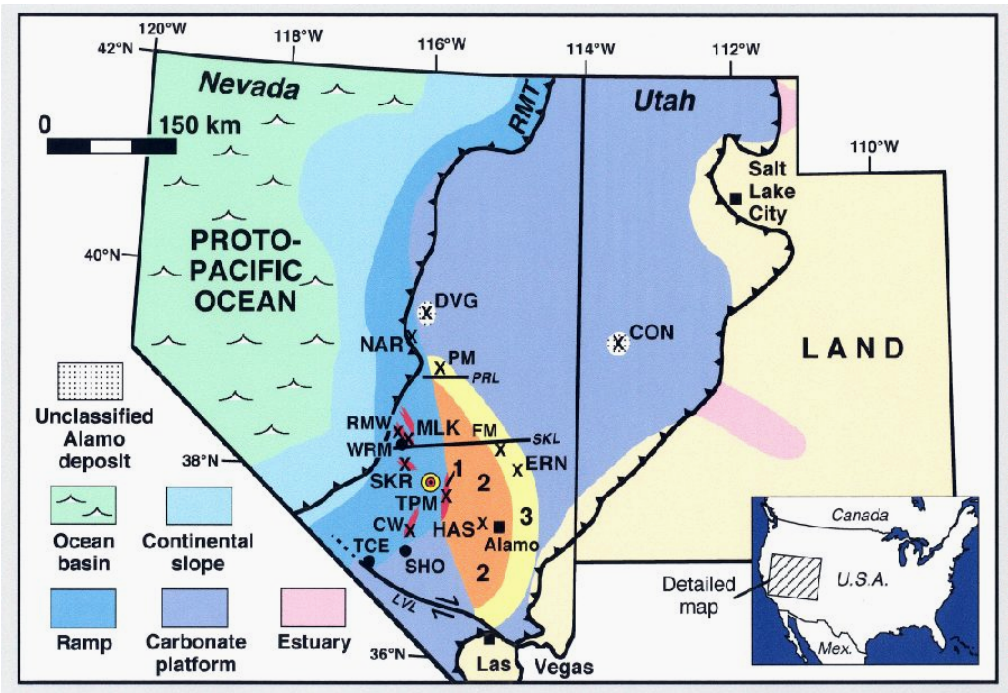
The Devonian saw the only major perturbation suffered by the fishes, the most important predators of that time. Jawless **Agnathans** were virtually exterminated, but they re-appeared during the Carboniferous. The jawed **Placoderms** met almost the same fate. They rose to prominence during this time, but their success was short lived and they disappeared completely by the end of the Devonian

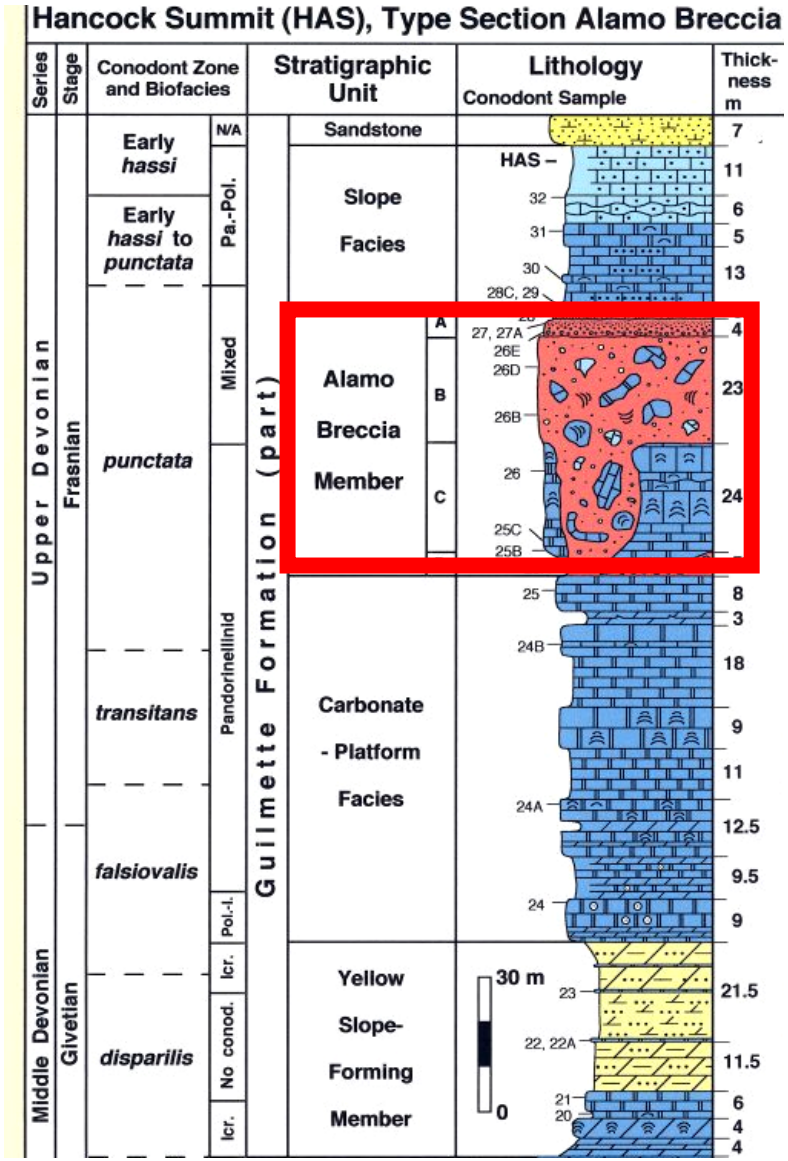




The Alamo impact - A smoking gun?

Recently discovered evidence for an impact in southern Nevada and associated impact breccia, however predates the main extinction events





Possible scenarios

The most common scenario involves global anoxia, as recorded in the two black shale units (Kellwasser Horizons). Global warming is thought to have lead to sea level rise, formation of warm and saline bottom waters, inducing globally stratified oceans and enhanced burial of organic carbon causing cooling and regression.

Algeo et al. (1995) proposed that the end-Devonian mass-extinction was “rooted” in the rise of land plants. They envisioned a scenario where plants accelerated the erosion of continents, thus enhancing the delivery of nutrients to the oceans, causing widespread eutrophication, high organic-carbon production and burial and hence widespread anoxia and possibly glaciation.

The Permian-Triassic boundary

The mother of all mass-extinctions

Passo di Sella, Dolomites, N-Italy

The Big Losers - The Coral reef gap

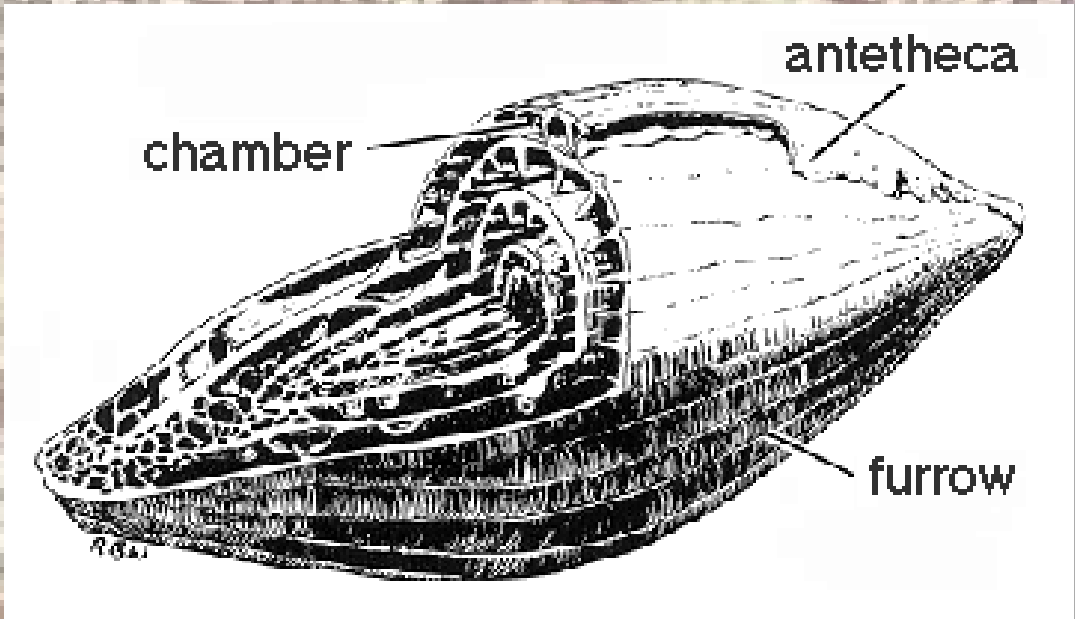
Two important reef-building groups of animals, the rugose and tabulate corals completely disappeared during the P/T boundary mass-extinction.

The crisis was so severe that no reefs existed for the first 10 million years of the Triassic.

We only know of microbial build-ups in southern China.

Univ. of Michigan Exhibit Museum of Natural History -- Life Through the Ages Diorama

The Big Losers - Fusulinids

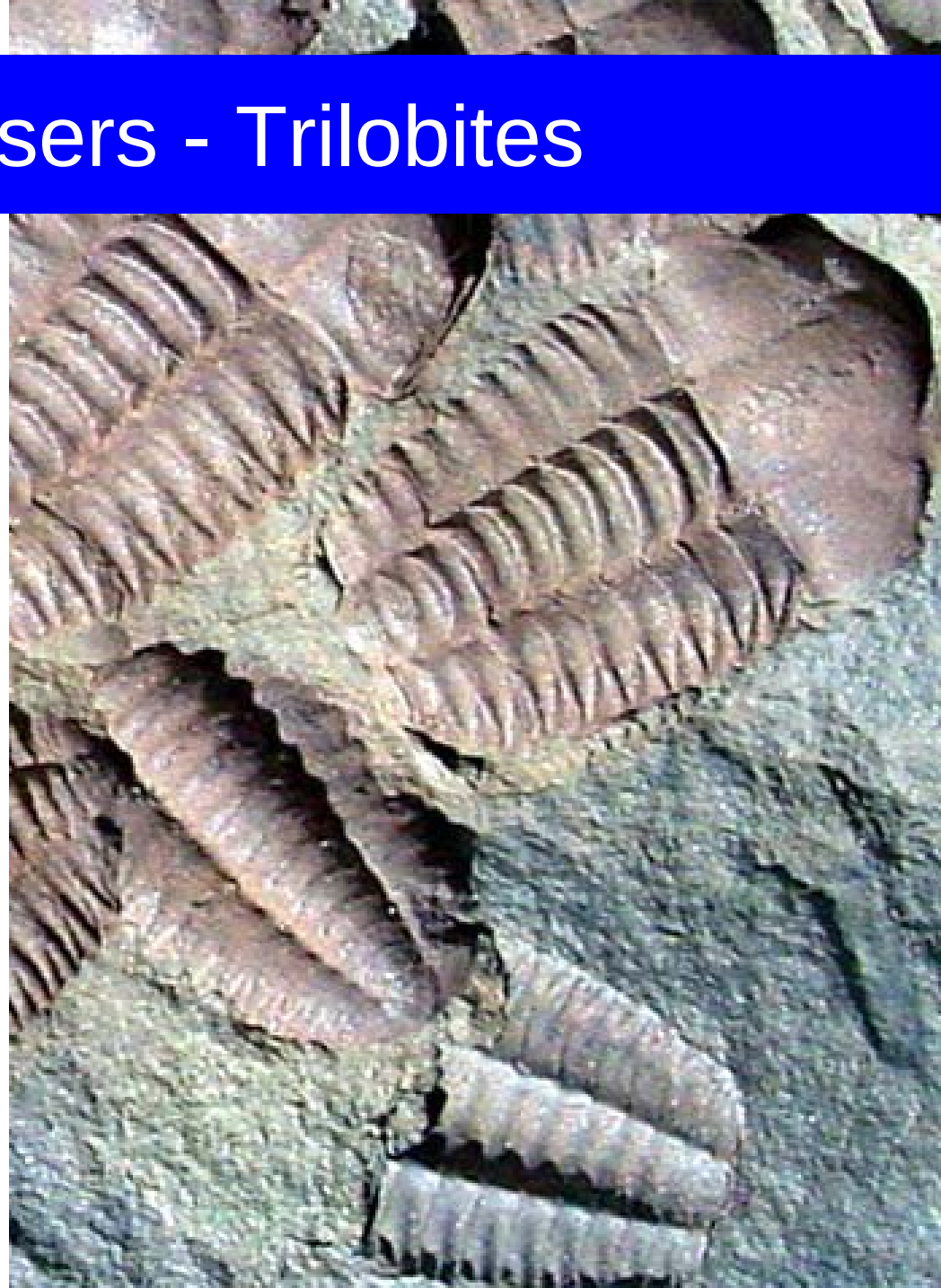


Large benthic foraminifera that were important rock-builders during the Paleozoic. Their peculiar shape and large size has been tentatively linked to symbionts.

The Big Losers - Trilobites

Trilobites were in steady decline from their high-point in the Cambrian and were insignificant in Late Permian reef environments with 3 small families. The P/T boundary event was the coup de grace for this group.

Extinction: 100%



The end of a Flora: Glossopteris

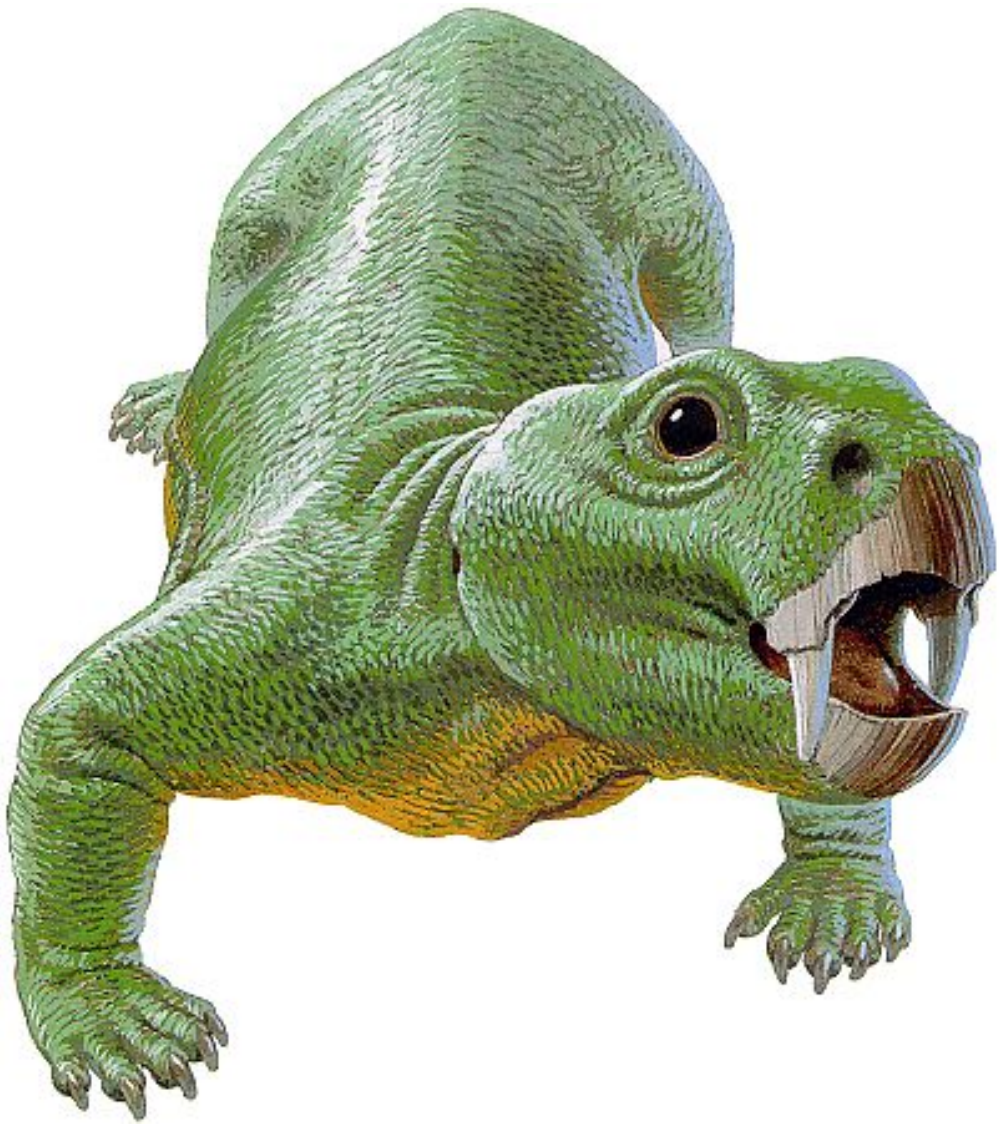
Glossopteris, una cordaitale

The Permian marks a long term overturn of the **Paleophytic** floras into the **Mesophytic** floras, much in line with the changes in the marine realm.

Plants that were used to wet habitats suffered while plants that favoured arid conditions, such as conifers and ginkophytes rose to prominence.

One important group of plants, the **Cordaites**, that had conquered most of Gondwana's high latitude regions suffered the most and became extinct at the P/T boundary.

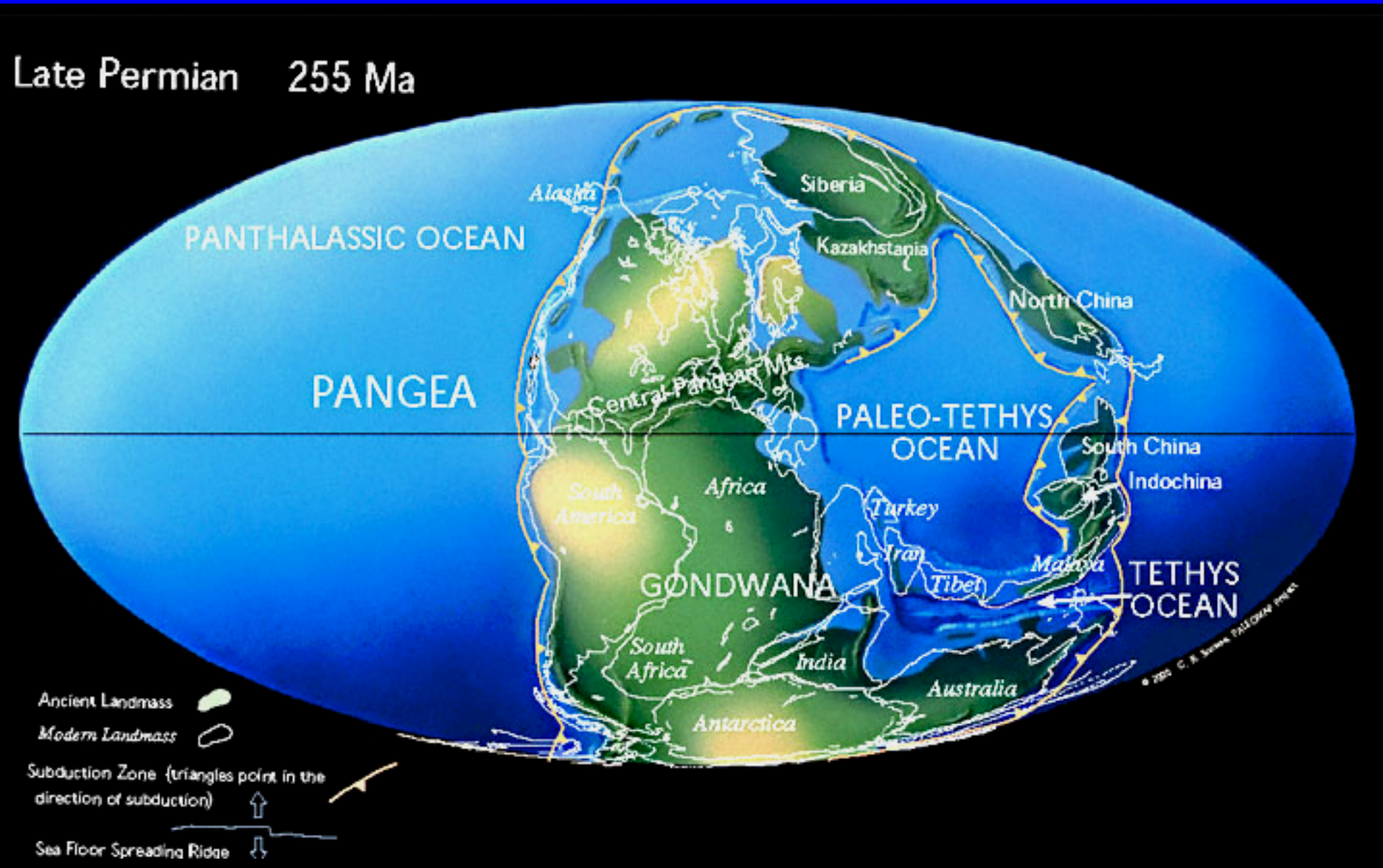
The Big Losers - Dicynodonts



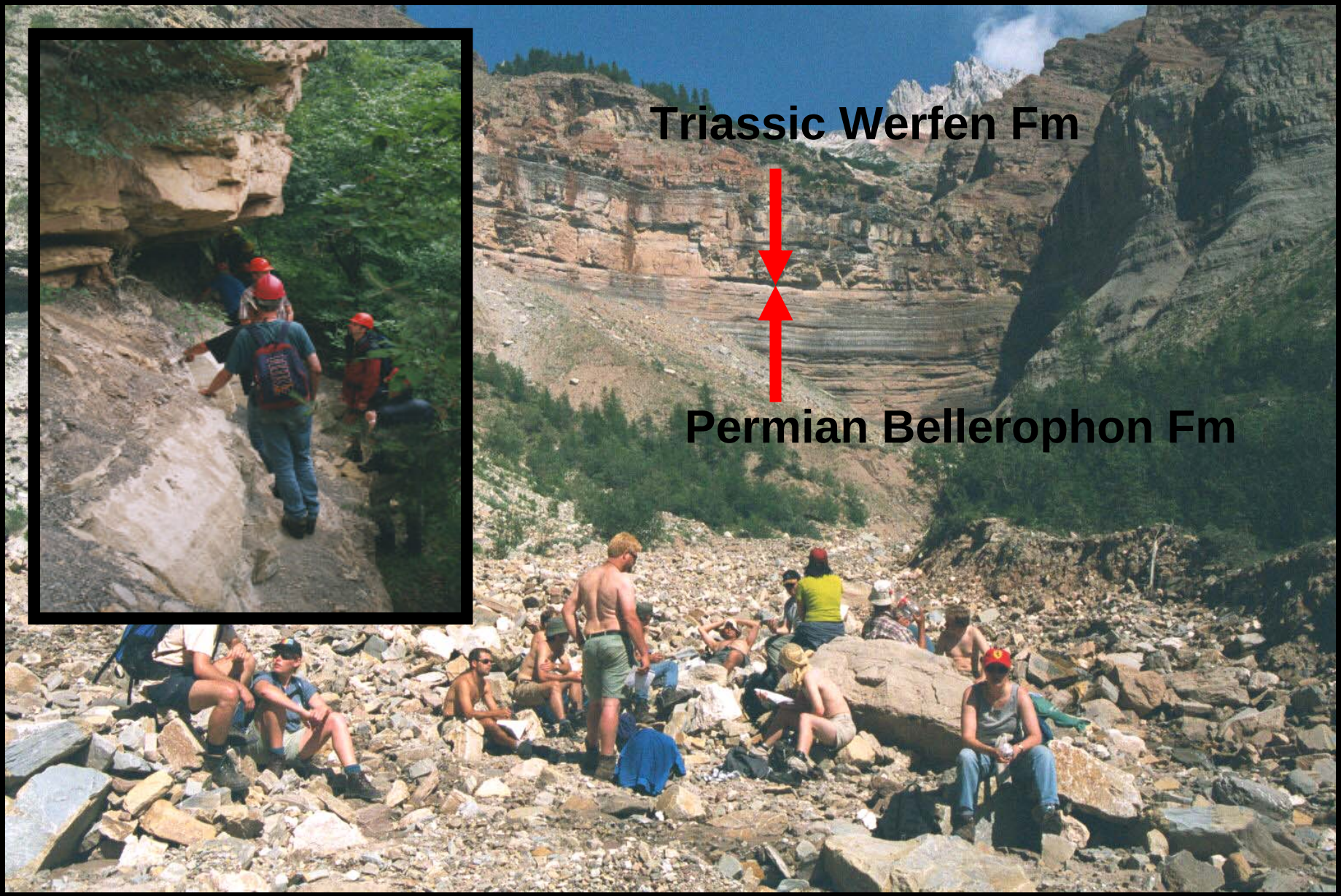
The Dicynodonts were an important group of Late Permian herbivorous Therapsid reptiles.

Of 35 Dicynodont genera in the Late Permian only two survived into the Early Triassic, including the widespread ***Lystrosaurus***, which is taken as a marker for the earliest Triassic in land deposits.

Pangea, aridity, regression



Permian-Triassic boundary, Butterloch Canyon, Italian Dolomites



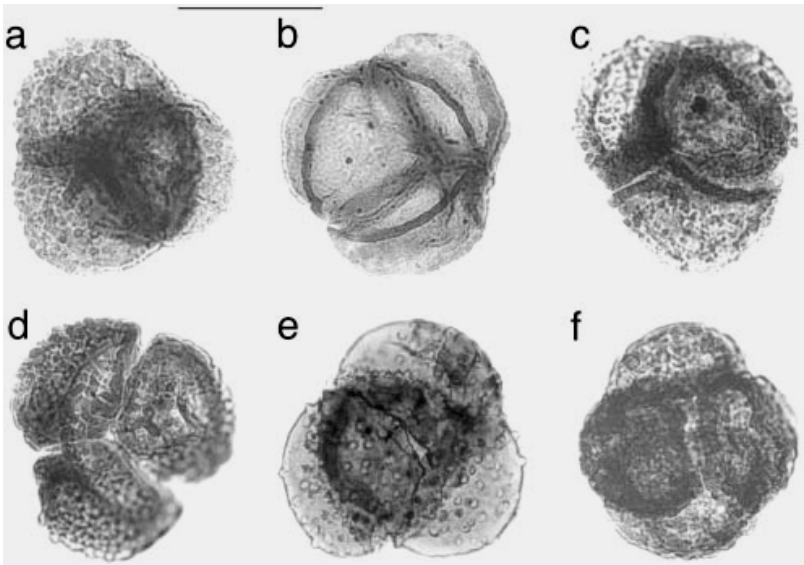
Laboratory for Palynology and Paleobotany excursion 2000

The Fungal spike

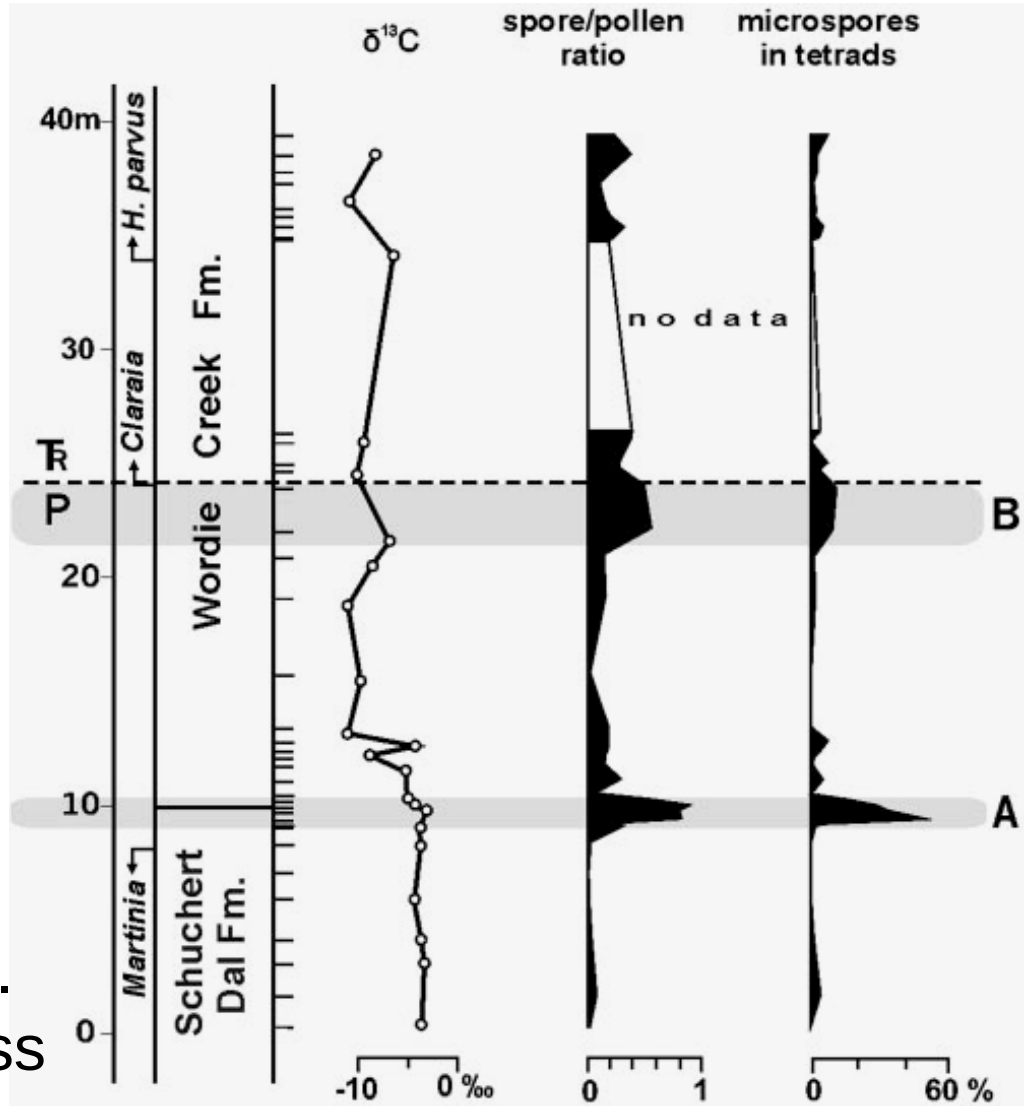
On land, the P/T extinction lead to a deep environmental crisis. **Palynology** has shown a change from conifer pollen to fern and other spores across the boundary. These two assemblages are separated by an assemblage almost 100% made up of fungal spores. This **“fungal spike”** is thought to represent the rotting of dead bio-mass. Conifer forests were replaced world-wide by a herbaceous vegetation.

Environmental mutagenesis

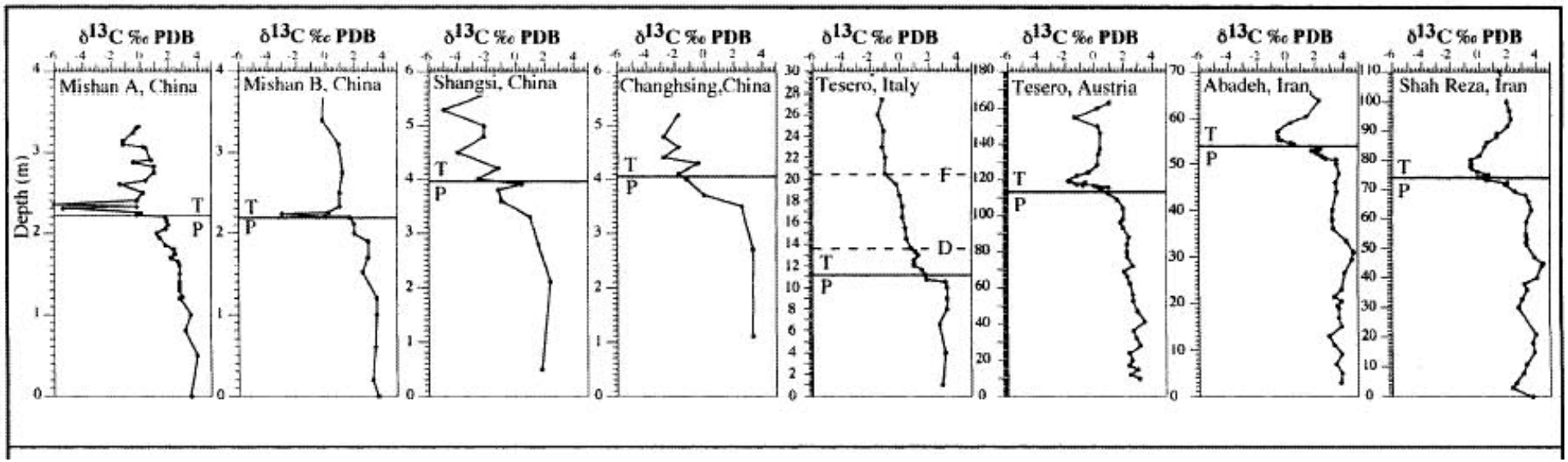
Visscher et al., 2004



P/T boundary worldwide marked by abundance of tetrads of lycopsid spores (here shown for Greenland). Indicate environmental stress



A global carbon isotope excursion



Permian-Triassic boundary beds from China, Italy, Austria, Iran and other places, show a distinct negative excursion in $\delta^{13}C$ obtained from bulk rock carbonate.

What can explain a global drop in $^{13}C/^{12}C$ ratios?

Dating the boundary

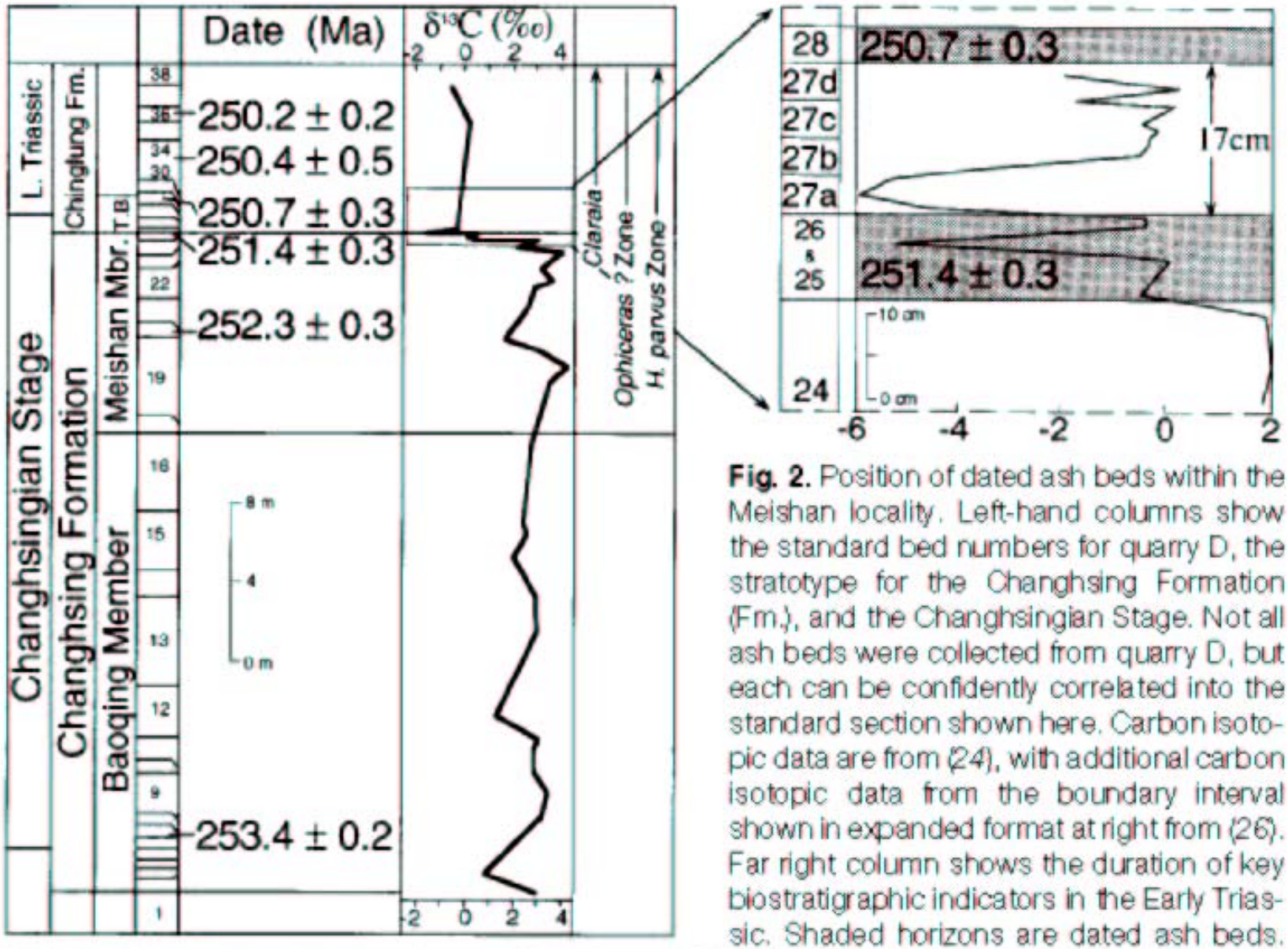


Fig. 2. Position of dated ash beds within the Meishan locality. Left-hand columns show the standard bed numbers for quarry D, the stratotype for the Changhsing Formation (Fm.), and the Changhsingian Stage. Not all ash beds were collected from quarry D, but each can be confidently correlated into the standard section shown here. Carbon isotopic data are from (*24*), with additional carbon isotopic data from the boundary interval shown in expanded format at right from (*26*). Far right column shows the duration of key biostratigraphic indicators in the Early Triassic. Shaded horizons are dated ash beds. T.B. signifies transitional beds with mixed Permian and Triassic fossils. Mbr., member.

The Siberian Traps

Siberian Traps are possibly the largest flood basalt province on Earth:

Covering 1.5 million km^2 and up to 400-3000m thick

It was long thought that the duration was extensive, but now it appears that the outflow occurred over very short time interval: ~600,000 years

Environmental effects of flood basalts

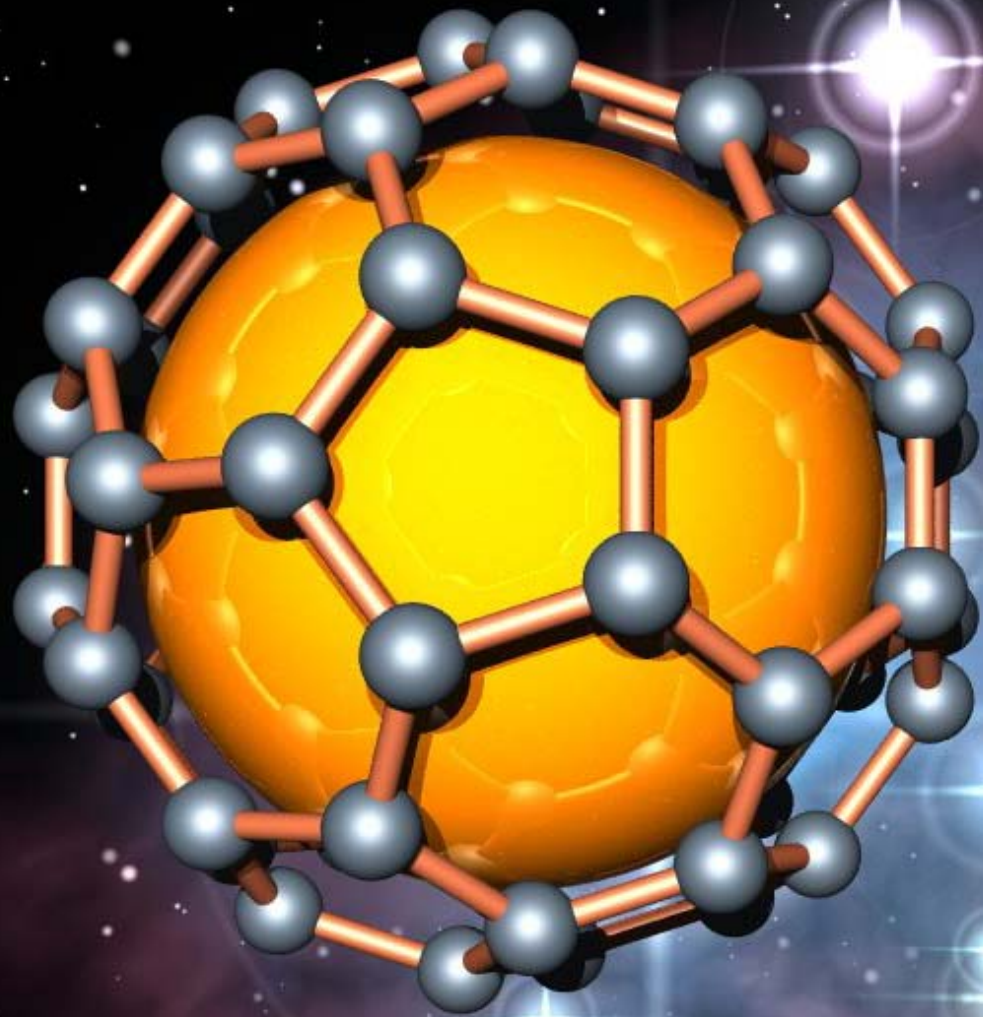
Volcanism releases massive amounts of gas to the atmosphere, including:

- CO_2 causing global warming
- SO_2 causing acid rain
- H_2SO_4 aerosols that activate Chlorine (Cl) compounds causing ozone depletion
- Bromine (Br) would have the same effect

Another possibility is that the ascending magma reheated and melted crustal rocks rich in organic compounds with elevated levels of CH_3Cl and CH_3Br (organohalogens) further exacerbating the effect.

Fullerenes - Bucky Balls - C60

Peculiar organic molecules that are especially abundant in meteorites. The ball shape can trap other elements or even gases inside. Analysis of fullerenes found in P/T boundary beds showed a helium gas contents with an extraterrestrial composition (based on $^{3}He/^{4}He$ ratio).

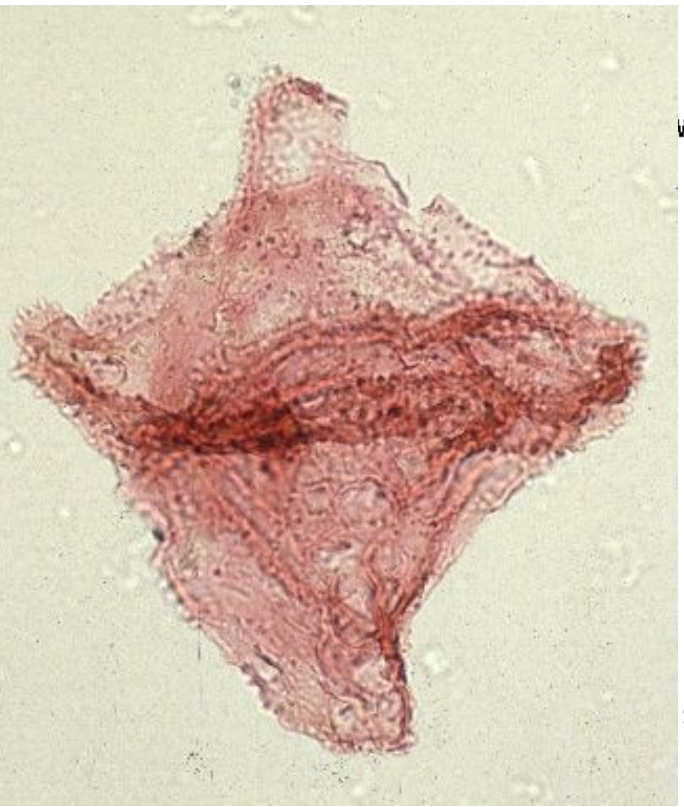


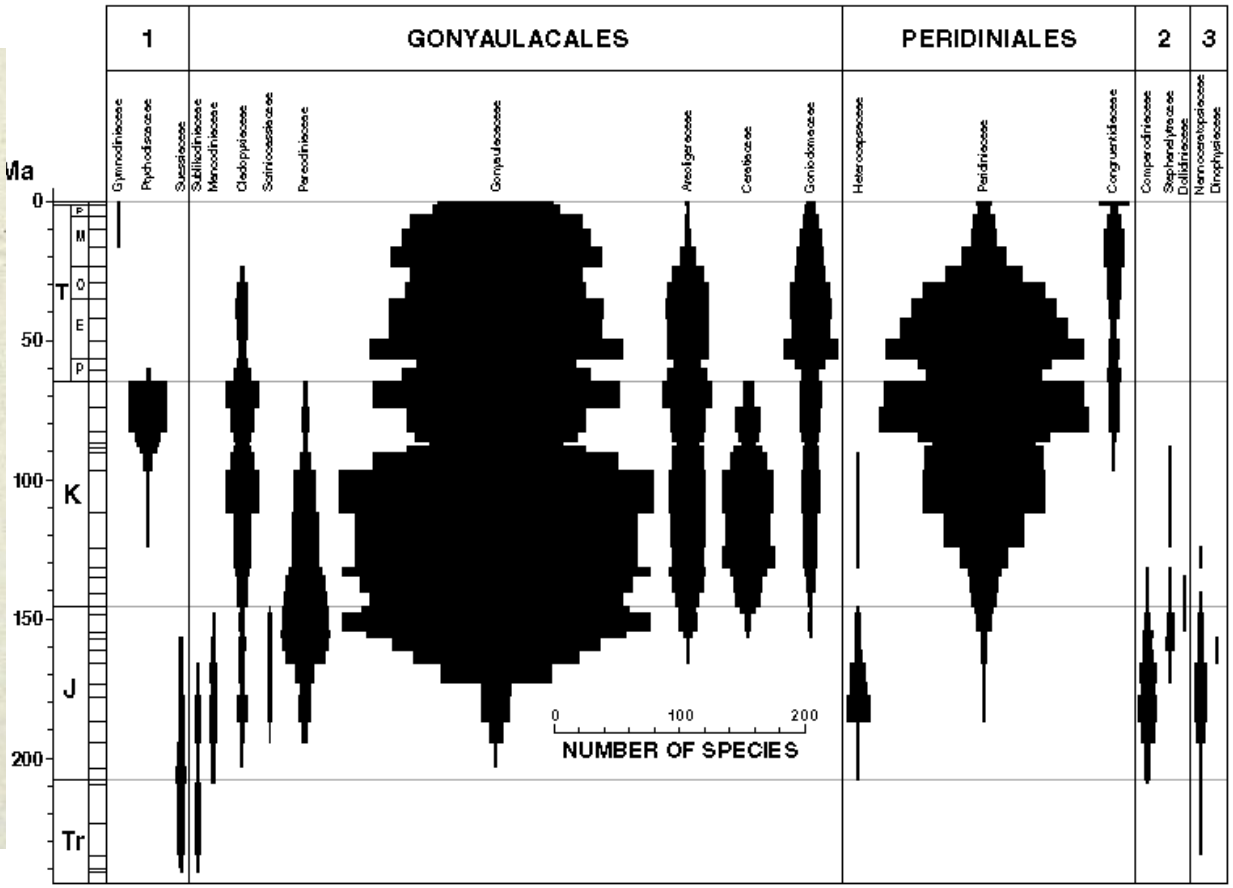
Murder on the Orient-Express

Much like the 10 perpetrators in Agatha Christie's detective novel " Murder on the Orient-Express", Douglas Erwin proposed that the end-Permian extinction was the result of several culprits acting together. Some acting over longer periods of time, others necessarily more catastrophic.

Thus, we have seen evidence for:
- sea level lowering, exposing shelf areas globally
- super-anoxia, even into shallow water
- flood basalt volcanism, releasing poisonous gases
- methane release, causing greenhouse warming
- impact of a meteorite or comet

And the winners are…… - phytoplankton





This is one of the oldest dinoflagellate cysts:
Sverdrupiella warepensis from Late Triassic of Australia

The Triassic-Jurassic boundary

The case for massive volcanism

Table 1.1 Extinction intensities at the five major mass extinctions in the fossil record: species-level estimates based on a rarefaction technique

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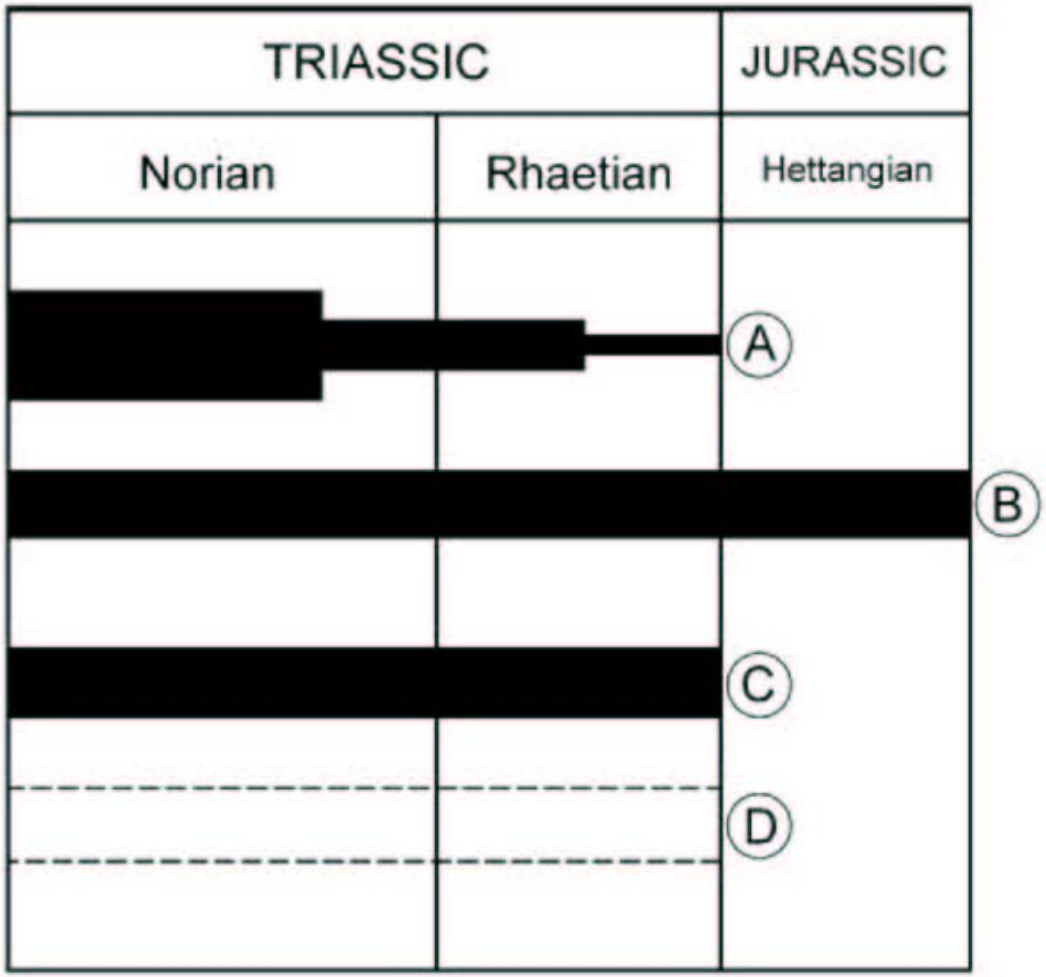
Different extinction patterns

Tanner et al. (2004)



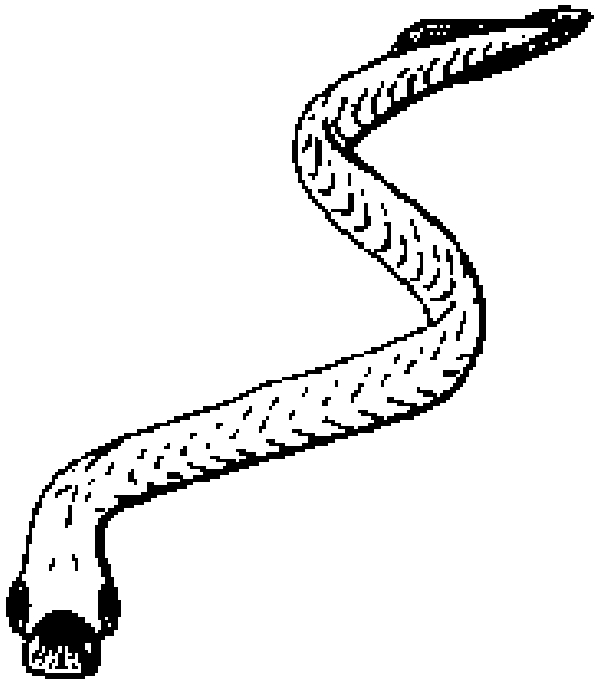
Conodonts, ammonites, bivalves

Foraminifera, ostracods, megaplant fossils

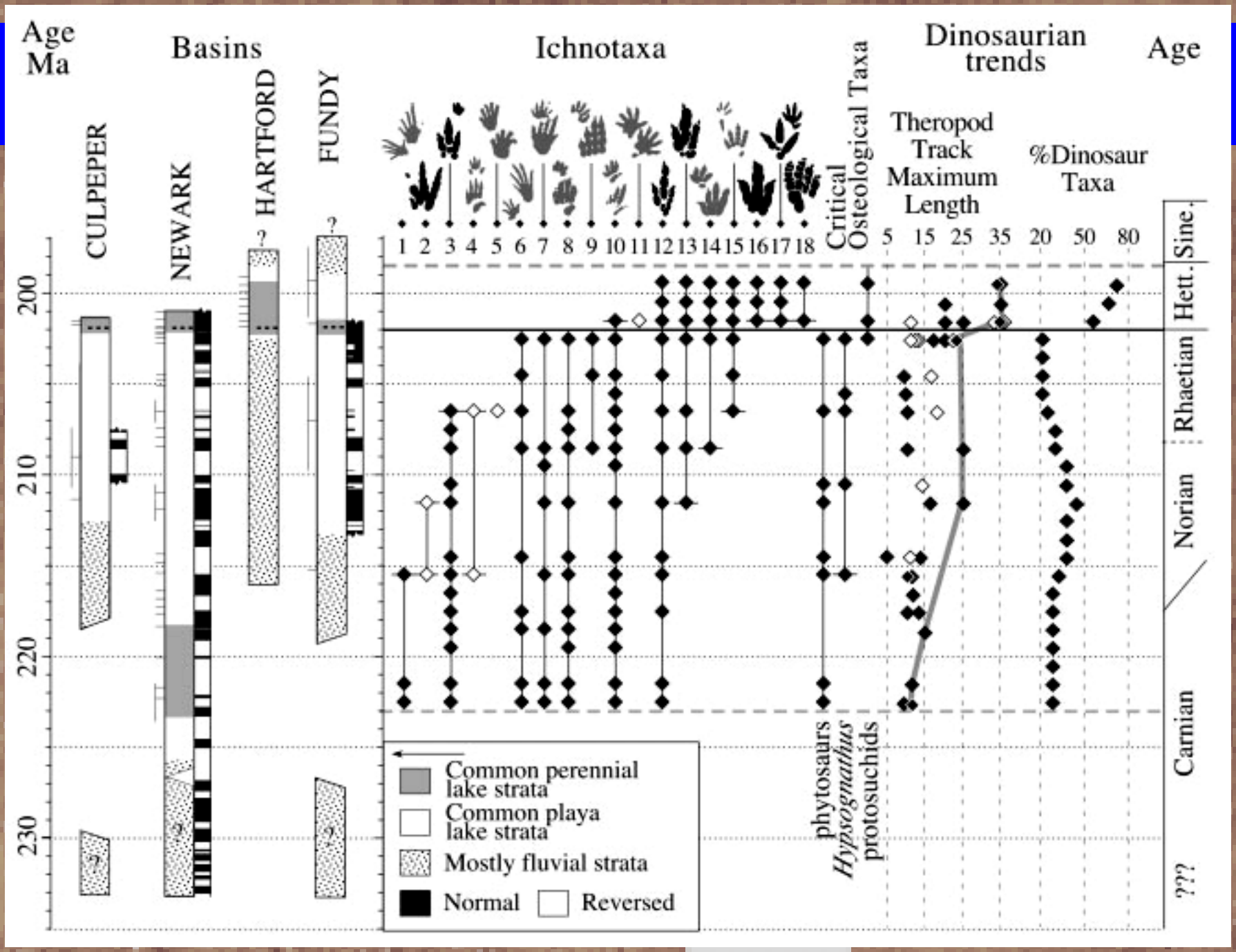
Palynomorphs, radiolarians

Terrestrial vertebrates

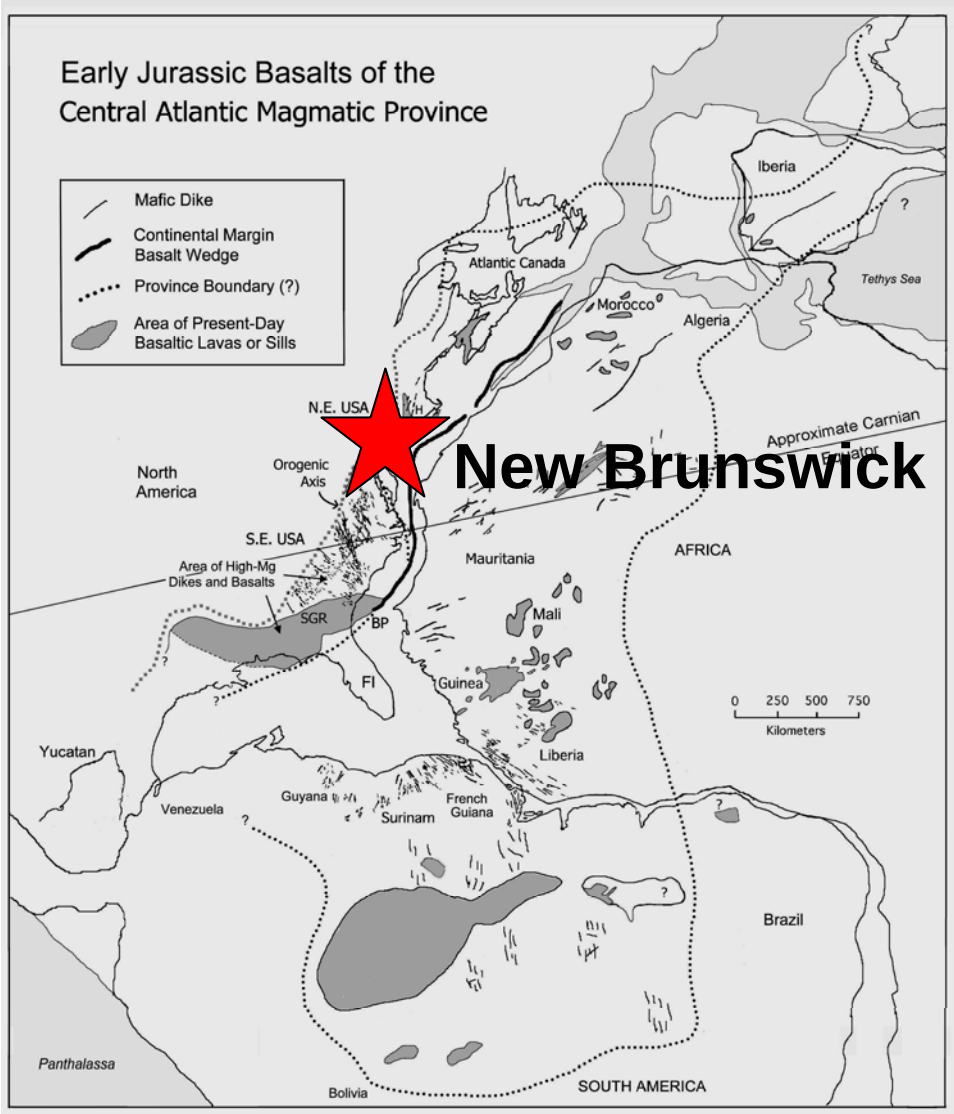
The Big Losers - Conodonts

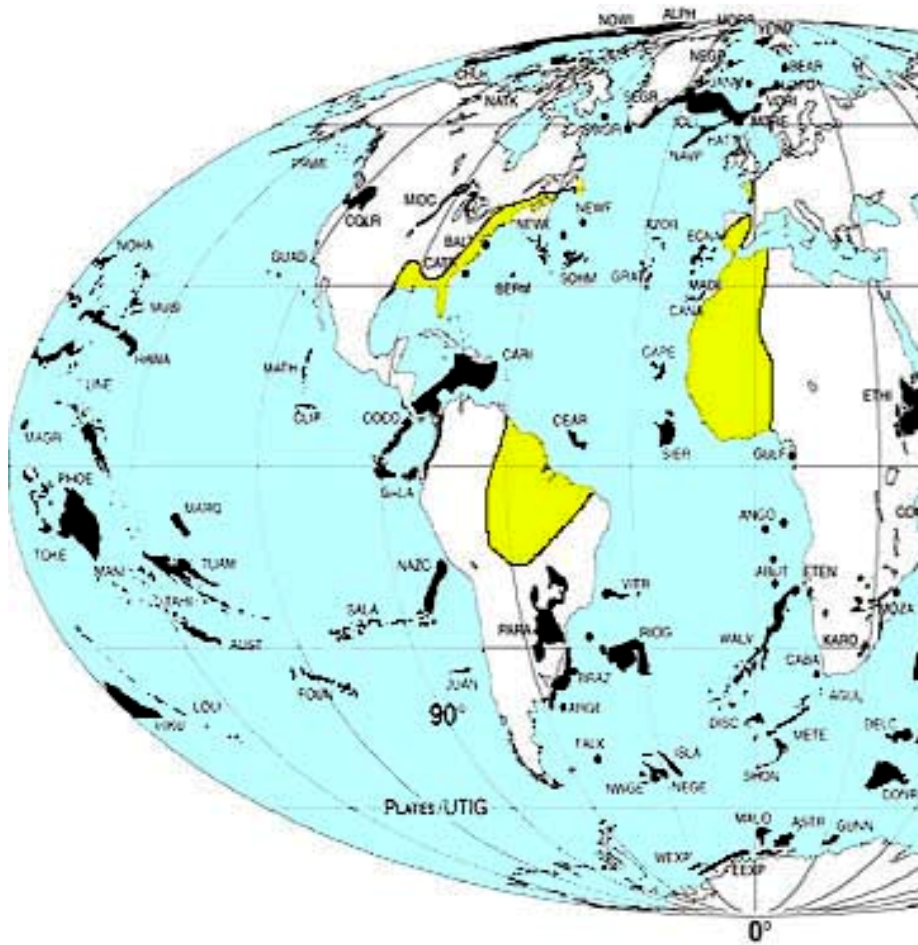


Dental apparatus of small worm-like animals.
Extinction: 100%

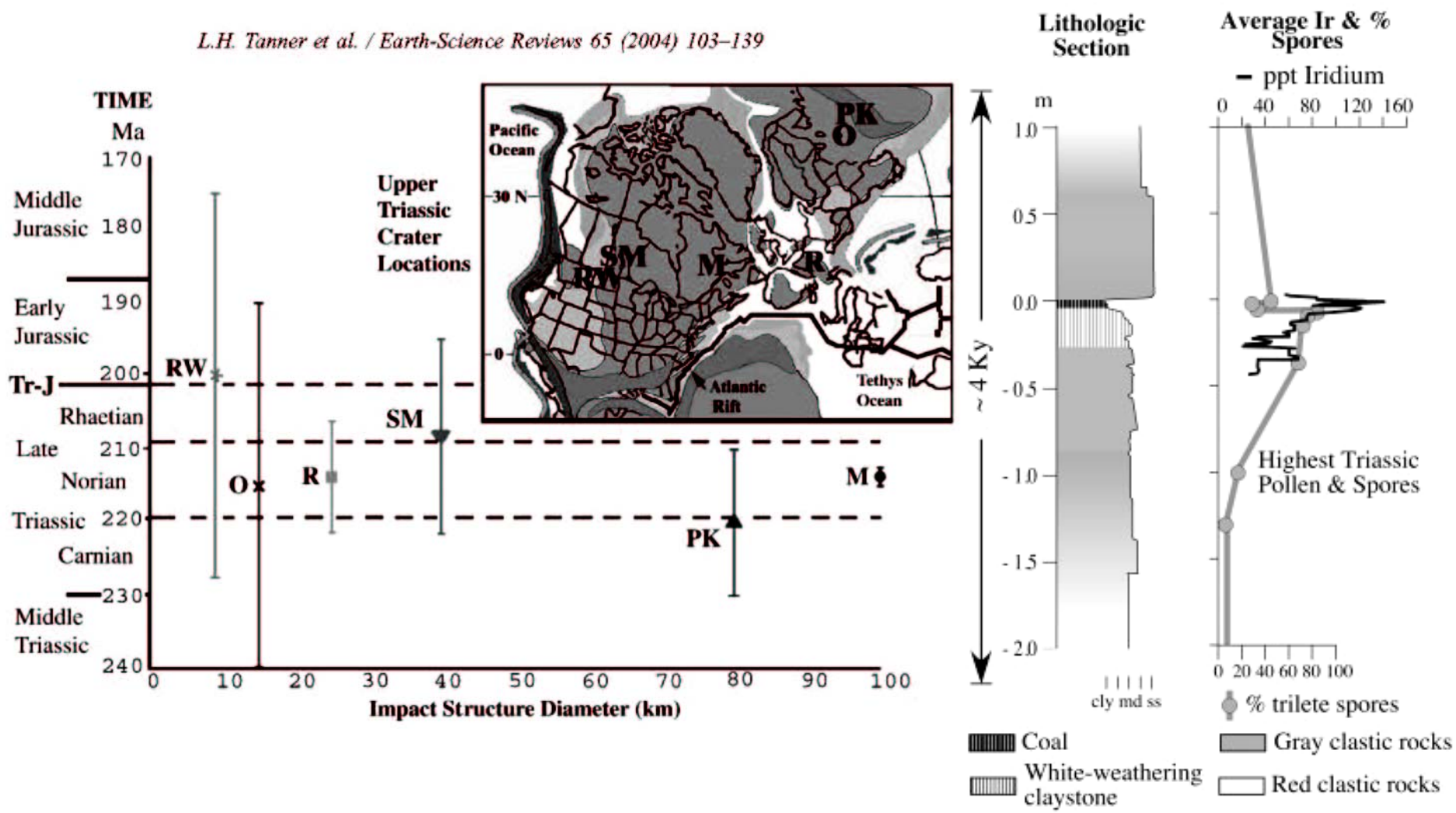

Age Ma
Basins
CULPEPER
NEWARK
HARTFORD
FUNDY
Ichnotaxa
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Critical Osteological Taxa
phytosaurs
Hypsognathus
protosuchids
Dinosaurian trends
Theropod Track Maximum Length
5 15 25 35
%Dinosaur Taxa
20 50 80
Age
Sine.
Hett.
Rhaetian
Norian
Carnian
???
200
210
220
230
Common perennial lake strata
Common playa lake strata
Mostly fluvial strata
Normal
Reversed

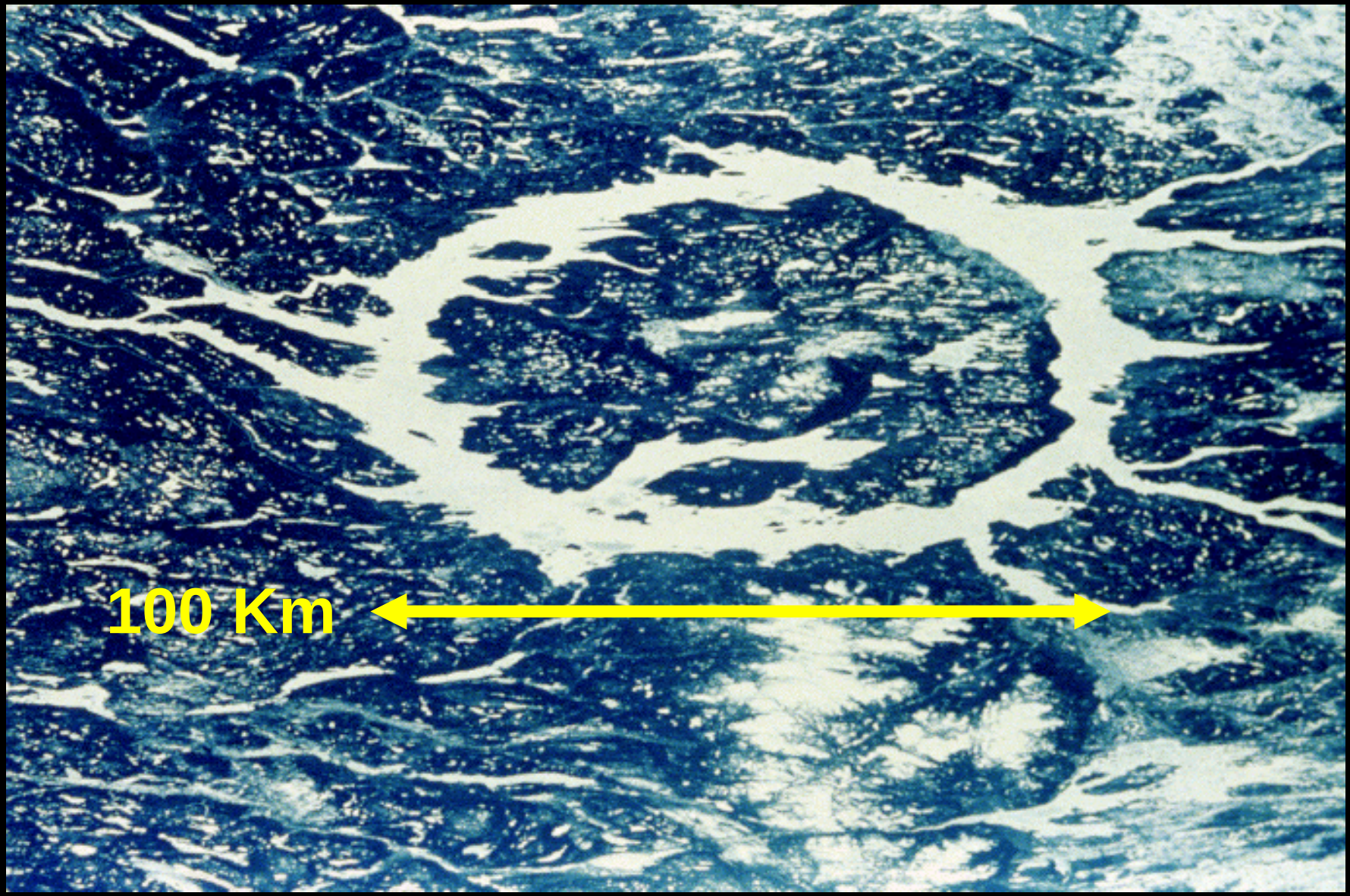
The Central Atlantic Magmatic Province





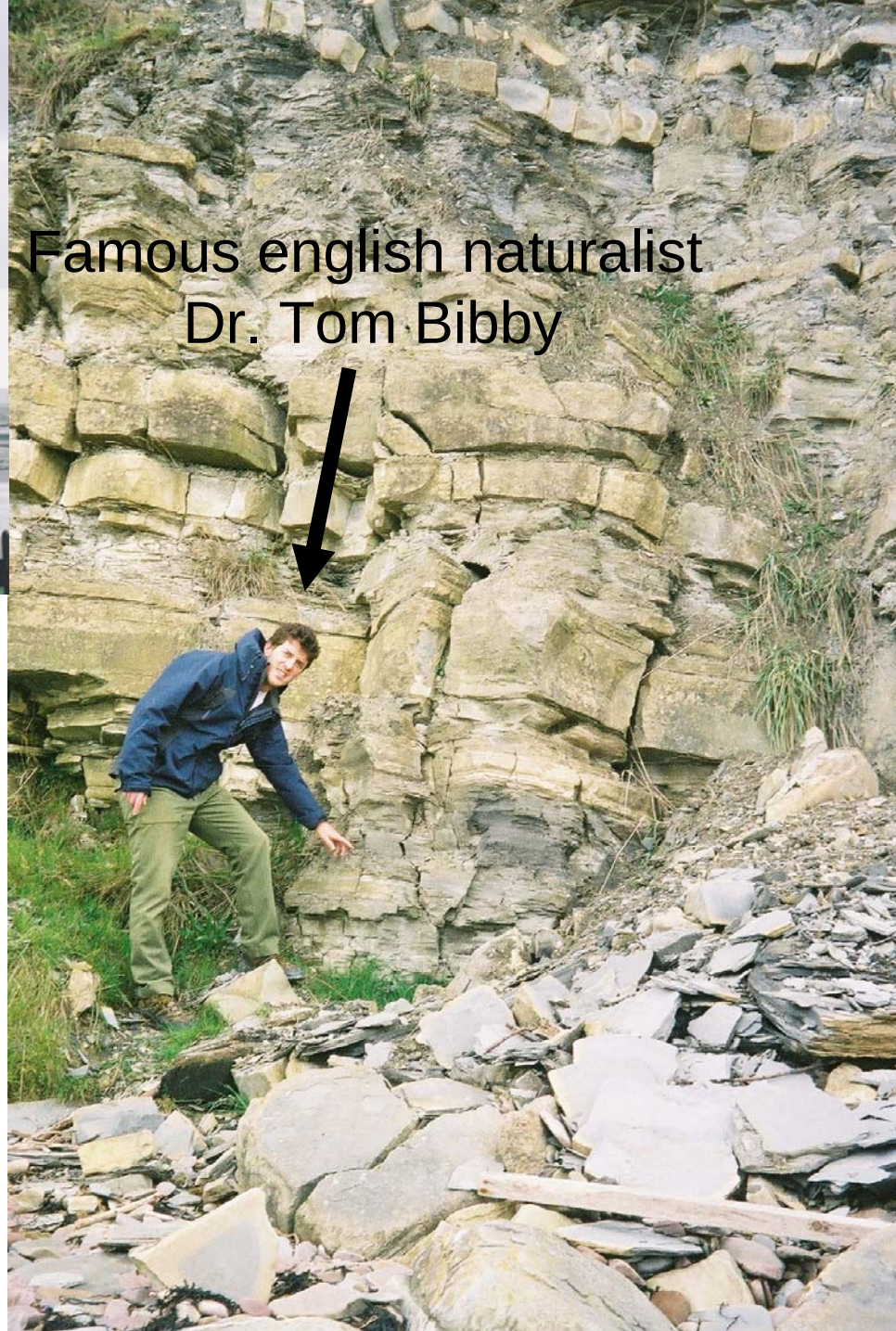
A Late Triassic impact?



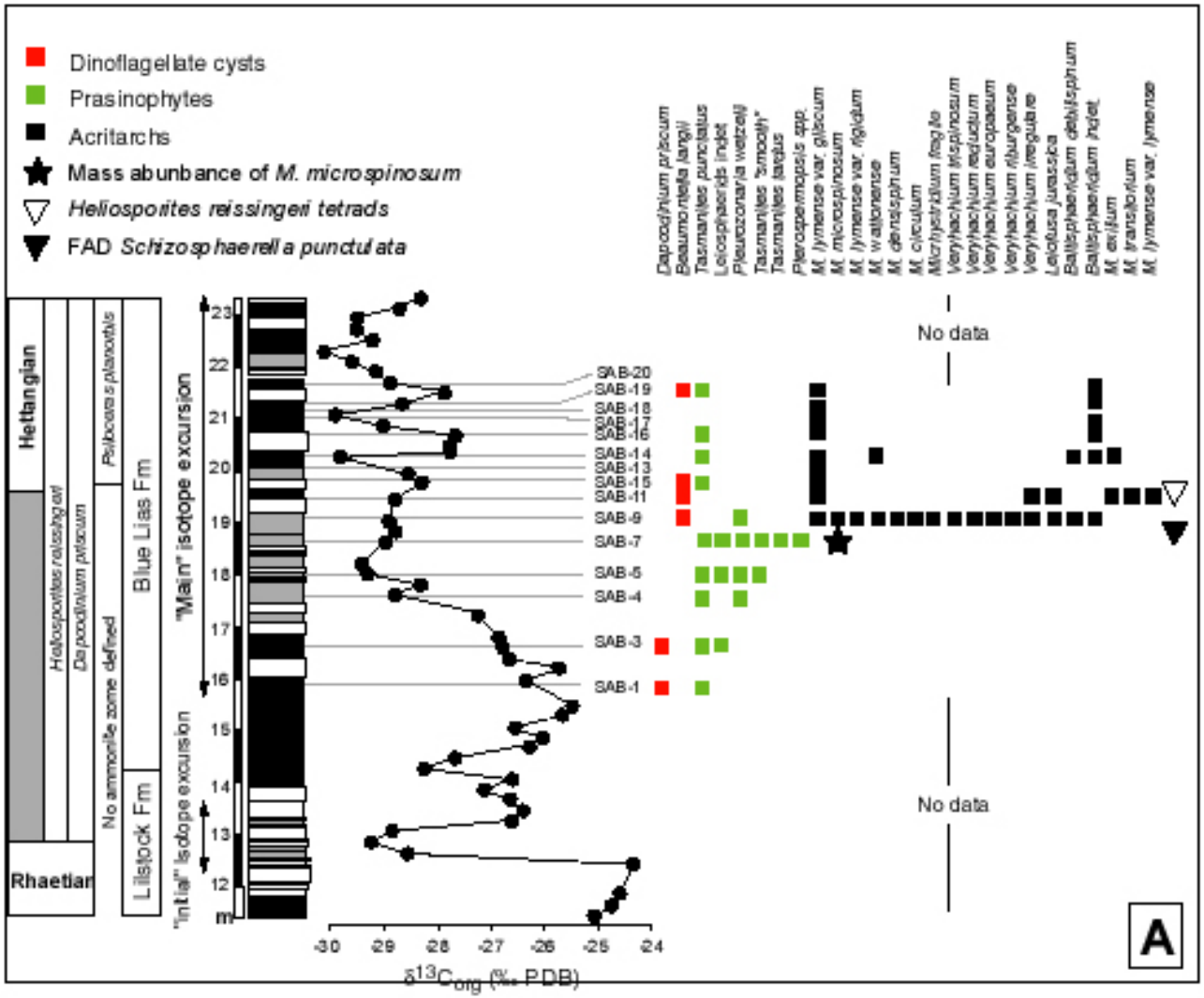


Manicouagan, Canada. Dated at ~210 Ma, Late Triassic

St-Audrie's Bay section in Somerset, UK, is among the best places in the world to study the T/J boundary. It represents a complete succession of marine sediments that lock within them the clues to this mass-extinction event.



Blooms of “disaster species” ??



The Cretaceous-Tertiary boundary

On a peaceful day, 65 million years ago.....

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"Today's asteroid encounter was a near miss, but some scientists warn that an actual impact could have serious long-term effects on life on Earth as we now know it."

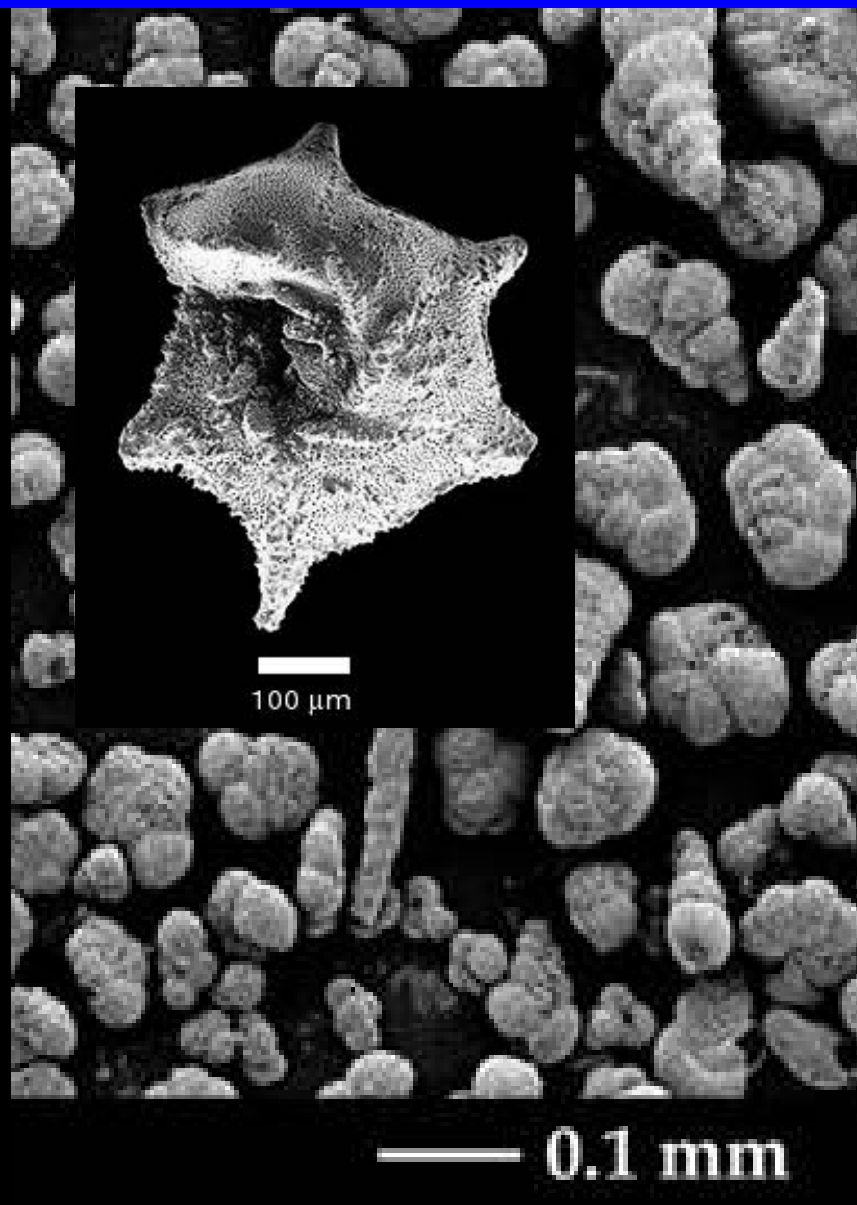
The Big Losers - Ammonites/Belemnites

Important groups within the Cephalopoda,like the ammonites and the belemnites, which had dominated marine life since at least the Triassic went completely extinct, but were in decline before the mass-extinction event.

The Big Losers - Calcareous plankton

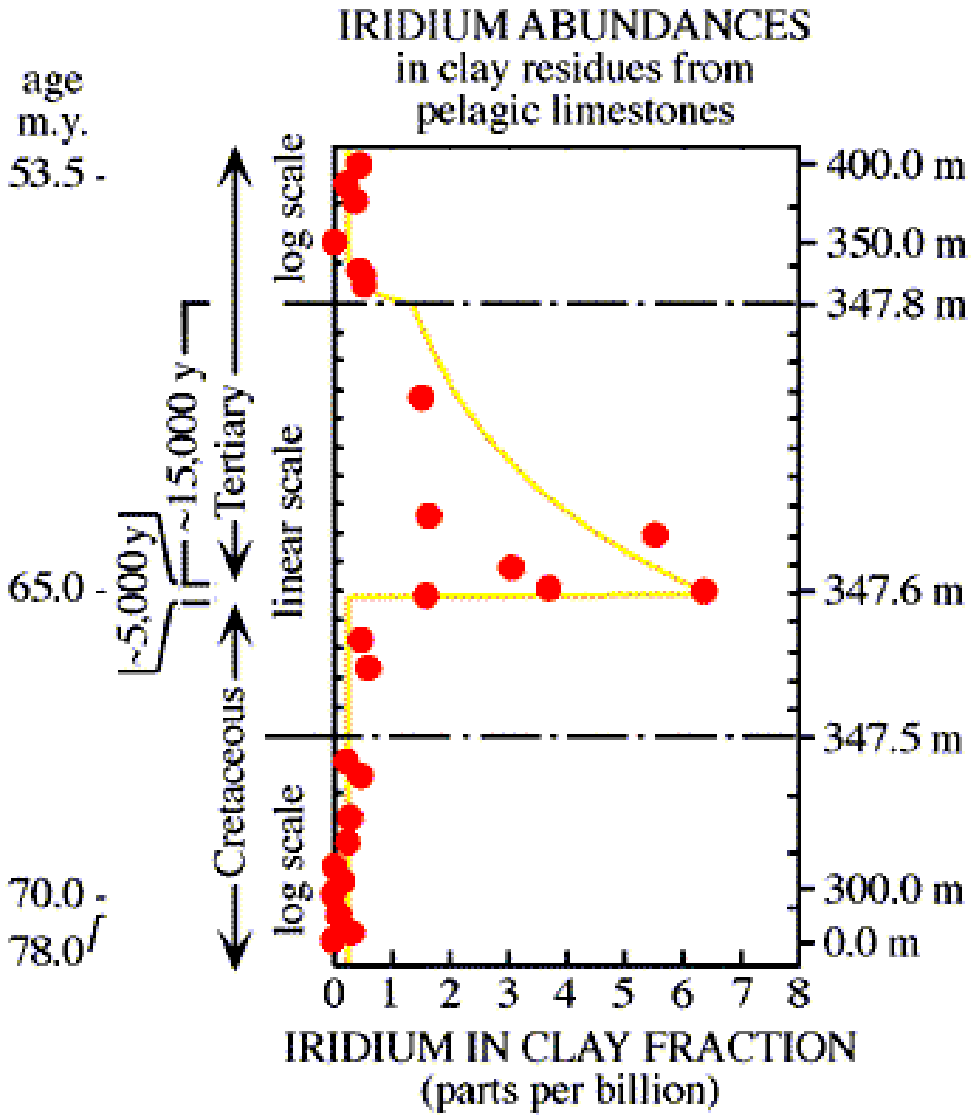
Calcareous plankton, such as planktonic foraminifera and coccolithophorids were very hard hit by the extinction event; so hard that marine photosynthesis was largely shut down.

Groups of organic-walled phytoplankton, such as the dinoflagellates were probably less severely affected because of their encysted benthic life cycle stage.

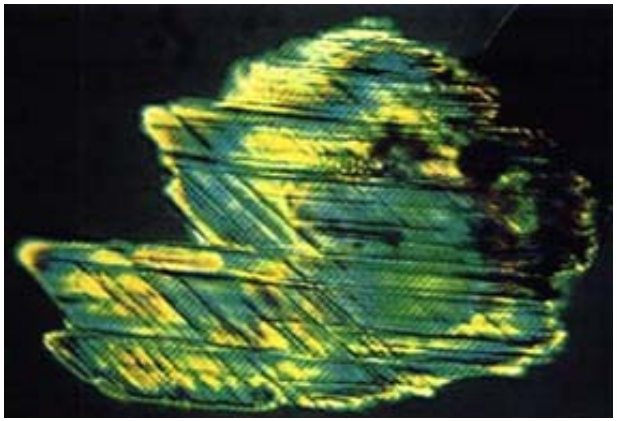


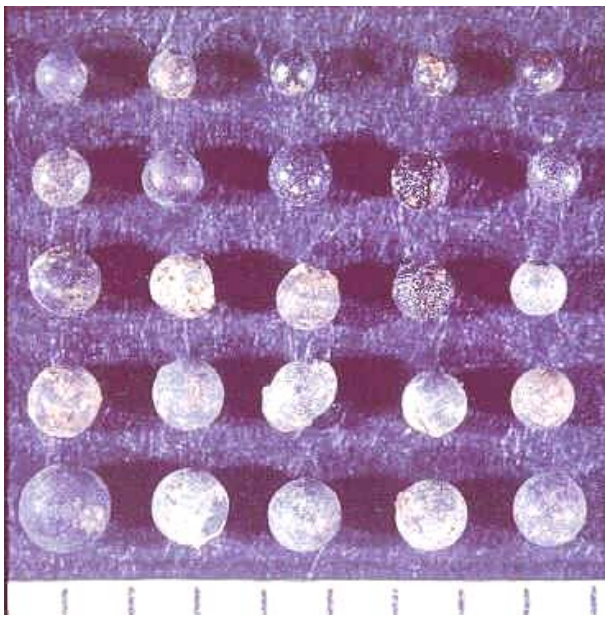
Iridium - a smoking gun

Father and son Alvarez in front of the K/T boundary in Gubbio, Italy



The evidence for K/T impact

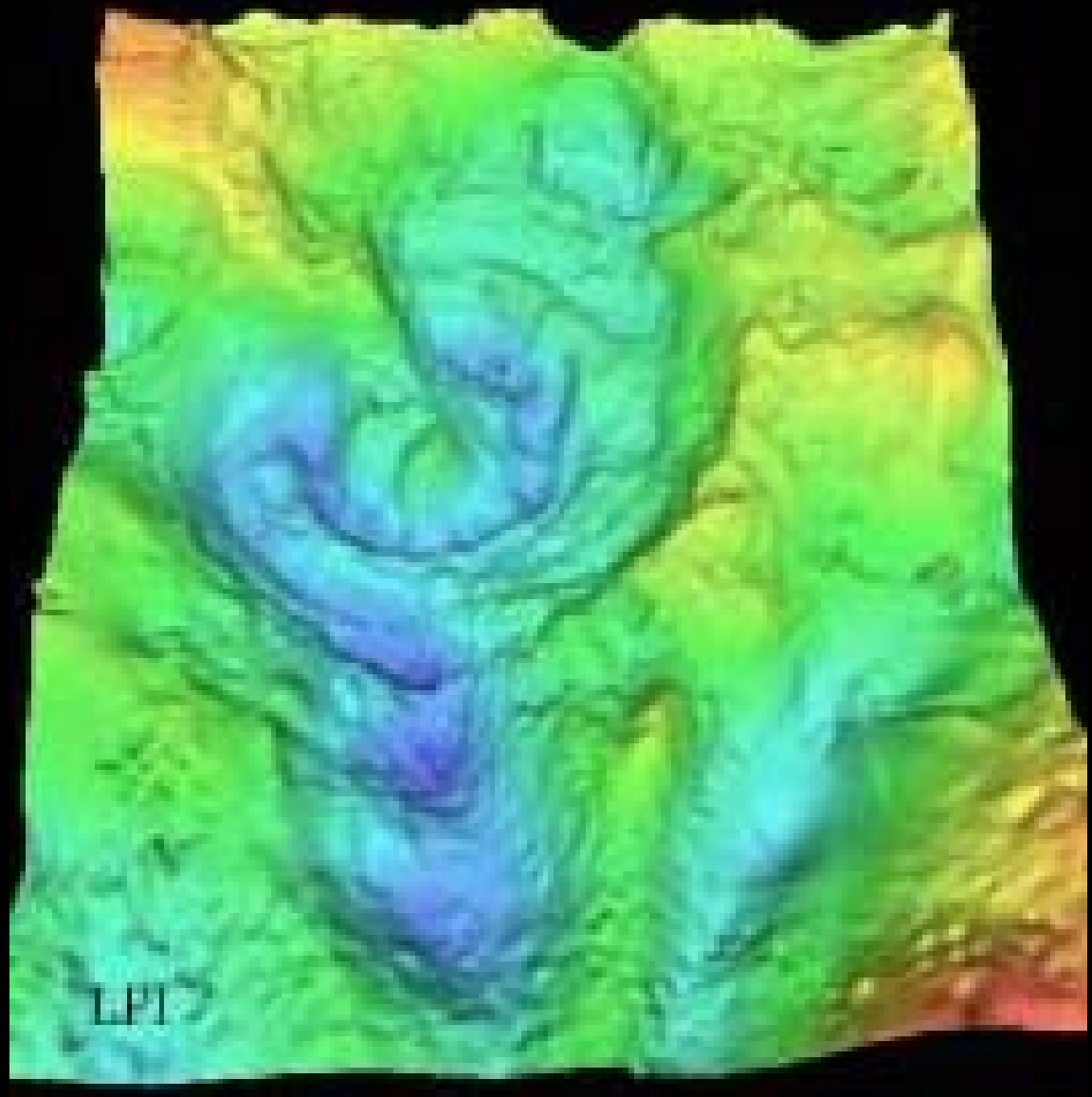




- Worldwide **Ir enrichment** in boundary clays
- Presence of **Magnesioferrite** (Spinel) derived from the vapor phase of an impacting bolide
- **Shocked quartz** representing shock metamorphism of silicate at the site of impact. Also found at sites of nuclear explosions.
- **Micro-tektites** or spherules

But where is the crater???

Impact crater at Chixculub, Yucatan

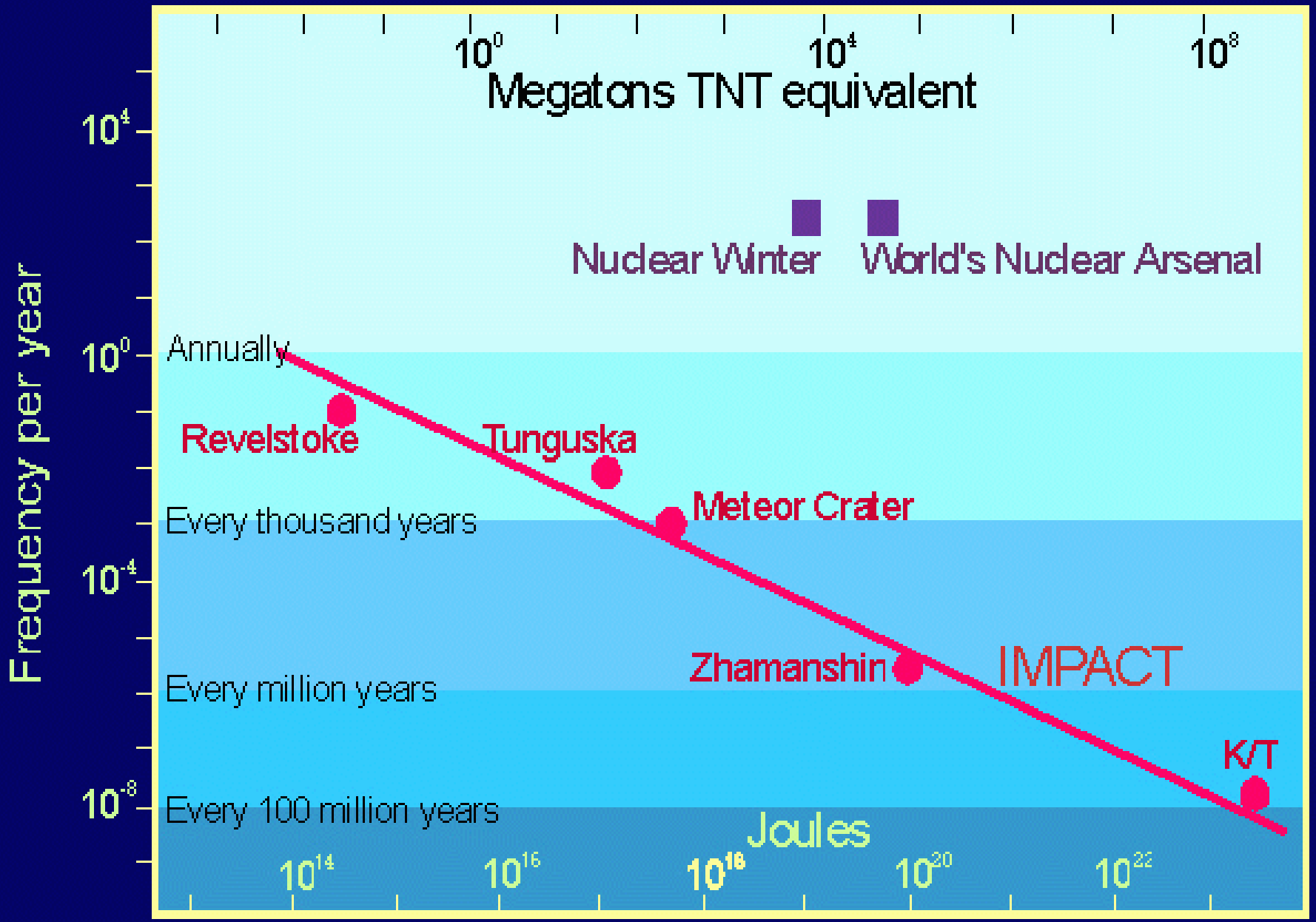


Barringer Crater (Meteor Crater) Arizona, USA.
This crater resulted from an impact 20.000-30.000 B.P.
It is the best preserved large crater today on Earth and has a diameter of ~1200 m. It corresponds to a collision with a iron meteorite of a 100.000 tons and a velocity of 15 km/s.
Power of the explosion: 100 megaton TNT.

Imagine an asteroid the size of Mount Everest slamming into Earth with a speed of up to 20-40 km/s

The energy can be calculated with: $E = 1/2mv^2$

$1*10^{16}$ J = 1 megaton of TNT


Megatons TNT equivalent
10^0
10^4
10^8
Frequency per year
10^4
10^0
10^{-4}
10^{-8}
Nuclear Winter
World's Nuclear Arsenal
Annually
Revelstoke
Tunguska
Every thousand years
Meteor Crater
Zhamanshin
IMPACT
Every million years
K/T
Every 100 million years
Joules
10^{14}
10^{16}
10^{18}
10^{20}
10^{22}

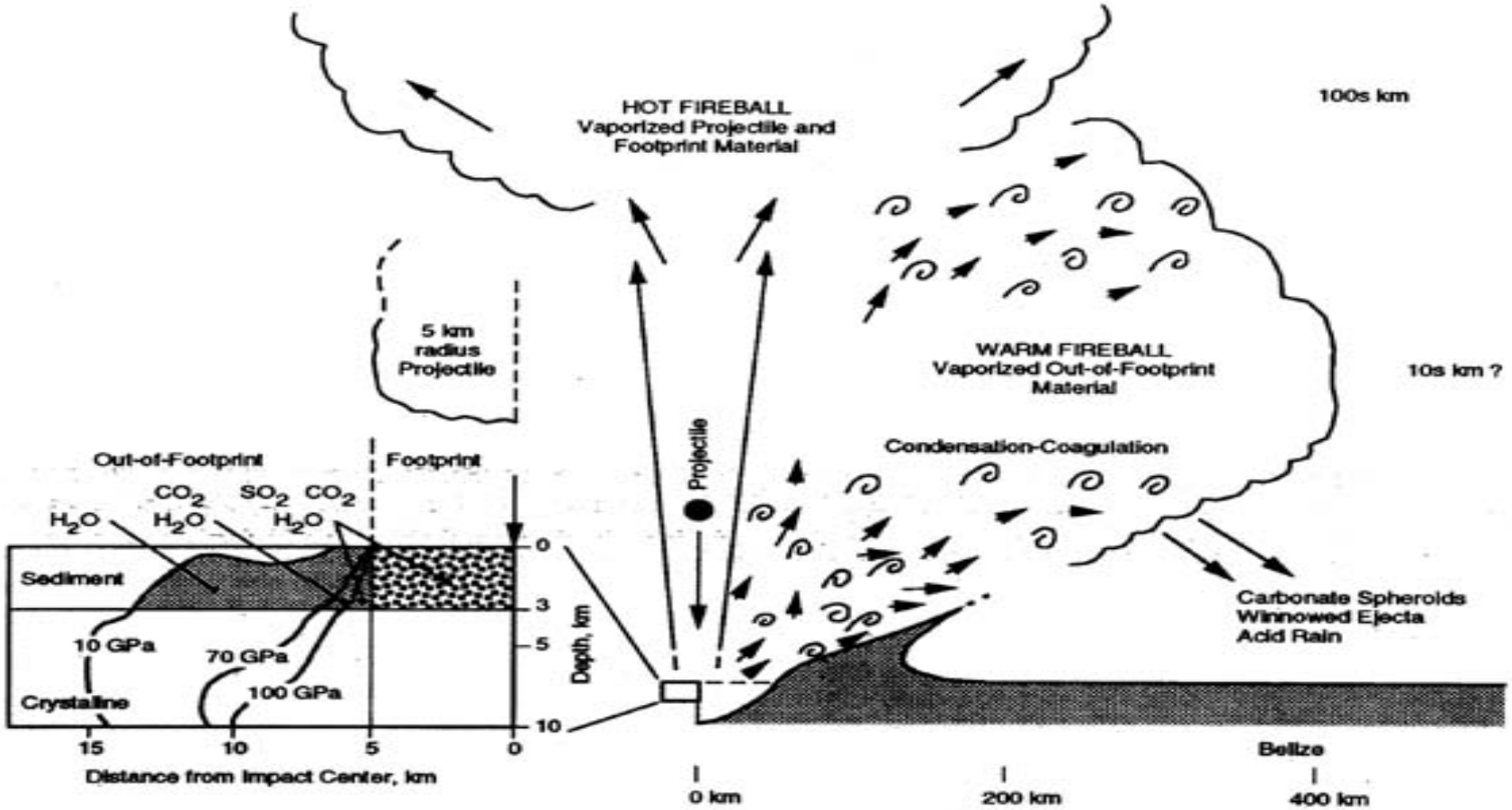
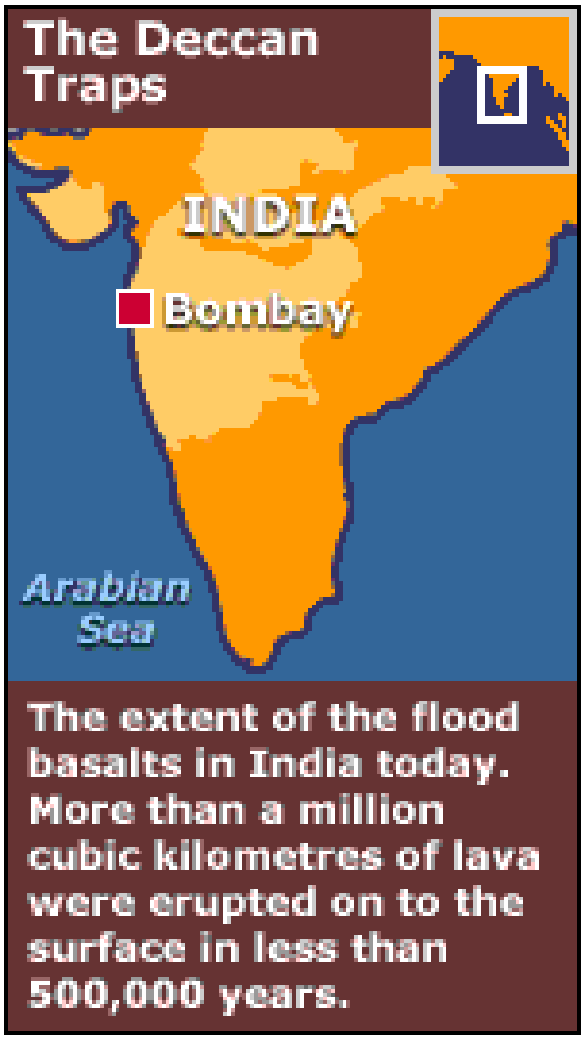


Figure 3. Model of vapor plume formation. Left side of diagram shows results of 2-D hydrocode model (left half only of symmetrical model) of a vertical impact of a 10 km diameter, 20 km/s, asteroid into a wet sedimentary layered target (adapted from *Pope et al.* [1994] and *Ivanov et al.* [1996]). Shown are the footprint and out-of-footprint regions with shock pressures (in GPa) and respective volatile species that are released. The right side of the diagram presents a schematic view of the origin and trajectories of the hot and warm fireballs that evolve from the footprint and out-of-footprint regions, respectively. The hot fireball blows out of the upper atmosphere and is distributed globally (in high-velocity impacts some material is ejected out of Earth orbit). Part of the warm fireball may also blow out of the upper atmosphere and spread globally, but a portion expands laterally, passing through the ejecta curtain, altering the trajectories of the finer ejecta. This lateral blast slows and cools rapidly, depositing particles that condense and coagulate in the plume: a possible origin of the carbonate spherules found in Belize and Mexico and intense sulfuric acid rain in North America (see text).

Impacts & Craters

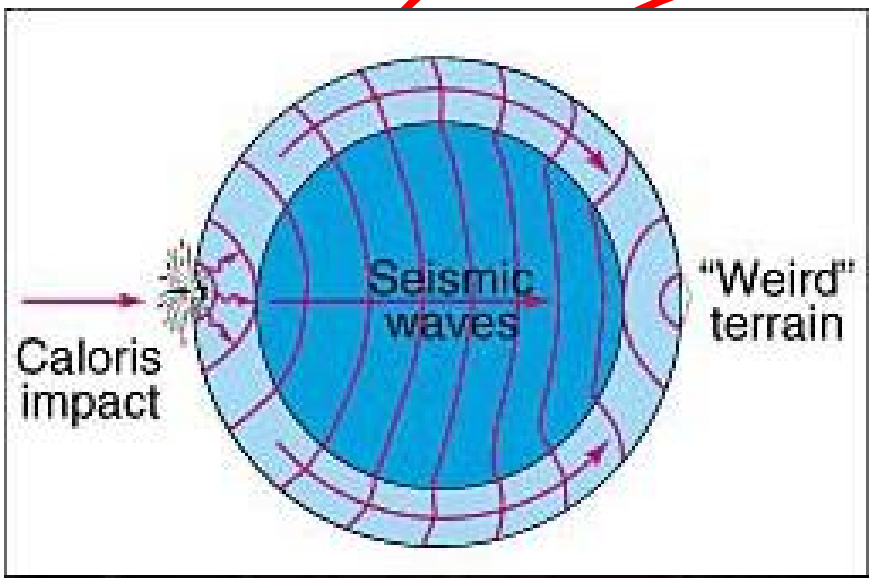
- **Tsunami waves** (>500m high) 1000 km from the impact site
- **Earthquakes** with magnitude 10-12 on Richter scale
- **Global wildfires** based on the presence of charcoal and polynuclear aromatic hydrocarbons in boundary clays.
- Effects of impact on Yucatan peninsula aggravated by:
  - Impact on shallow water carbonate platform
  - Release of CO_2, SO_2 and SO_3
  - Release Cl and Br
- **Sulfate aerosols** were converted to acid rain
- **Shock heating** of the atmosphere resulted in nitric acid rain
- Short term effect will have been cooling, but the long term effect might have been global warming
- The explosion of the bolide is likely to have released large quantities of heavy metals (Ni) that poisoned organisms.

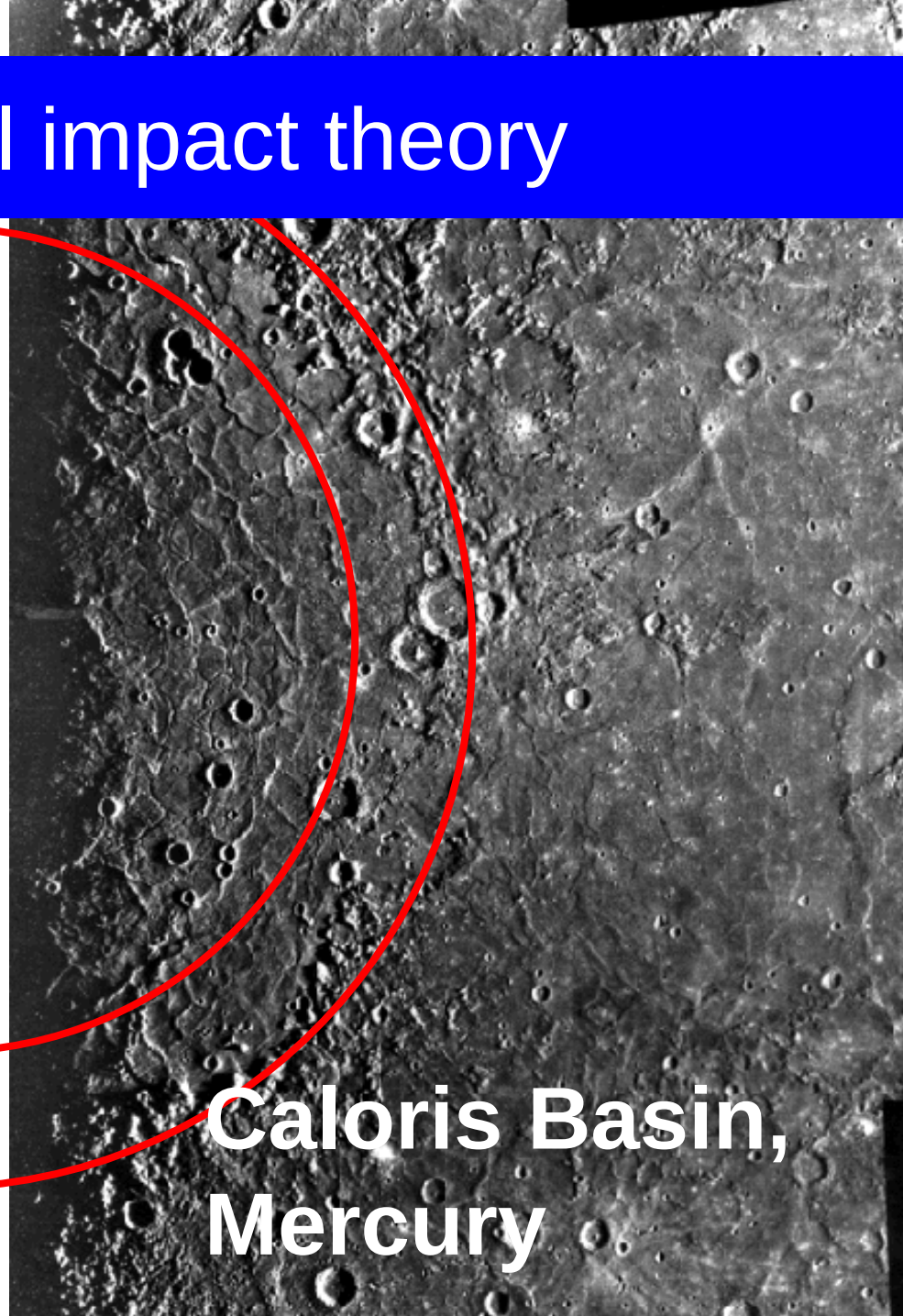
The Deccan Traps



The extent of the flood basalts in India today. More than a million cubic kilometres of lava were erupted on to the surface in less than 500,000 years.

The antipodal impact theory





Caloris Basin, Mercury

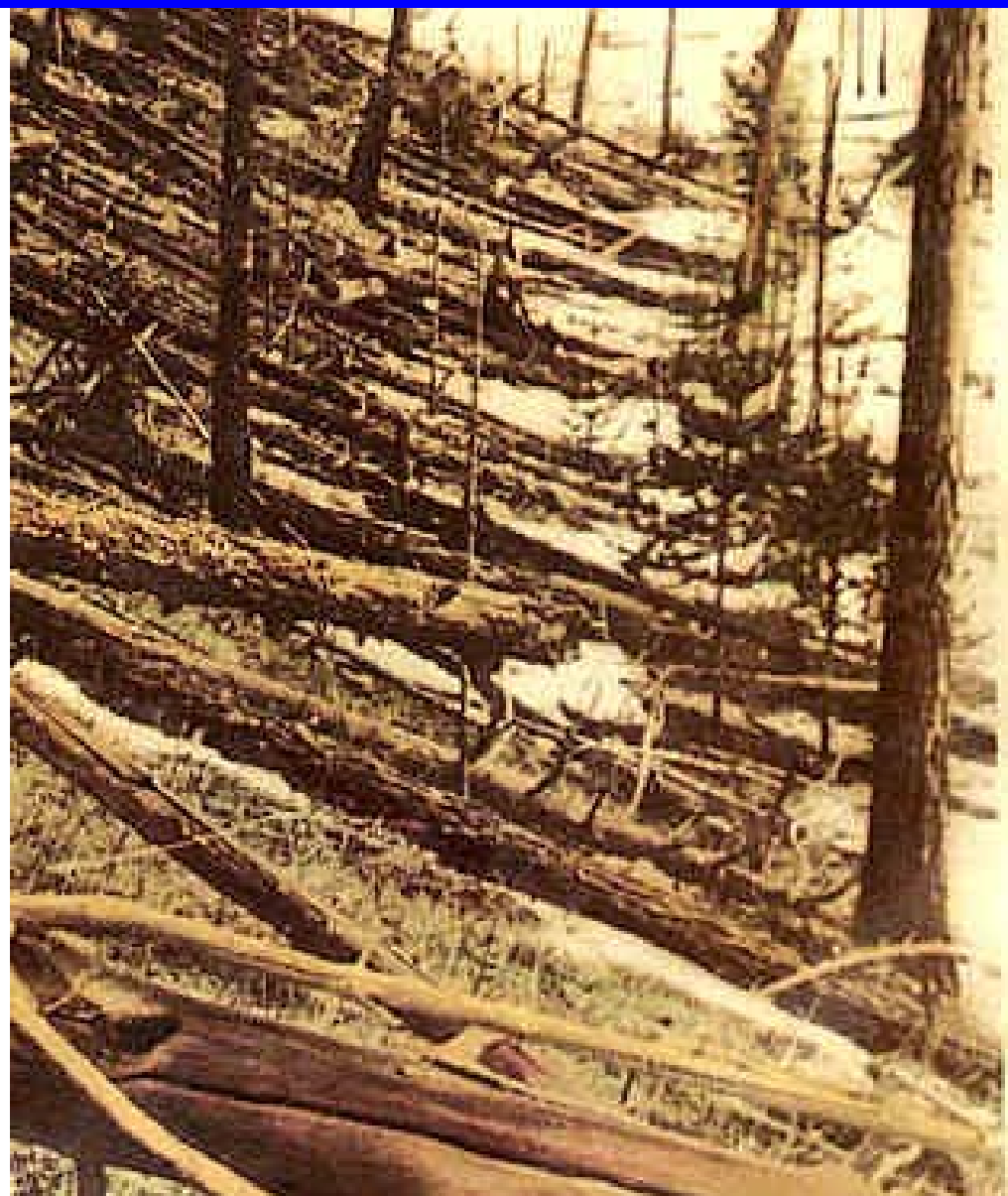
SUMMARY

The Future

The 6th extinction

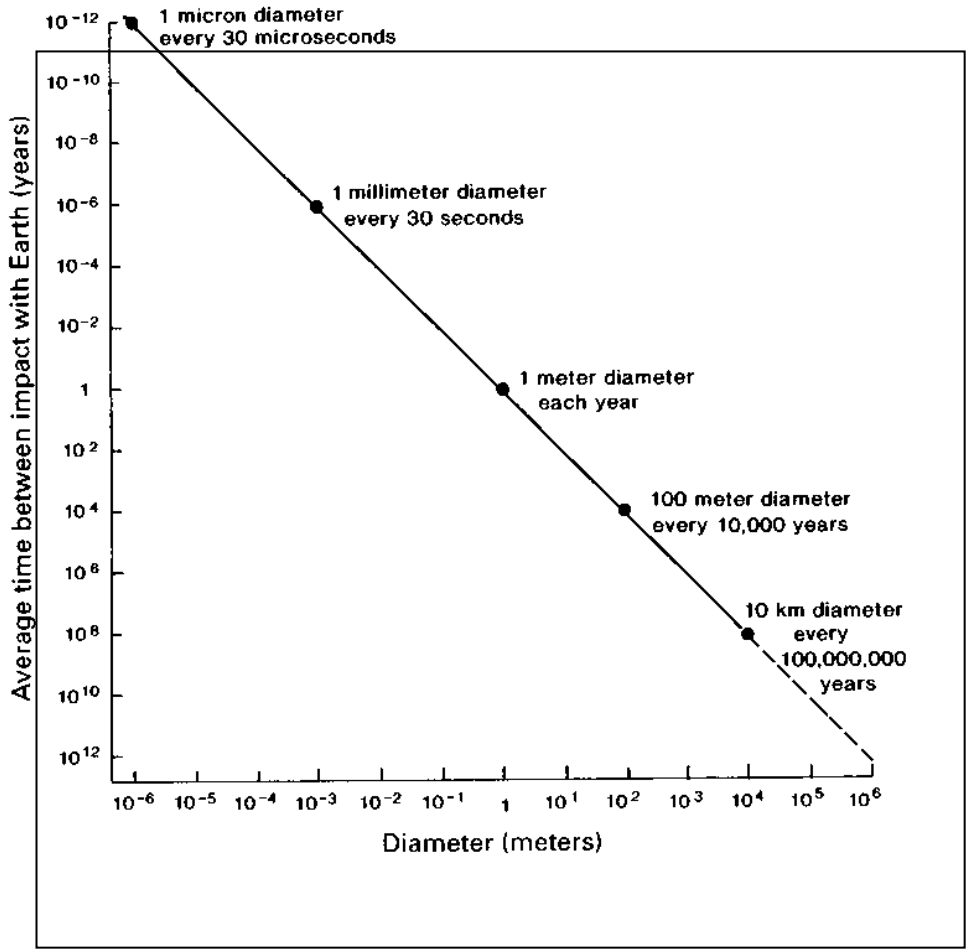
The Tunguska-event

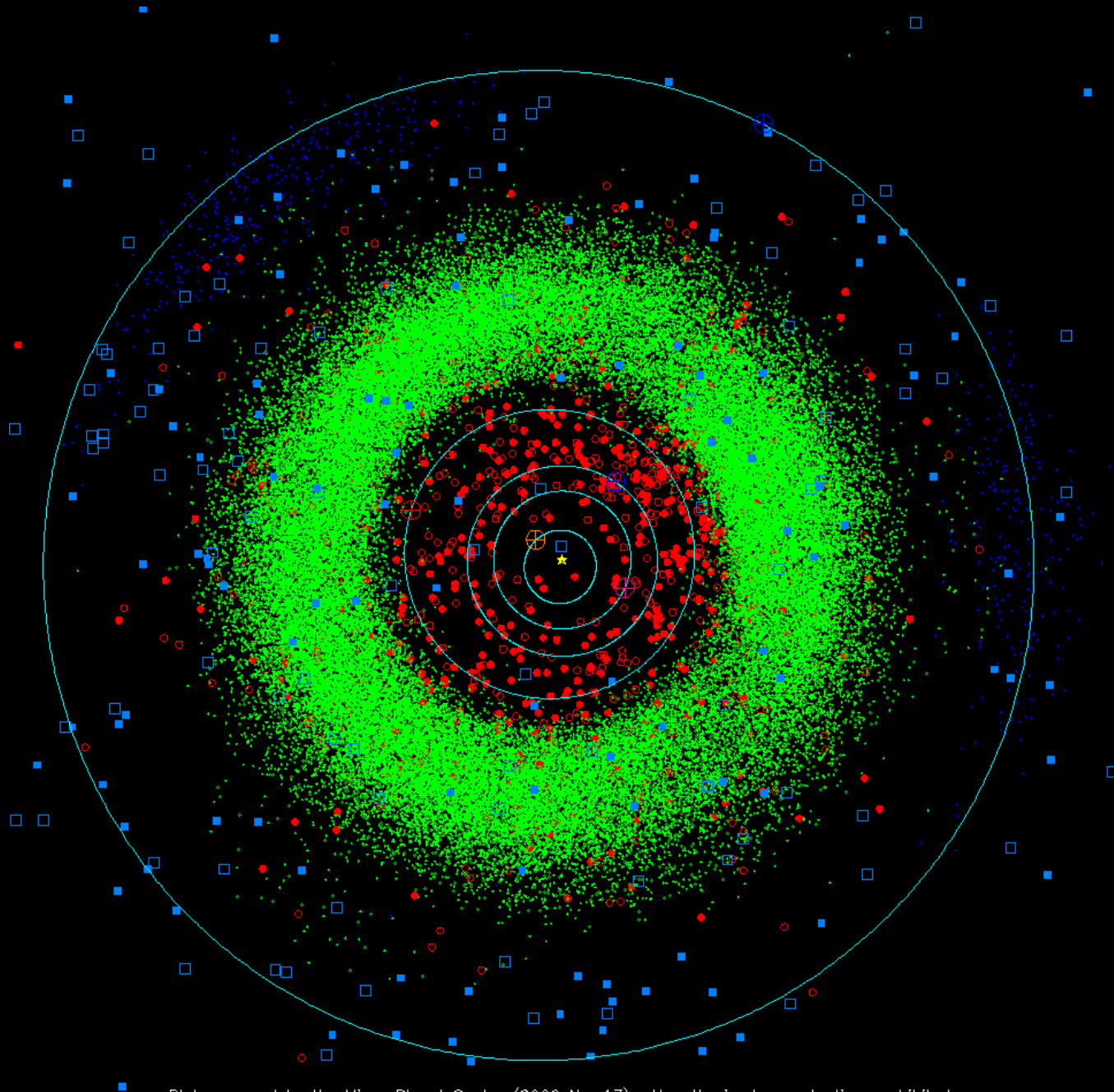
- On the 30th of June 1908 a large meteorite or possibly a comet exploded above Siberia in a remote non-populated area
- No crater was found, but trees in an area of 40 km were blown to ground
- The sound of the explosion was heard in London
- The power of the explosion was estimated to represent 1000 Hiroshima A-bombs



The Future

- A large asteroid 1997 XF11 (1.6 km diameter) will be passing by Earth in 2028 at a very close distance: only 1.000.000 km
- Other estimates speak of only 50.000 km !!!!!!
- On impact with Earth this asteroid might create a global catastrophe we will not survive

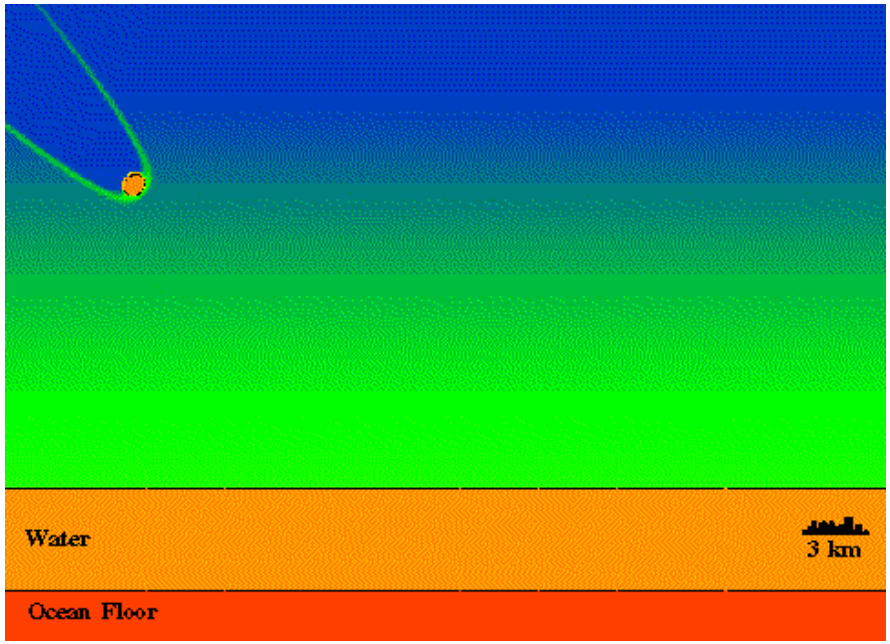


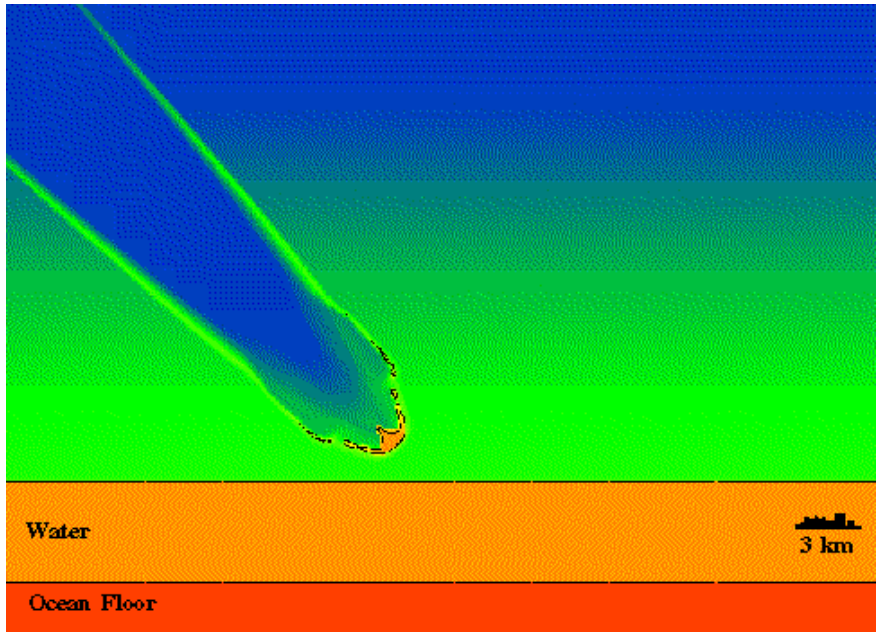

Plot prepared by the Minor Planet Center (2000 Nov.17). Unauthorized reproduction prohibited.

The Future

- There are currently 108 PHA's, which means *Potentially Hazardous Objects.*

- These objects are being watched and their trajectories calculated.
- US congress has demanded NASA to make a greater effort in tracing and cataloging these PHA 's.
- It is believed that NEOs (near Earth objects) that are on a collision course with Earth might be deviated with neutron bombs.


Water
3 km
Ocean Floor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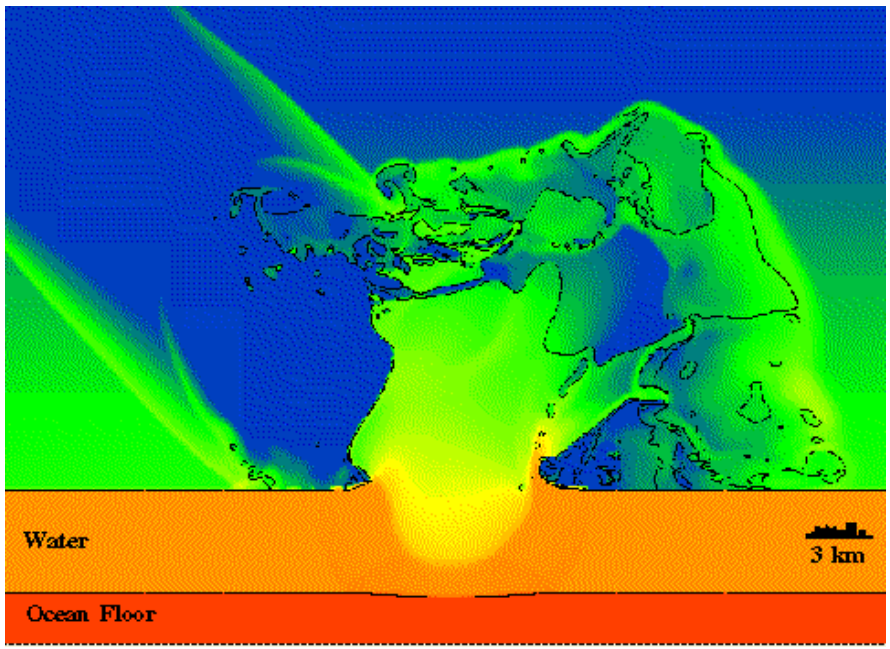
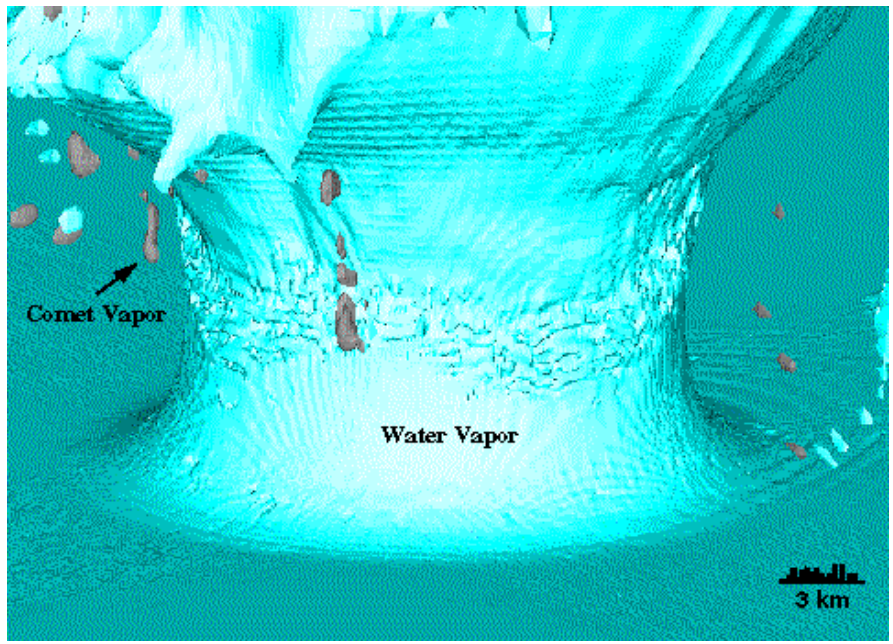

Water
3 km
Ocean Floor


Comet Vapor
Water Vapor
3 km