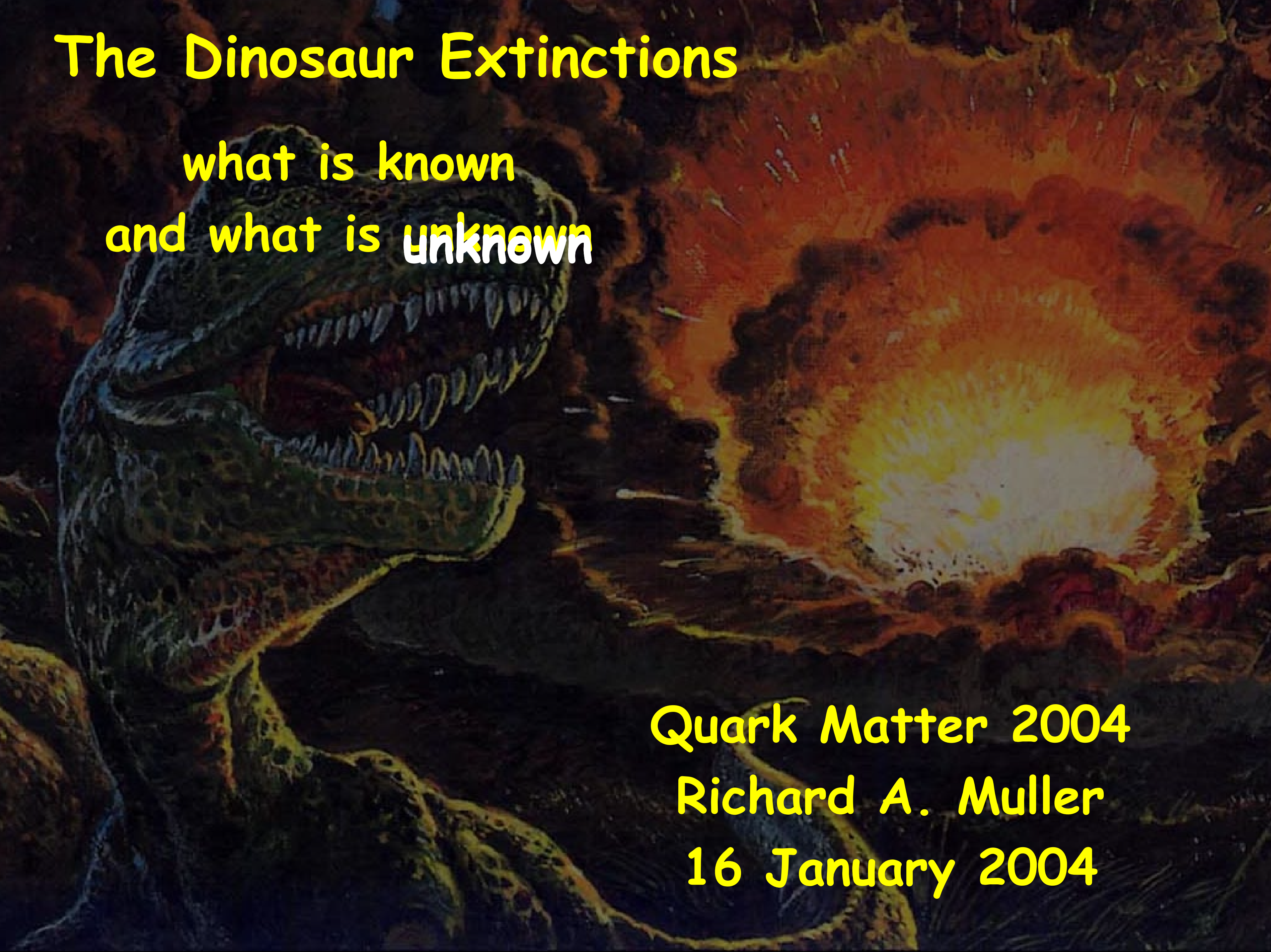


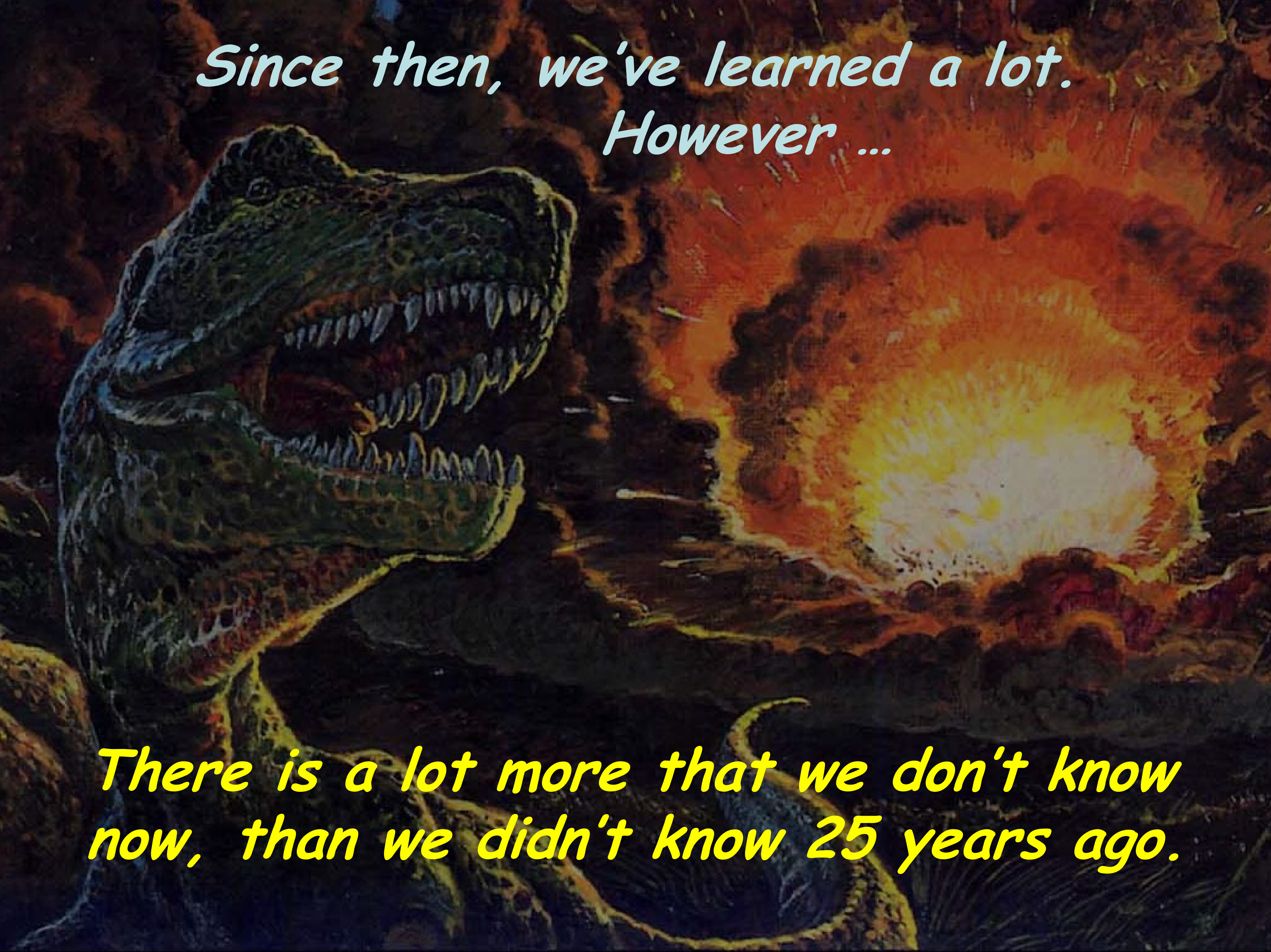
The Dinosaur Extinctions

what is known
and what is unknown

Quark Matter 2004
Richard A. Muller
16 January 2004

1978
Luis Alvarez
and
Walter Alvarez

with Frank Asaro & Helen Michel, analyzed a thin layer of clay, and deduced that an asteroid or comet had killed the dinosaurs.


Since then, we've learned a lot.
However …
There is a lot more that we don't know now, than we didn't know 25 years ago.

1812: George Cuvier discovers *extinctions*

Rock from sediment preserves the history of life

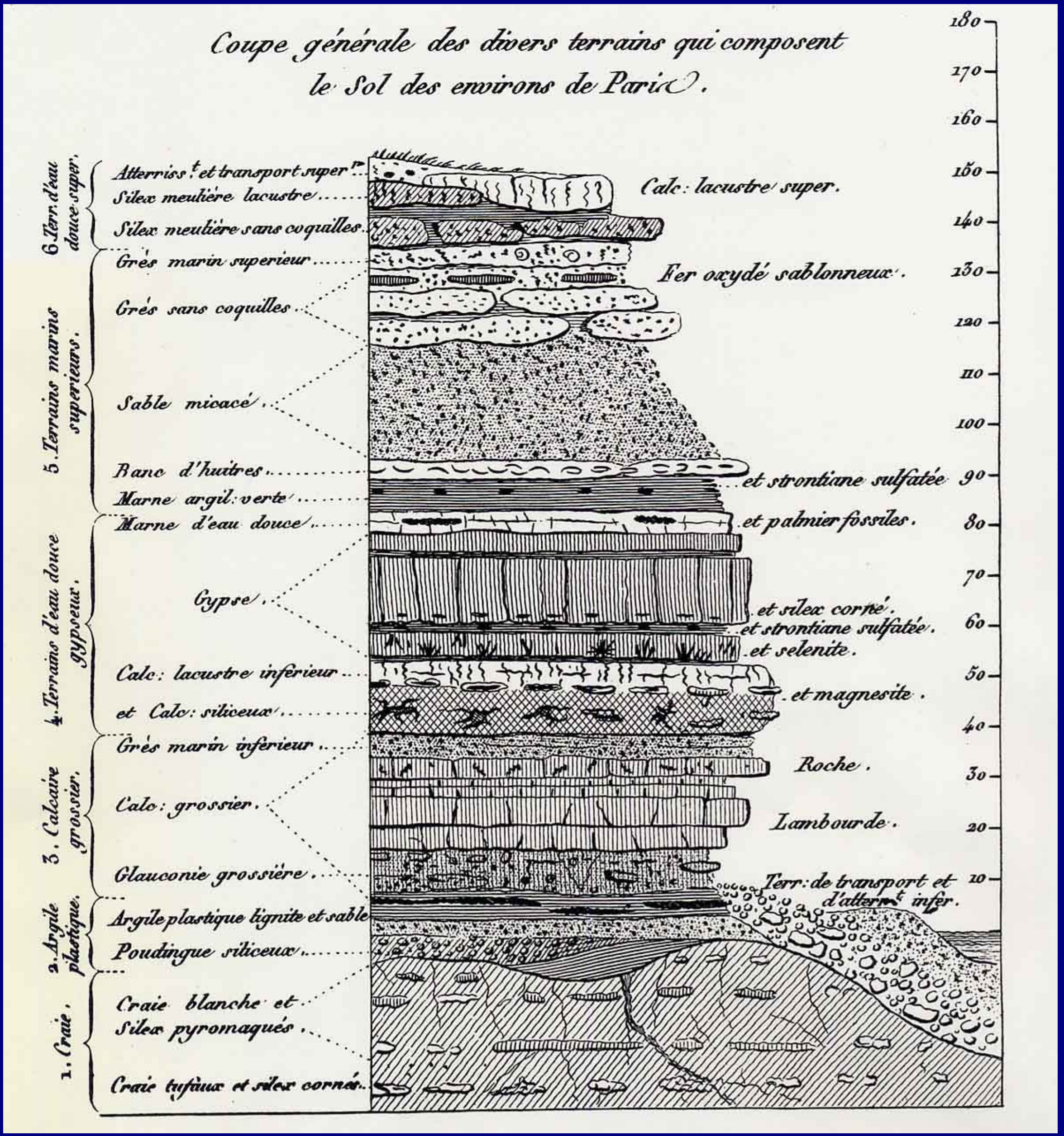
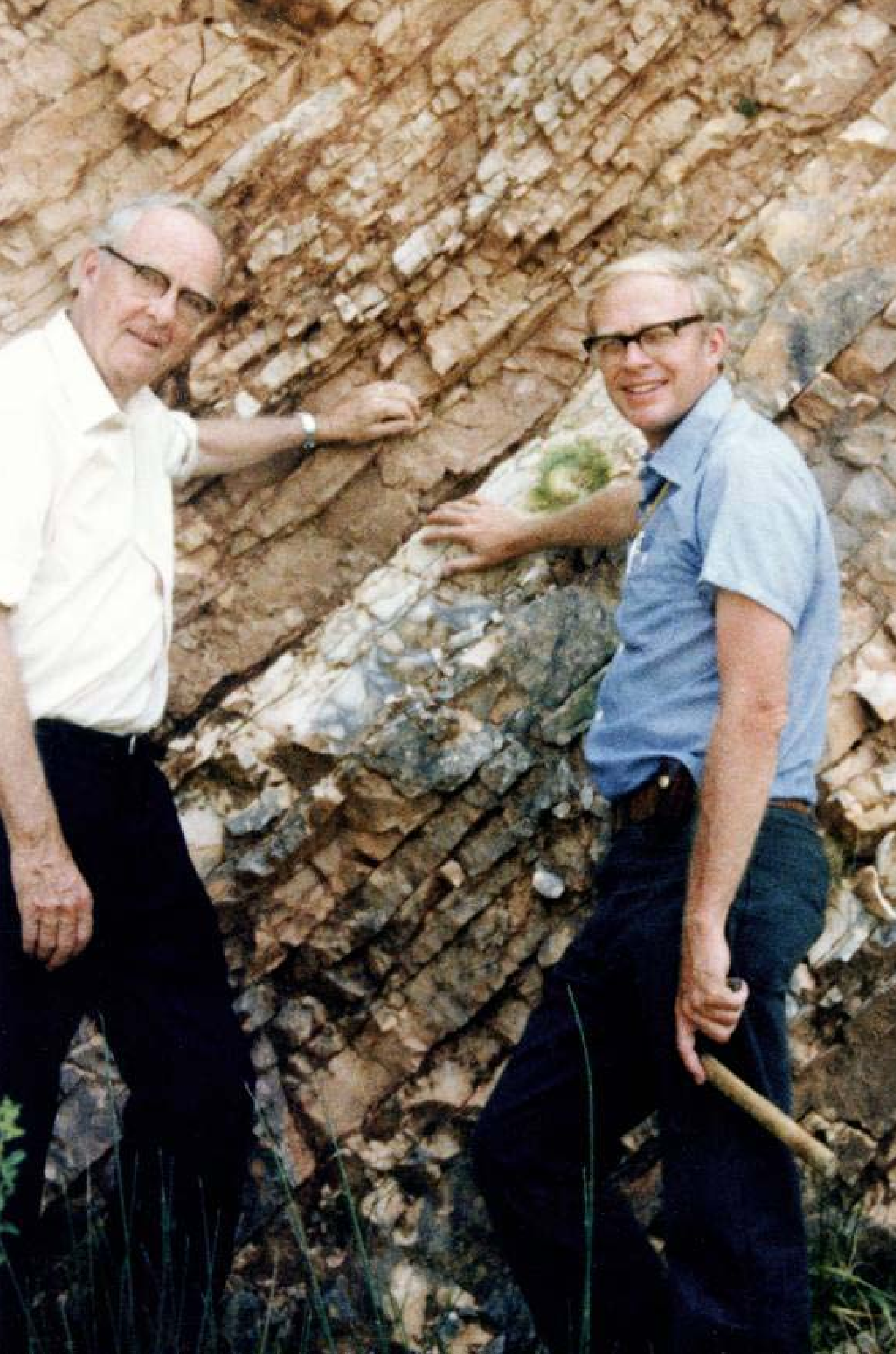
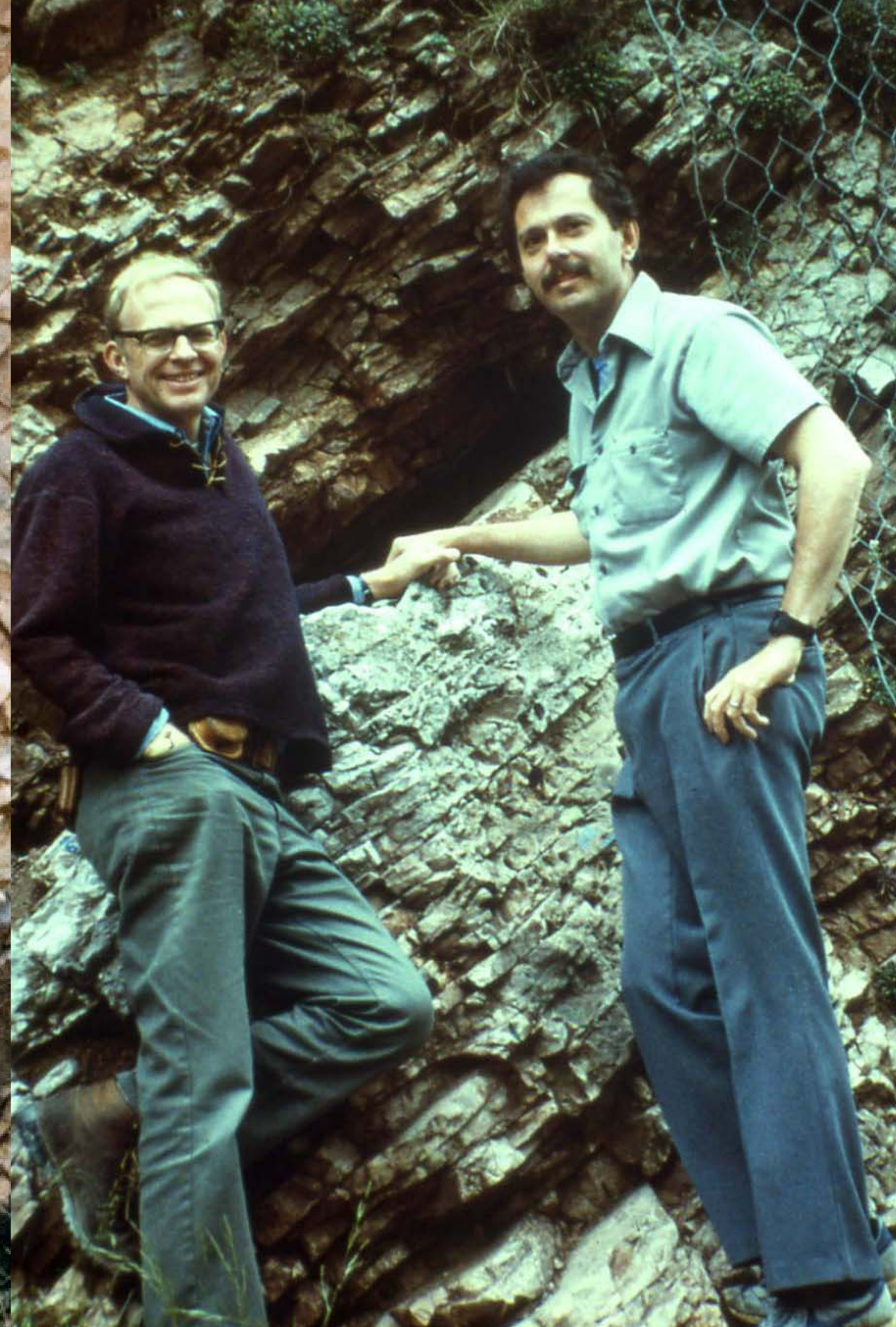
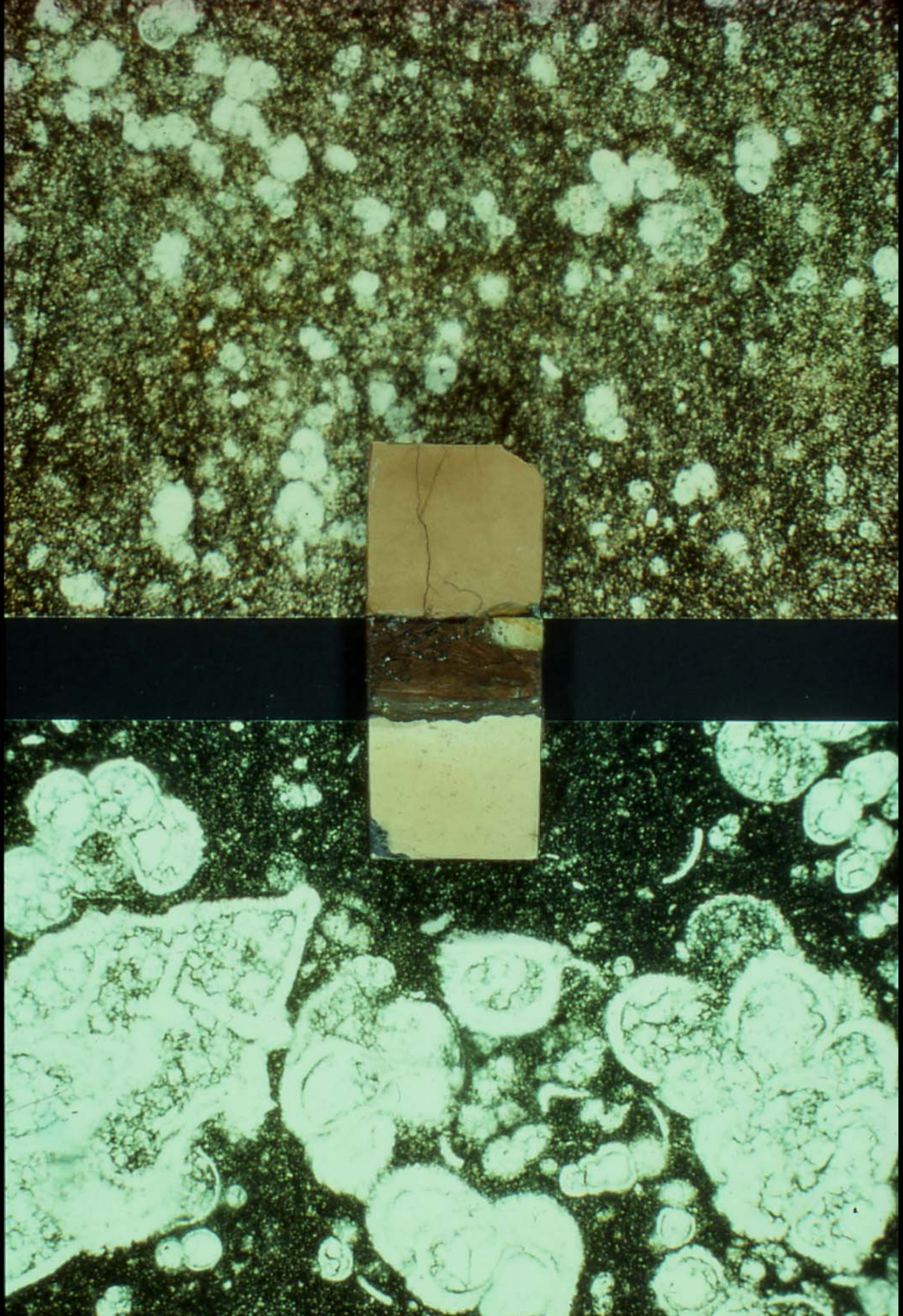
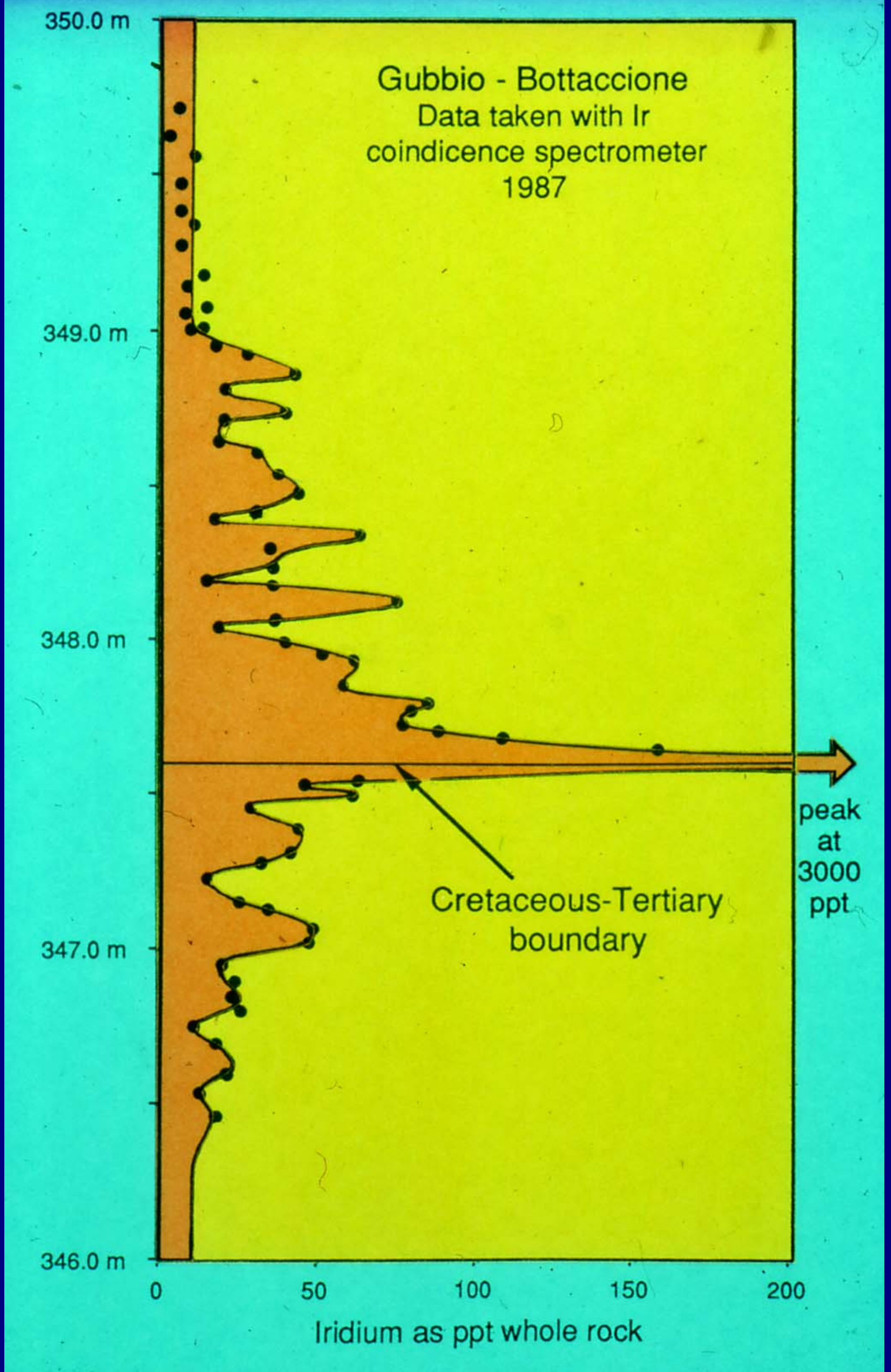


Figure from Cuvier: *Discourse on the Revolutions of the Surface of the Globe* (1812)

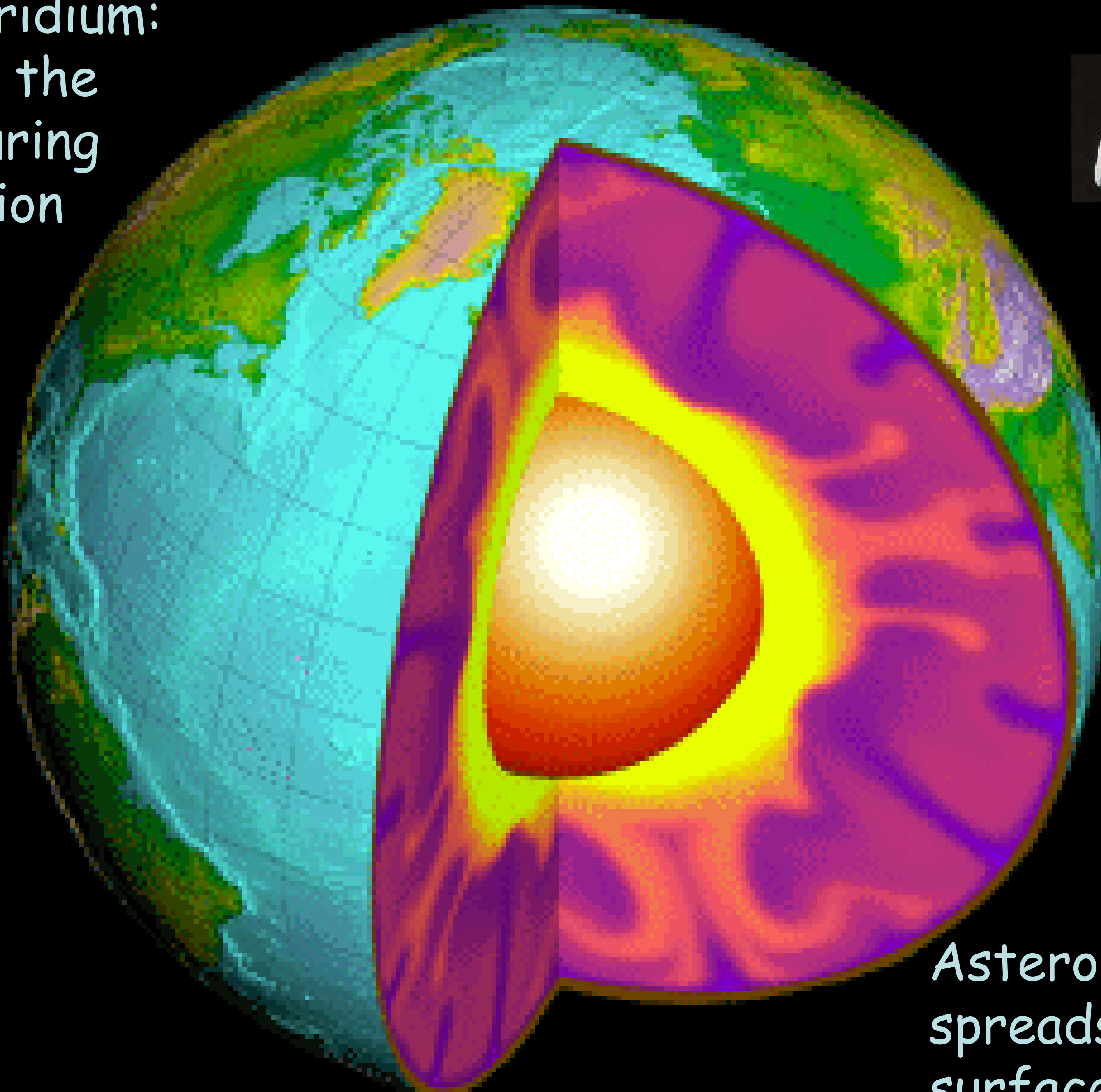





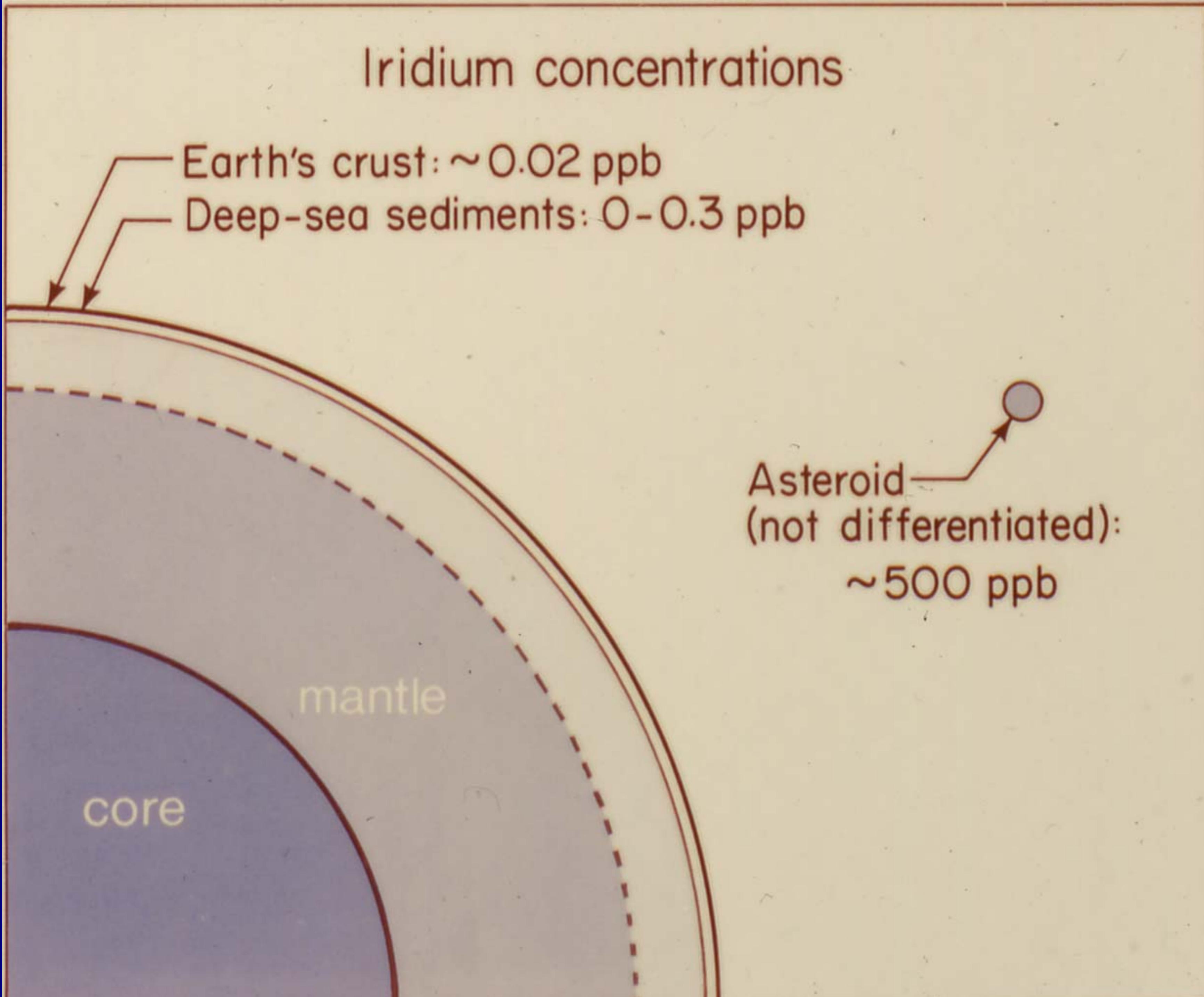
Mass extinction

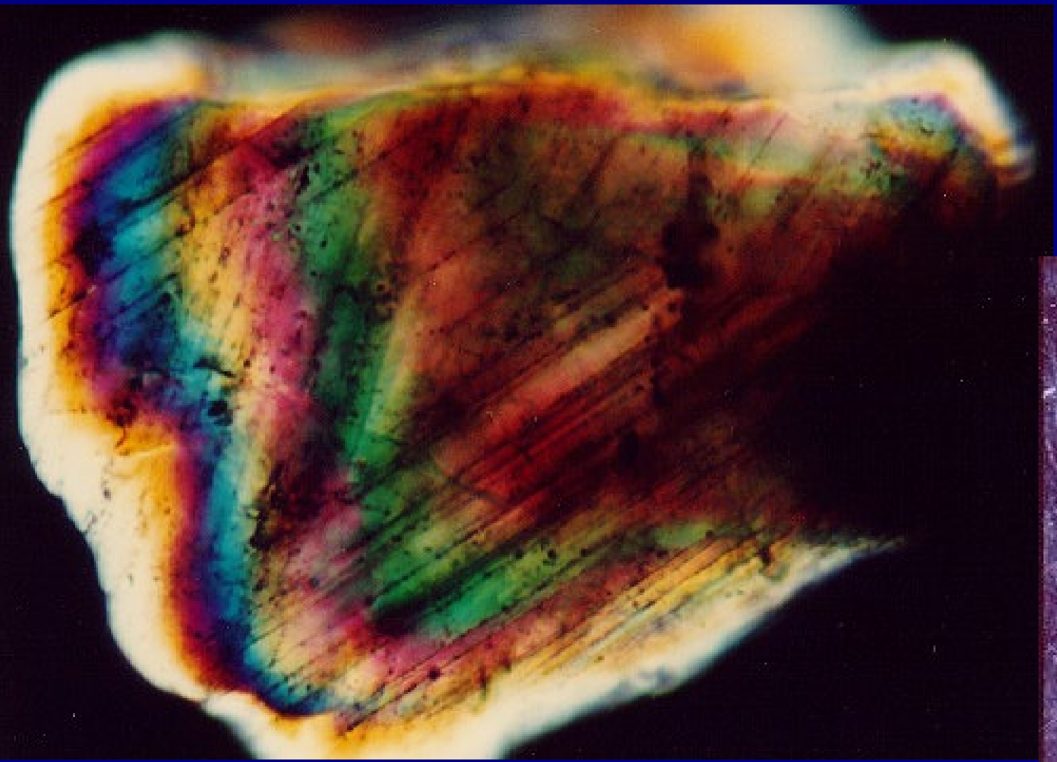

Gubbio - Bottaccione
Data taken with Ir
coindicence spectrometer
1987
350.0 m
349.0 m
348.0 m
347.0 m
346.0 m
Cretaceous-Tertiary
boundary
peak
at
3000
ppt
0
50
100
150
200
Iridium as ppt whole rock

Earth iridium:
sunk to the
core during
formation



Asteroid iridium:
spreads on the
surface

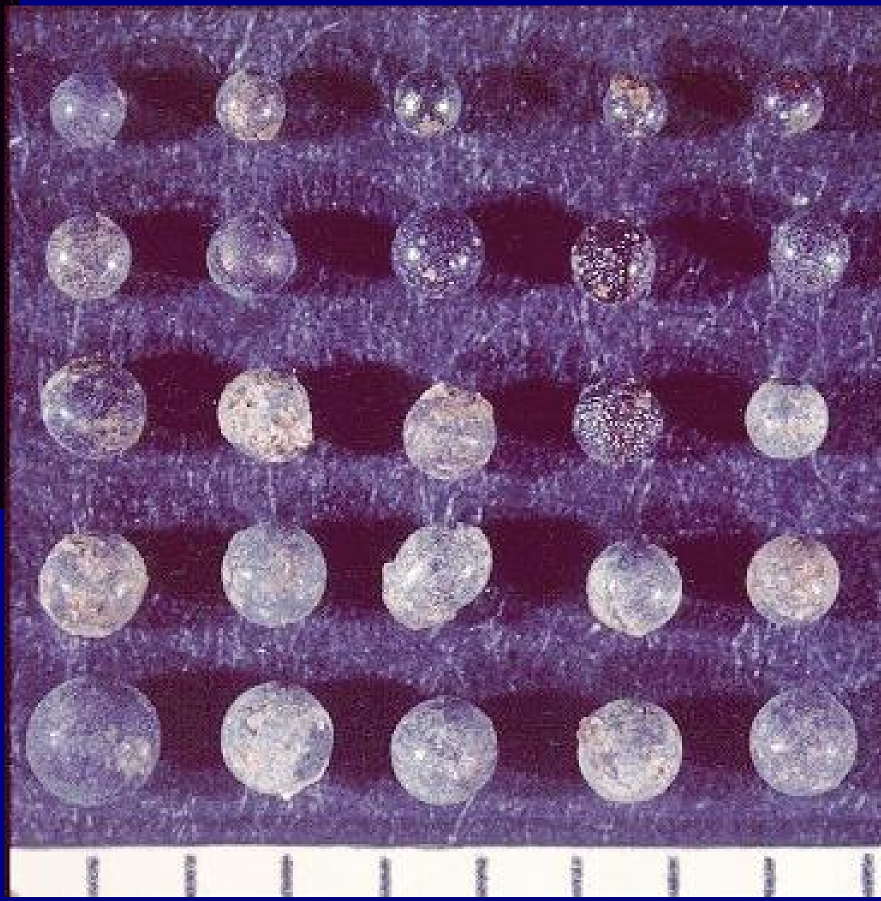

Iridium concentrations
Earth's crust: ~0.02 ppb
Deep-sea sediments: 0-0.3 ppb
Asteroid
(not differentiated):
~500 ppb
mantle
core



Shocked Quartz

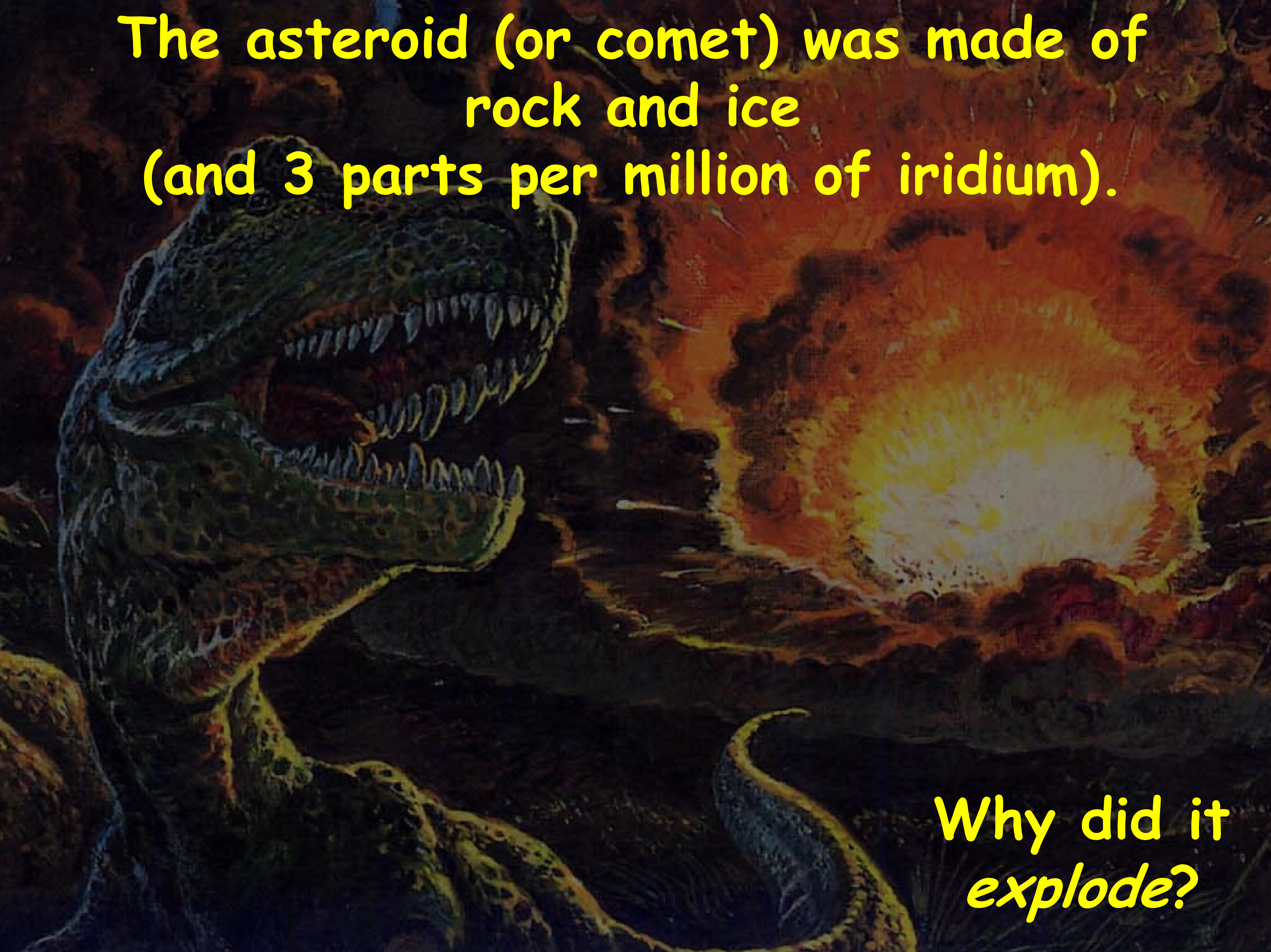
(courtesy of Alan Hildebrand)

micro tektites



1 mm

(courtesy Geological survey of Canada)



The asteroid (or comet) was made of rock and ice (and 3 parts per million of iridium).

Why did it *explode*?

a little physics:

kinetic energy of asteroid/comet

Kinetic energy = (1/2) m v^2

For v = 30 km/sec = 3 $x10^6$ cm/sec

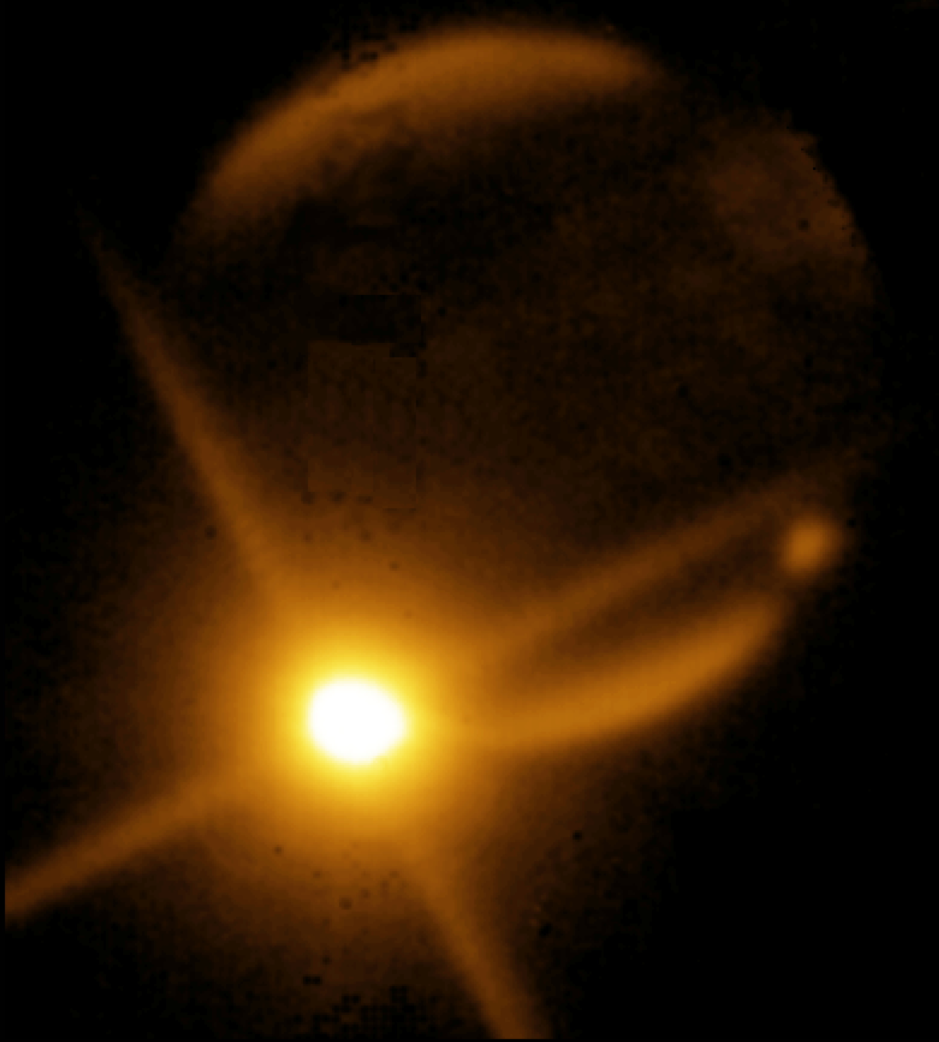
Kinetic energy per gram = (1/2) v^2

= 4 $x10^{12}$ erg/gm = 4 $x10^5$ joule/gm

= 10^5 cal/gm = 100 Cal/gm

= 100 x TNT

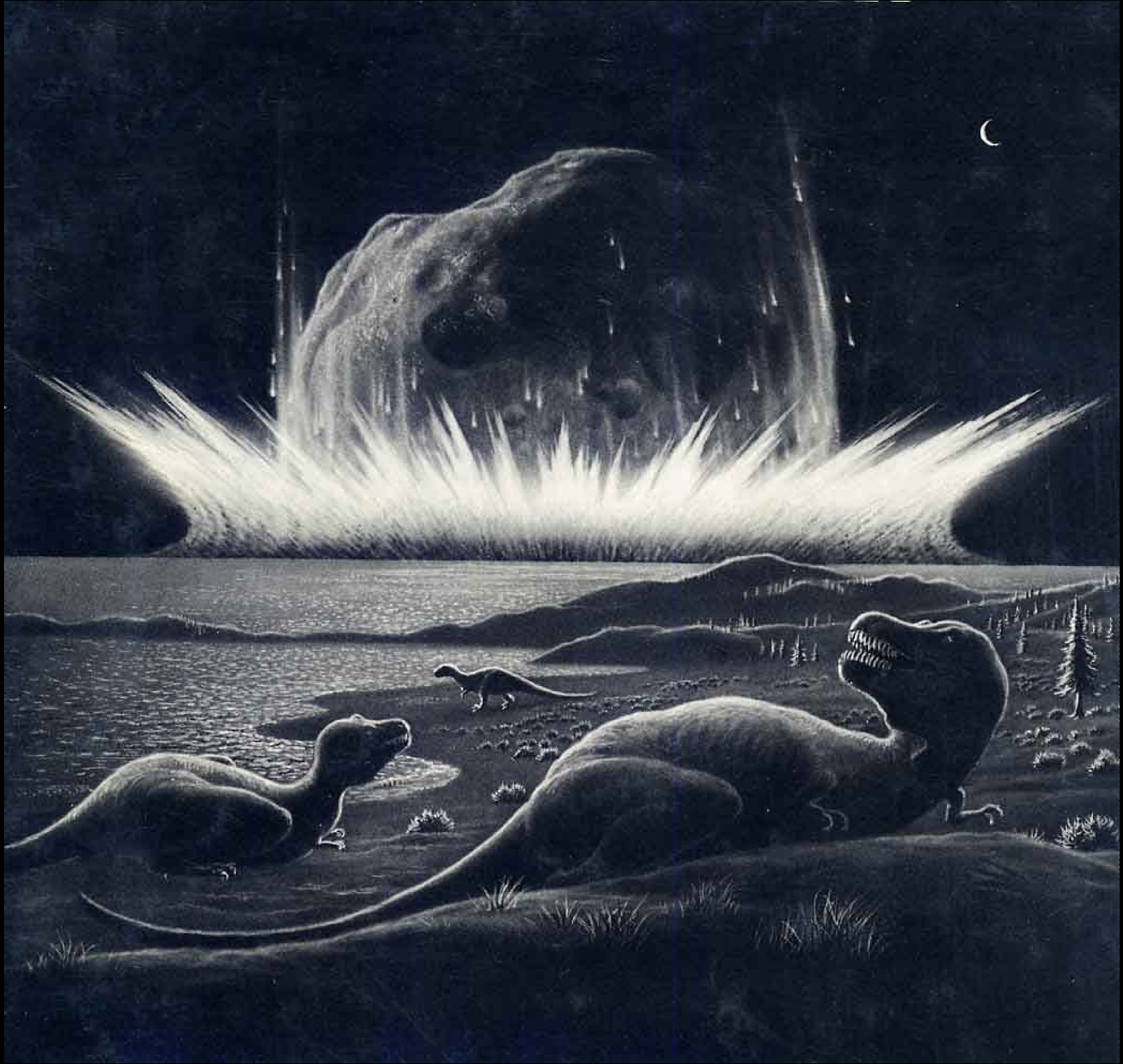
1 km comet impact on Jupiter
July 18, 1994
Velocity ≈ 60 km/sec
Energy = 0.004 Cretaceous impact



An Art Gallery:

Dinosaurs notice the impact

by John Dawson



Don Davis


PREHISTORIC WORLD
IMAGES™
J. Moravec
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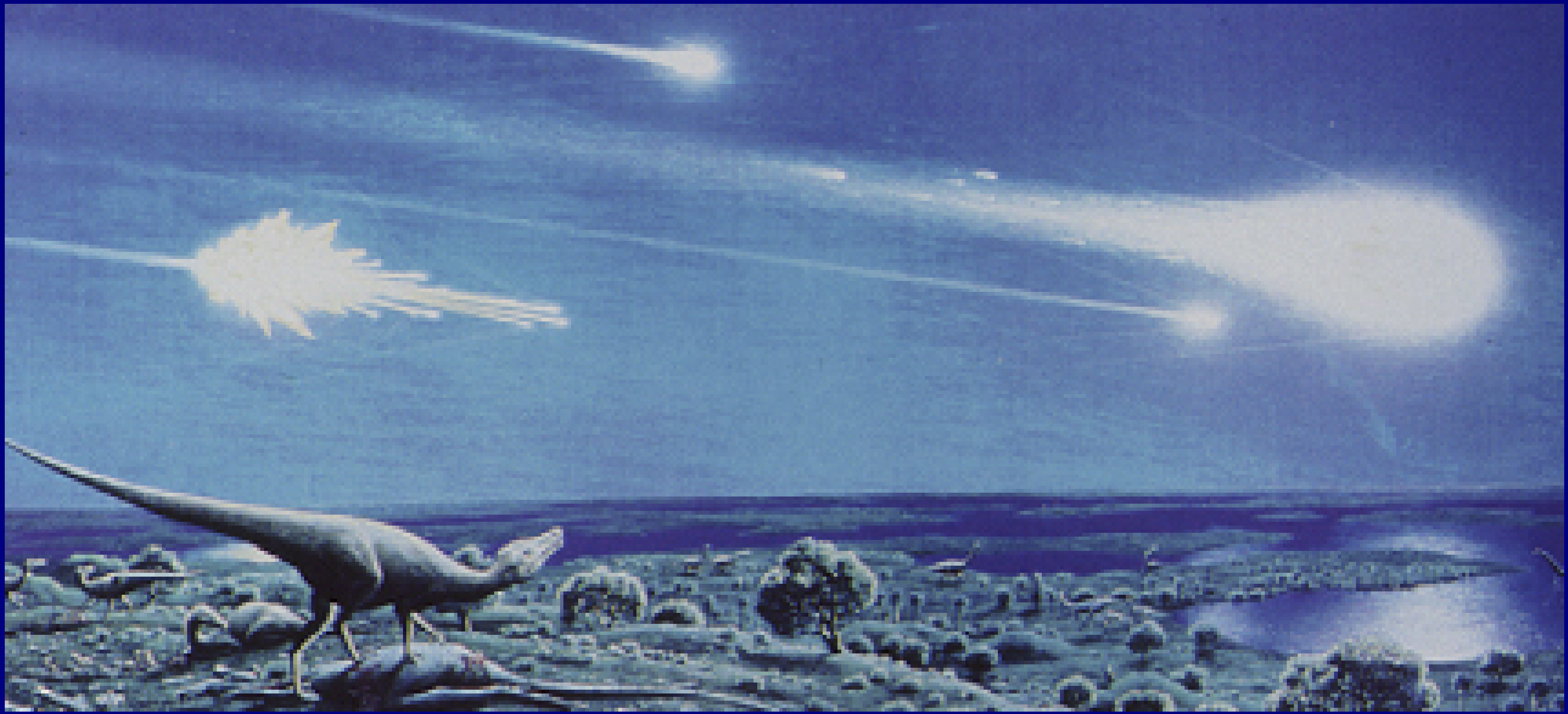
Vincent Perez

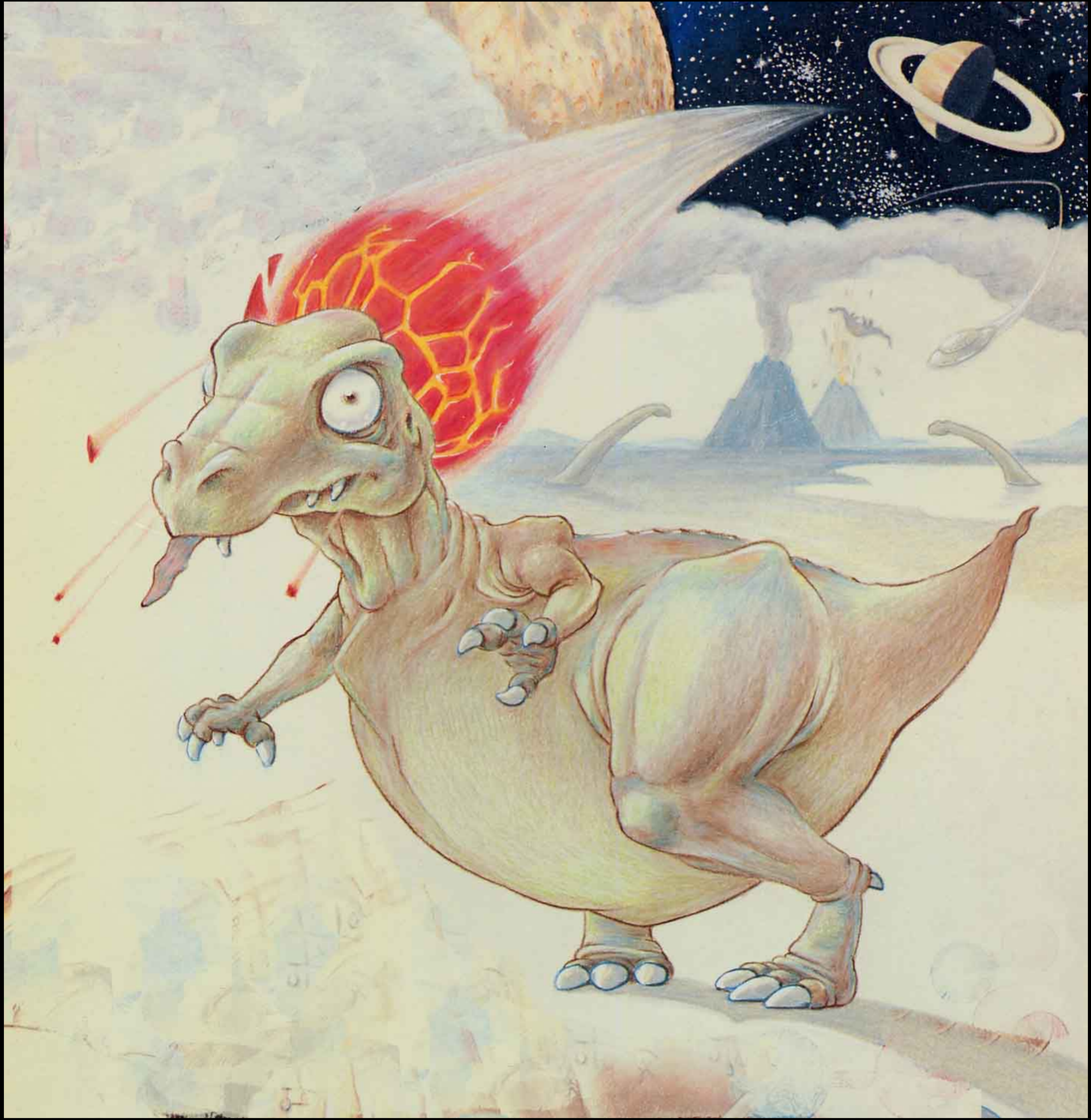
Cover art by Braldt Braids


T-Rex
Hanno Kuhn
Wilfried Kuhn
RIO GRANDE GAMES

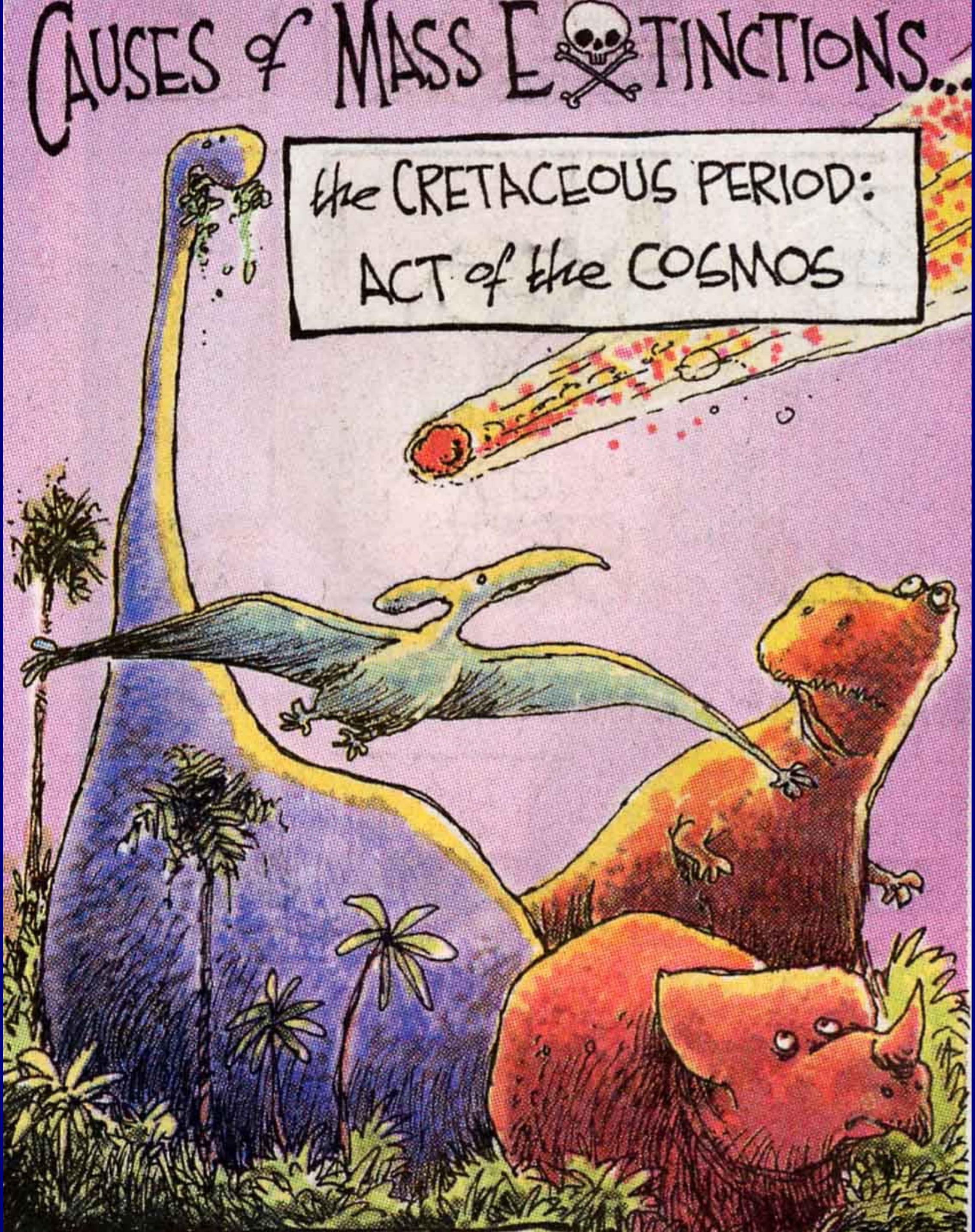


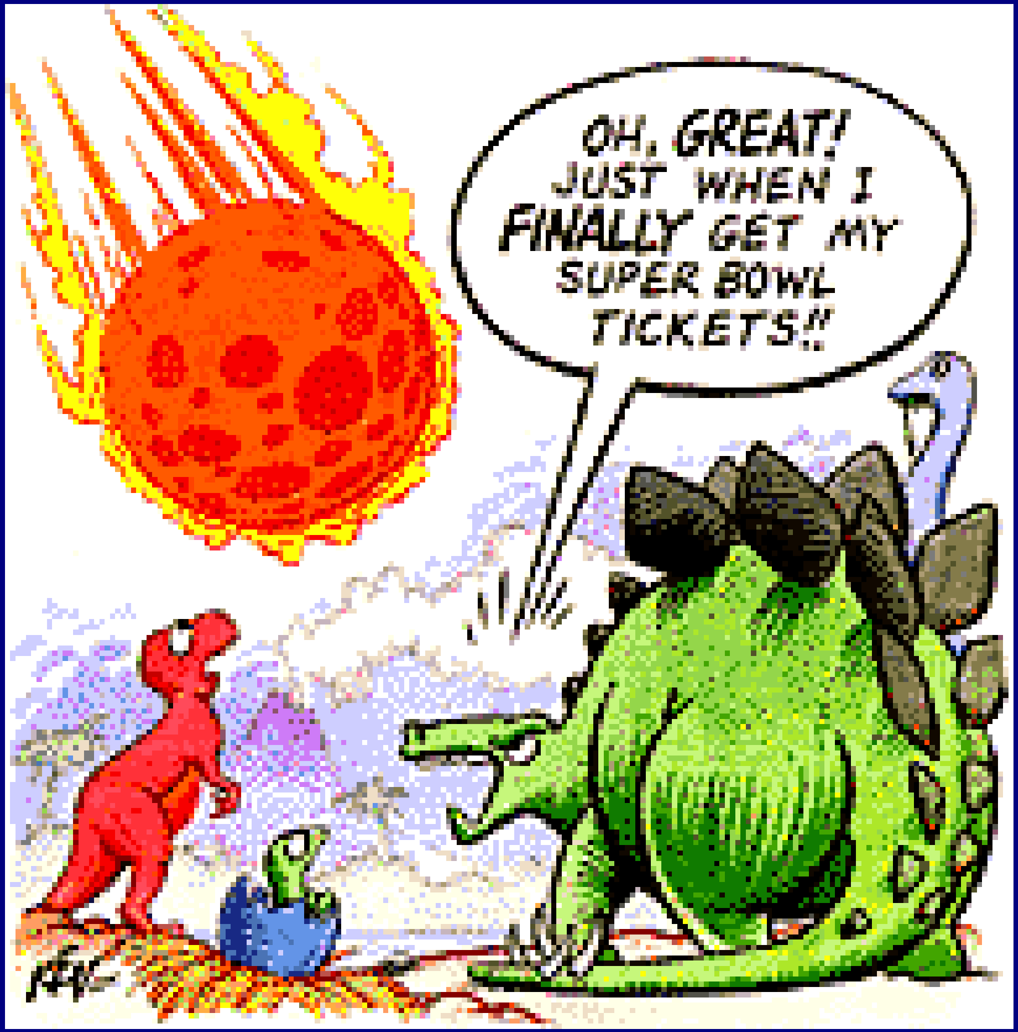
Don Davis

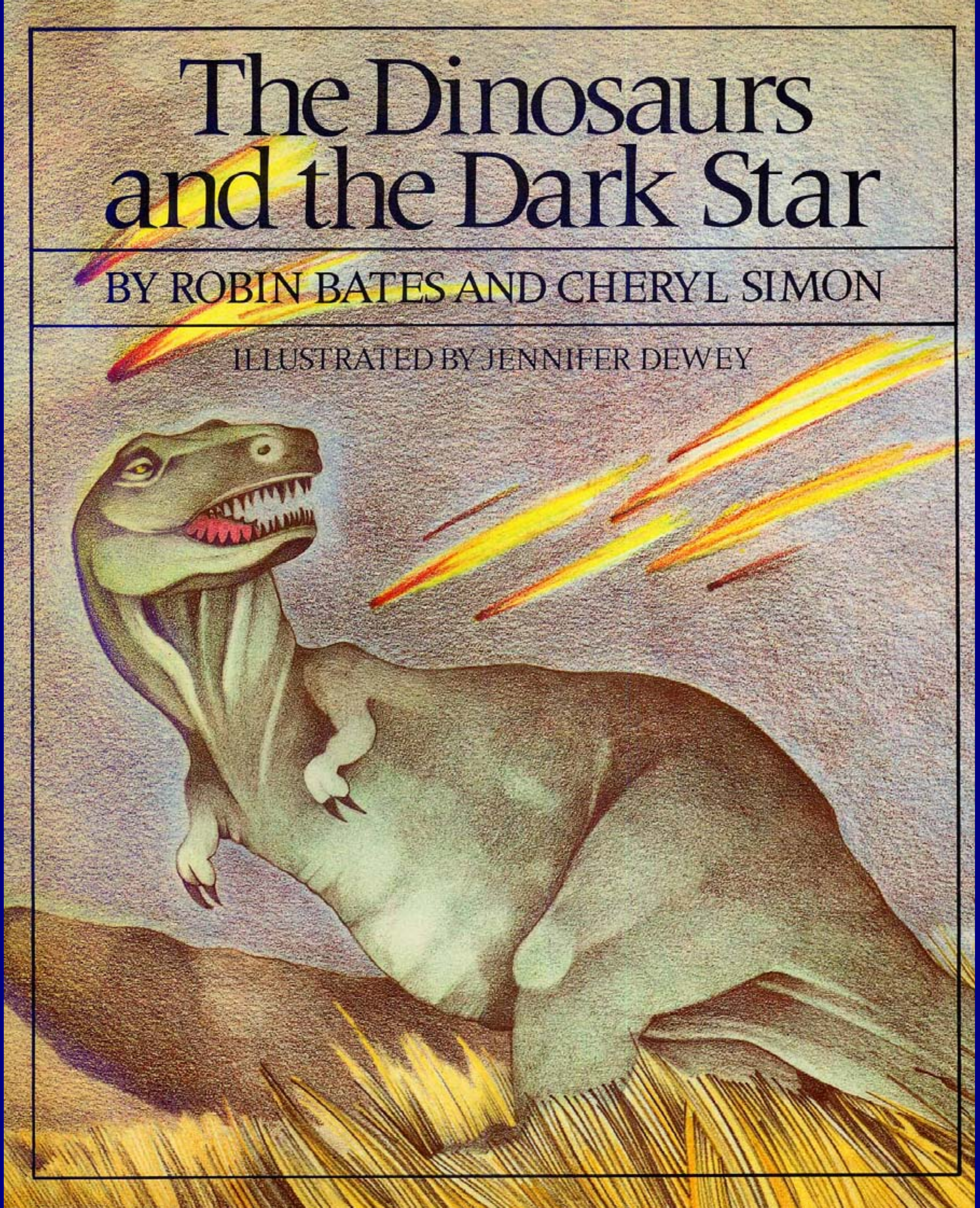
Don Davis

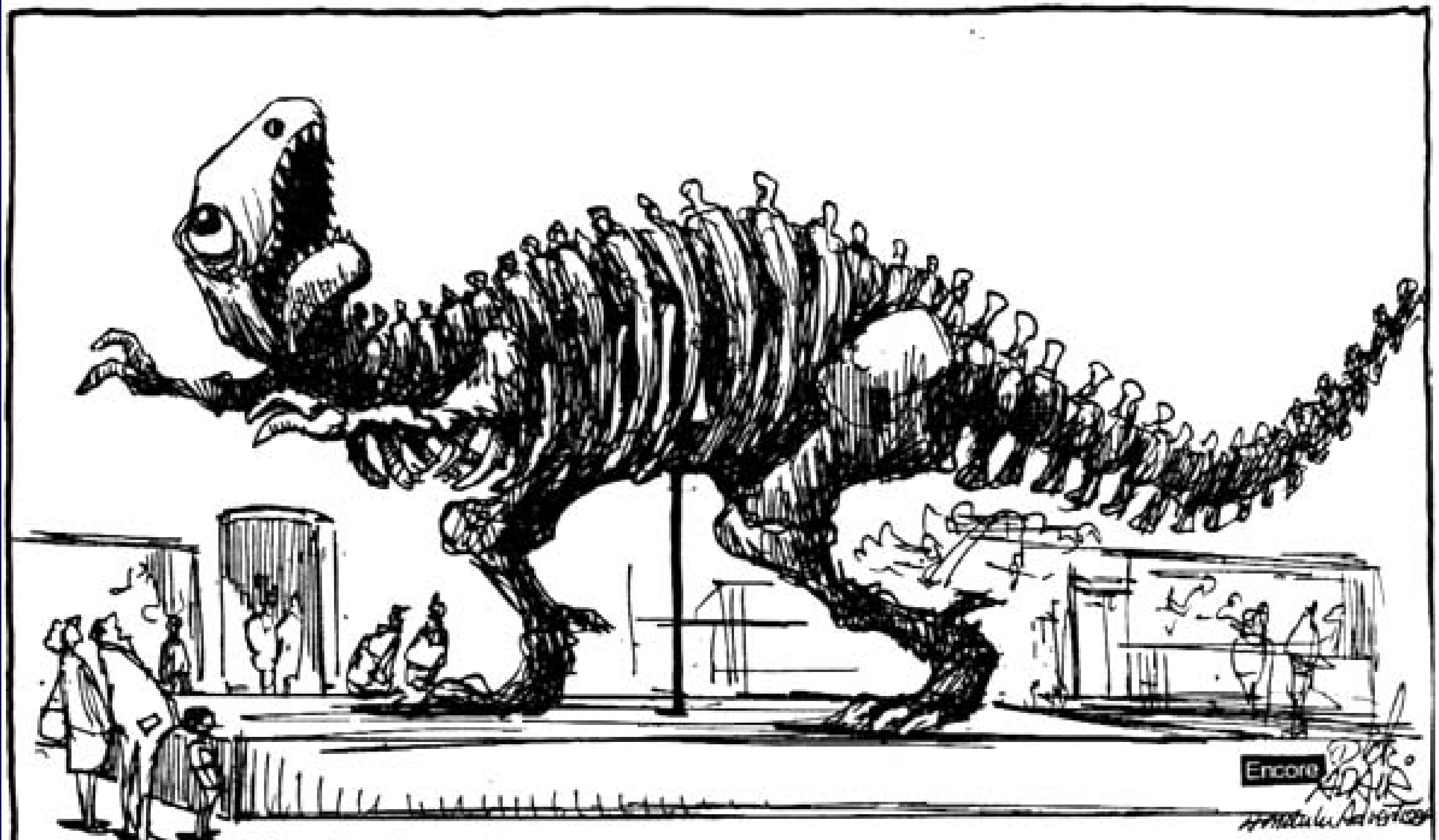


Tom Weller


CAUSES of MASS EXTINCTIONS...
the CRETACEOUS PERIOD:
ACT of the COSMOS

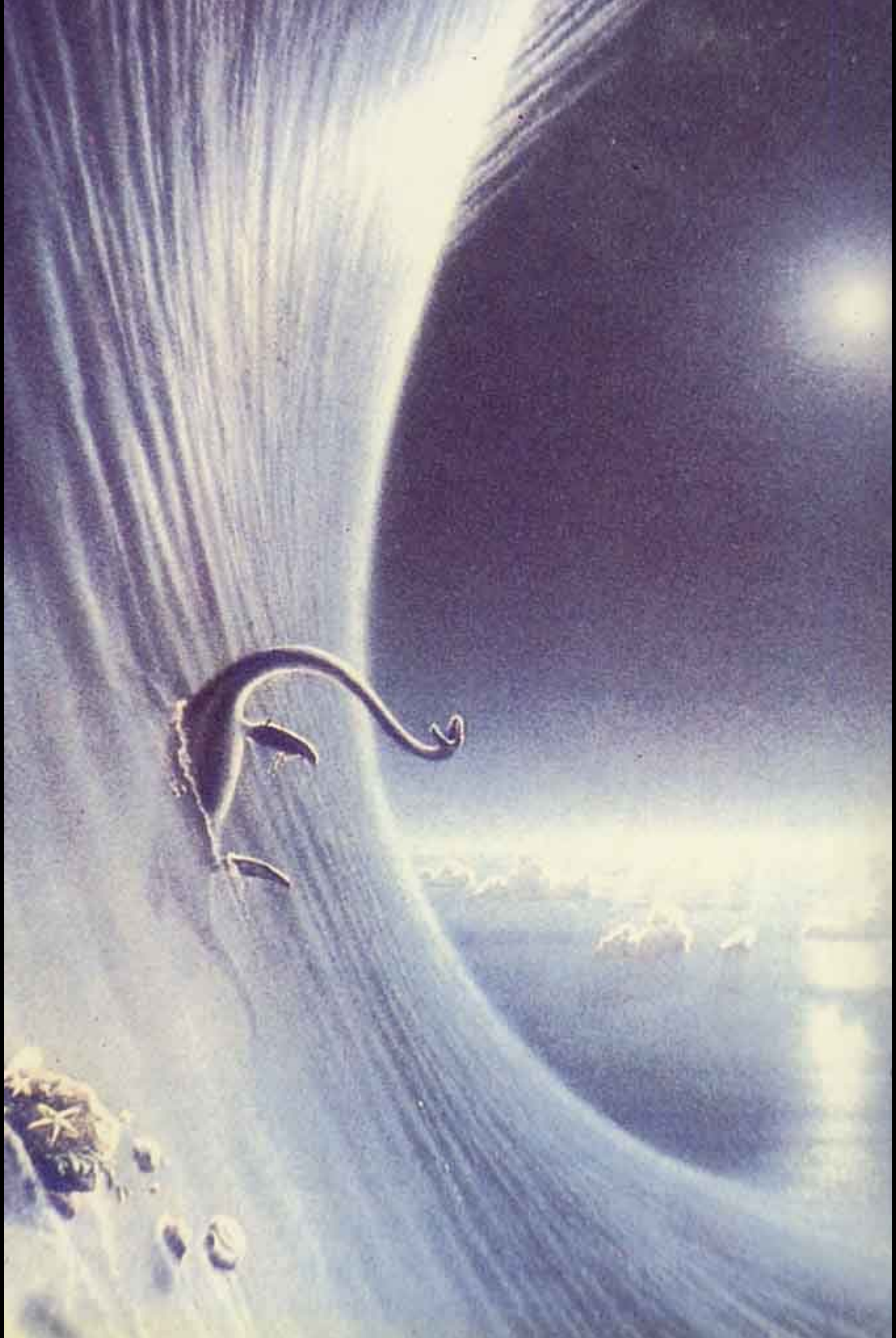

OH, GREAT! JUST WHEN I FINALLY GET MY SUPER BOWL TICKETS!!


The Dinosaurs and the Dark Star
BY ROBIN BATES AND CHERYL SIMON
ILLUSTRATED BY JENNIFER DEWEY



‘No doubt about it... an asteroid killed the dinosaurs!’

Ron Mi



Don Davis

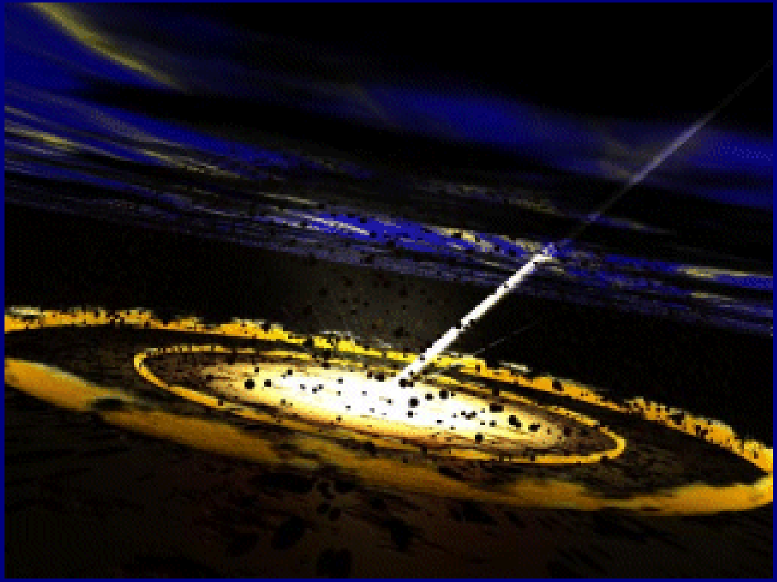
Art Gallery II:
the impactor was big

for reference:
Gaspra

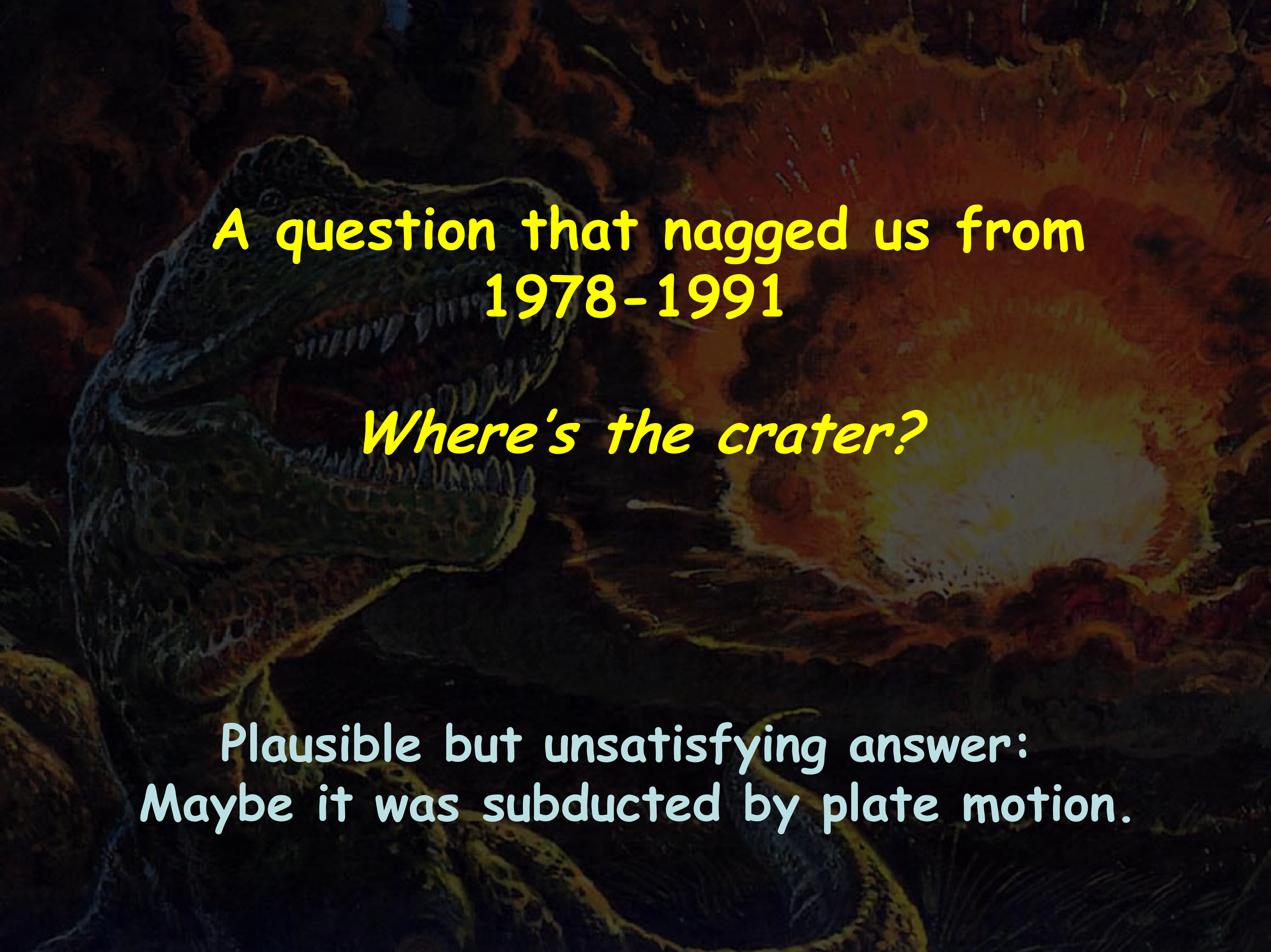

for reference:
Gaspra
Don't think "rock." Think "mountain."

(It wasn't really *that* big.)




DEEP
IMPACT
SUMMER 1998



A question that nagged us from 1978-1991

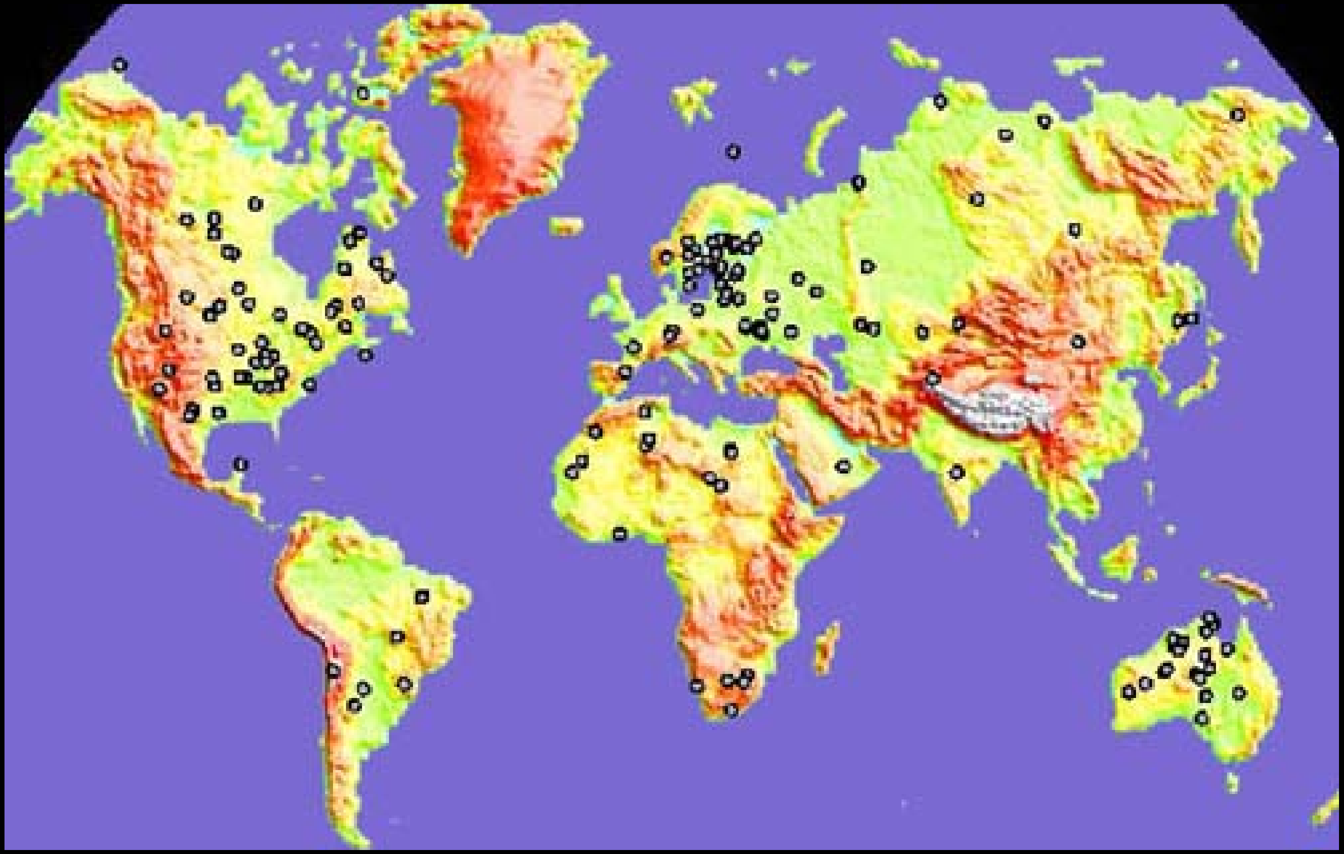
Where's the crater?

Plausible but unsatisfying answer:
Maybe it was subducted by plate motion.


Barringer meteor crater
in Arizona
diameter
1 km

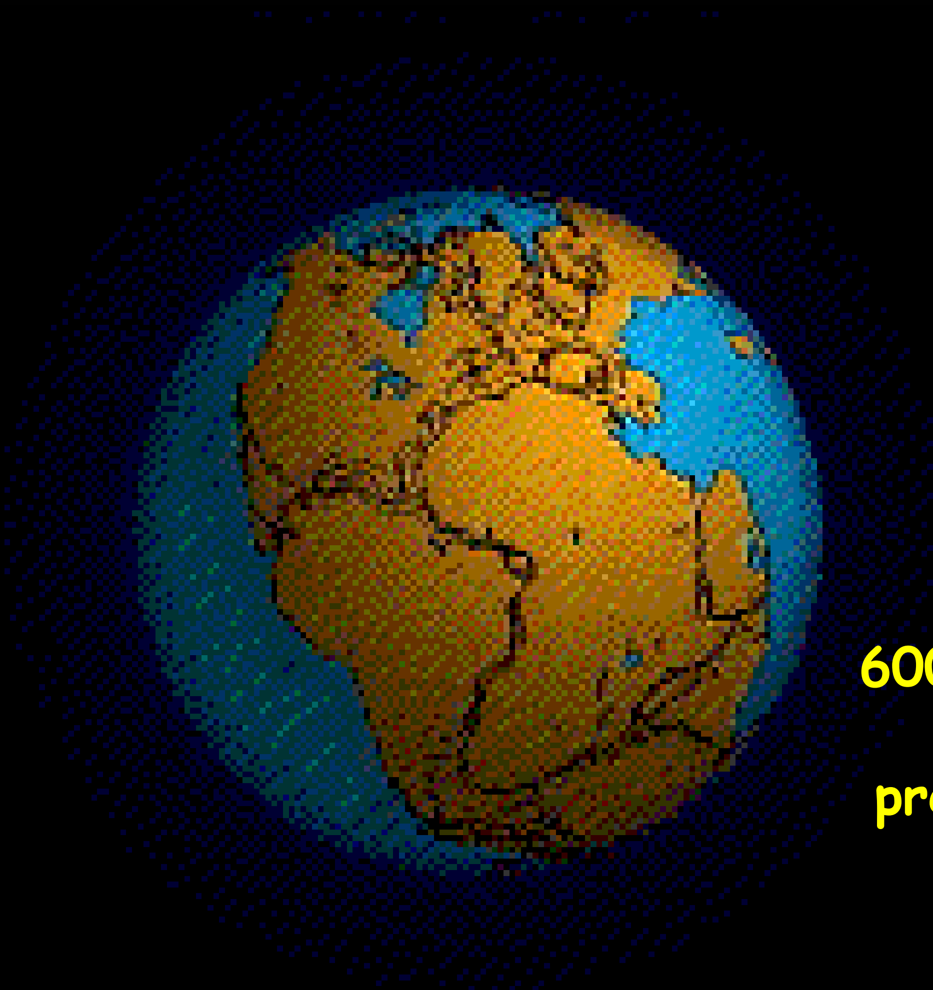

Manicouagan Crater (Canada)
diameter 45 miles

known Earth impact craters



distribution roughly follows distribution of geologists

Was the crater subducted? Plates move …

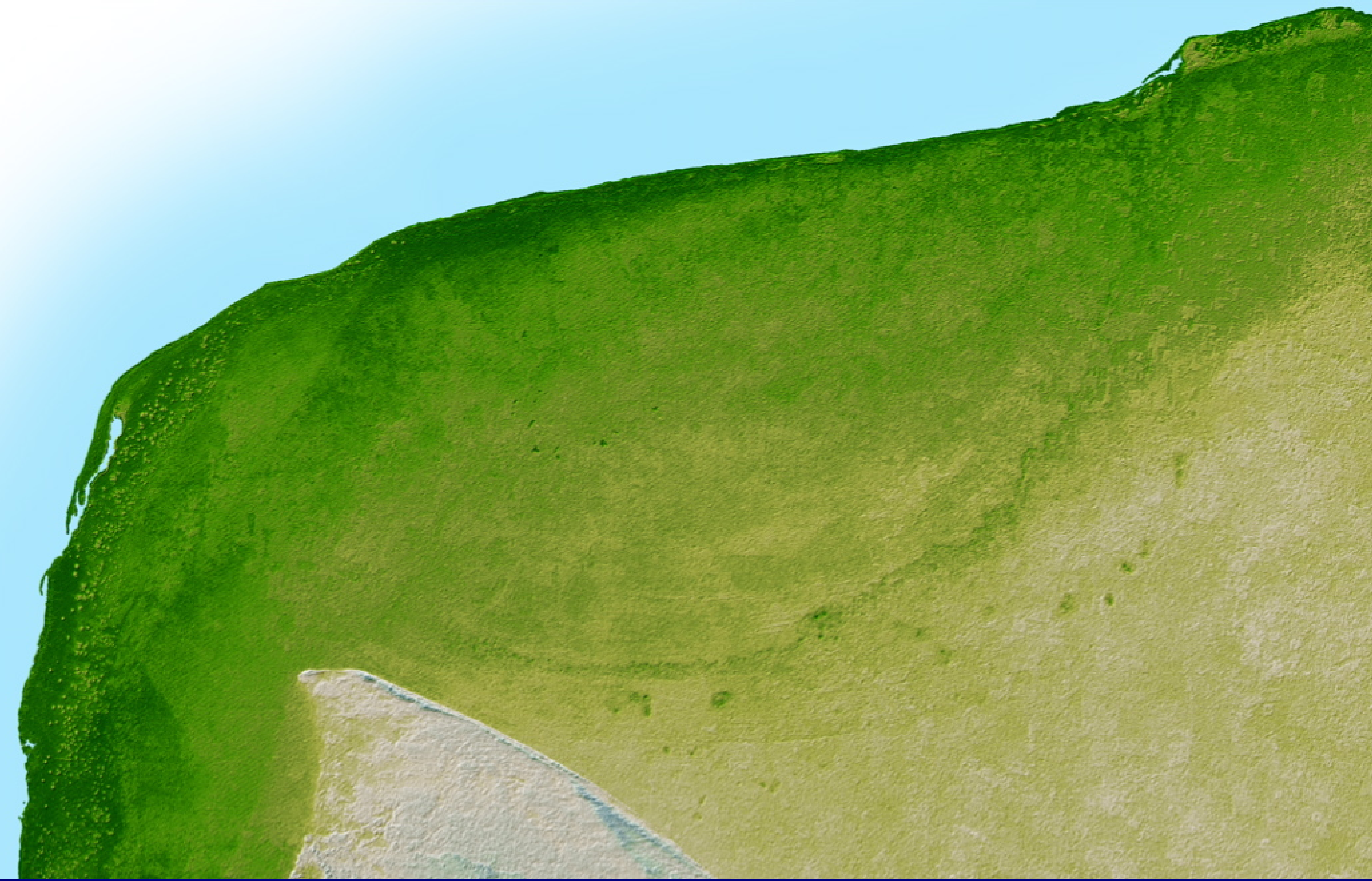


600 Myr
to
present

continents break, oceans appear, and *disappear*

Surprise! Chicxulub

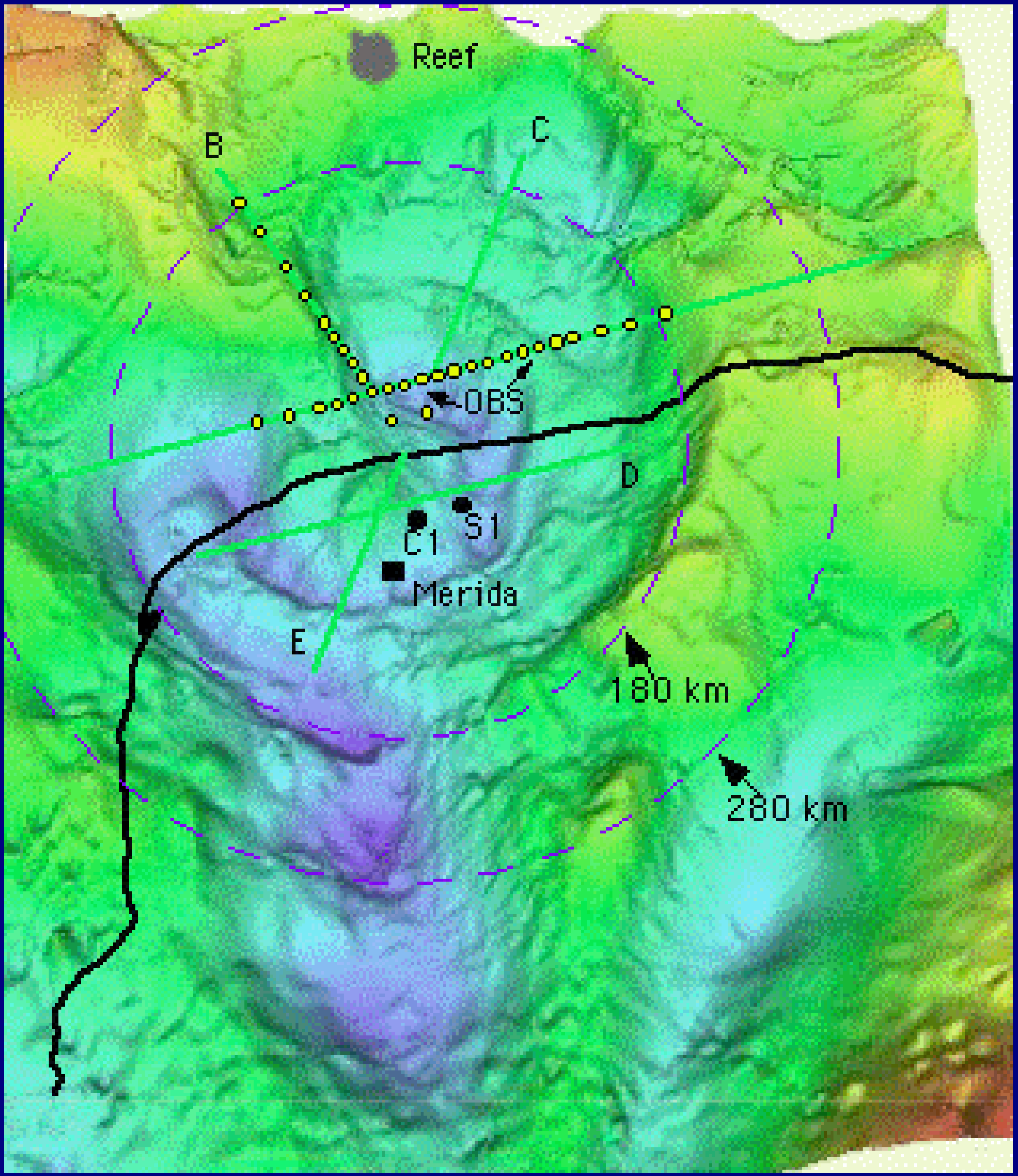
1981: Penfield & Camargo
1991: Hildebrand et al.



Yucatan Penninsula North
(NASA Radar Topography Mission)


nature
INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
Volume 376 No. 6539 3 August $8.50
Chicxulub crater revealed
Transmission of fatal familial insomnia
Runaway telomerase mutants
The bomb 50 years on
Labelling techniques
PRODUCT REVIEW

Chicxulub gravity image

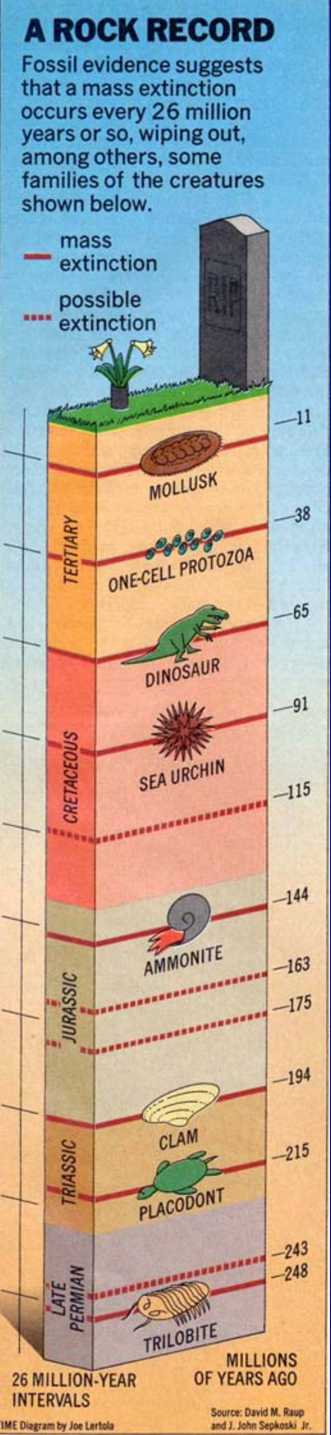


from V.L. Sharpton

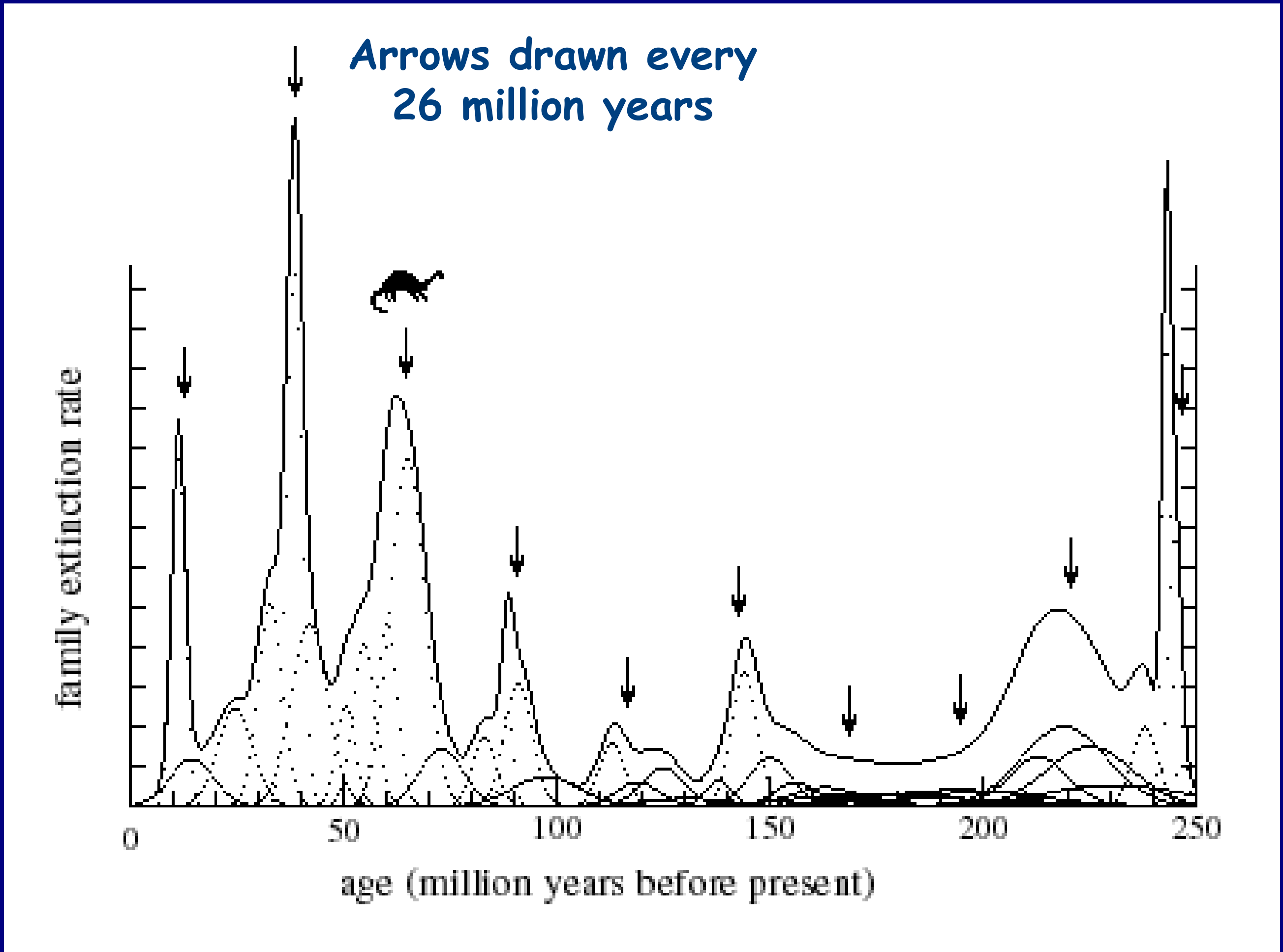
1984

Paleontologists
David Raup & Jack Sepkoski

Extinctions recur on a *very* regular schedule.



Regularly scheduled extinctions for the last 250 million years



D. Raup and J. Sepkoski, 1984

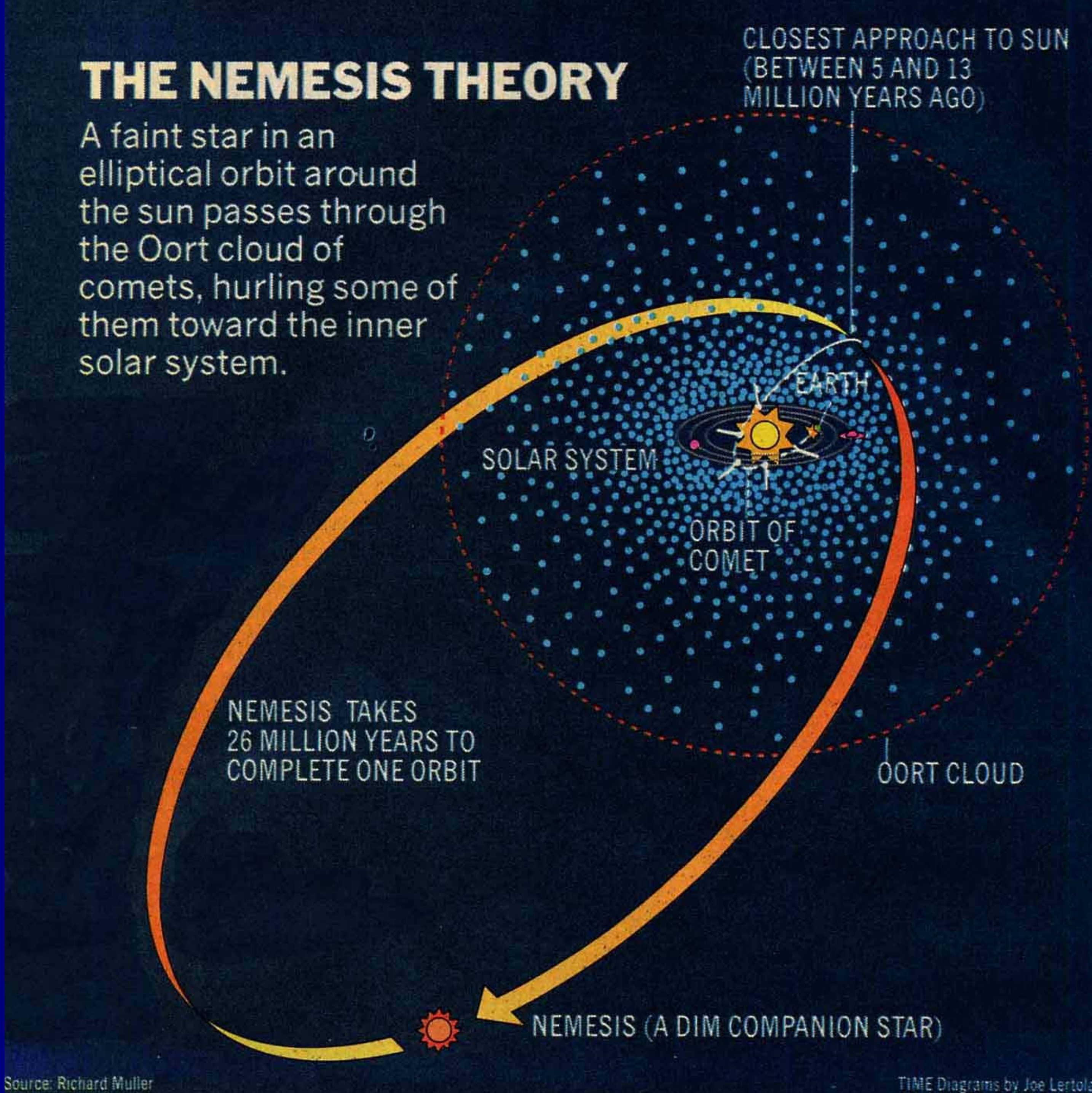
possible explanations:

- ~~oscillations up and down in galaxy~~
- Planet X
- Nemesis ?

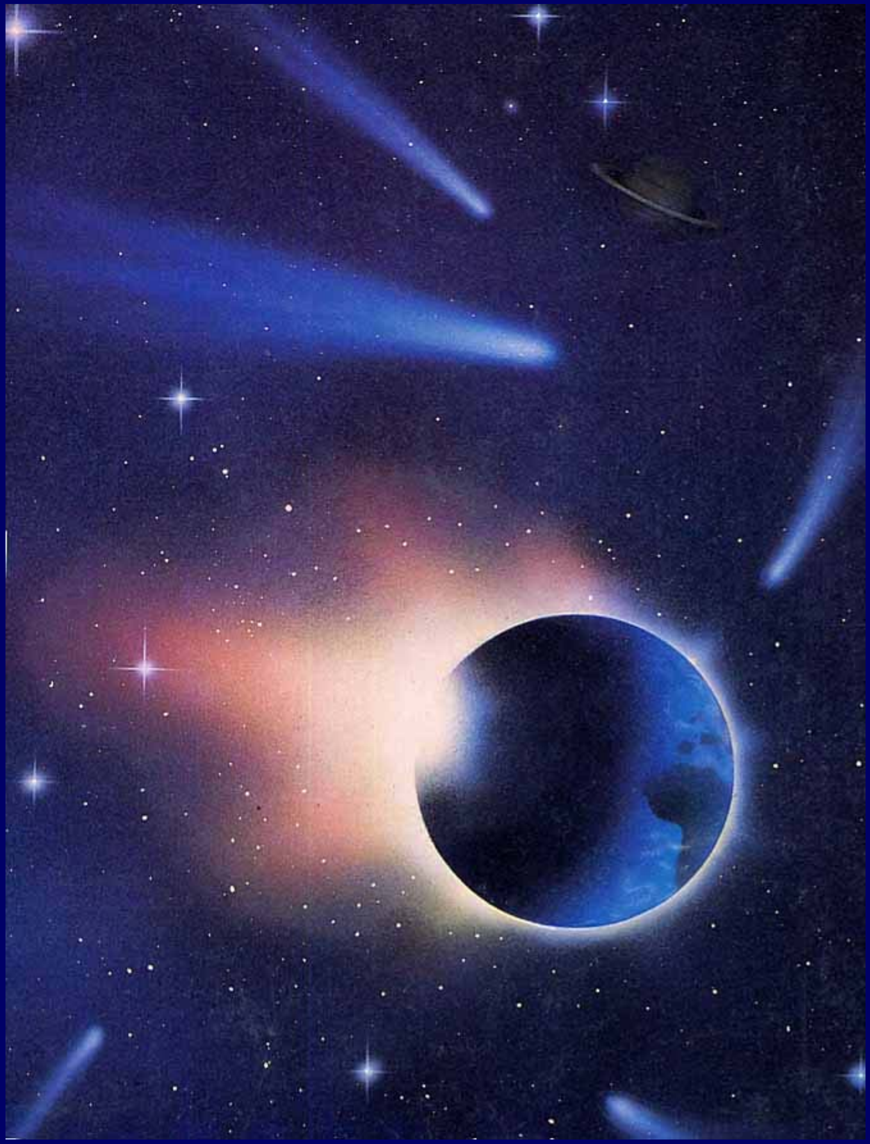
comet shower

(an idea of Jack Hills)

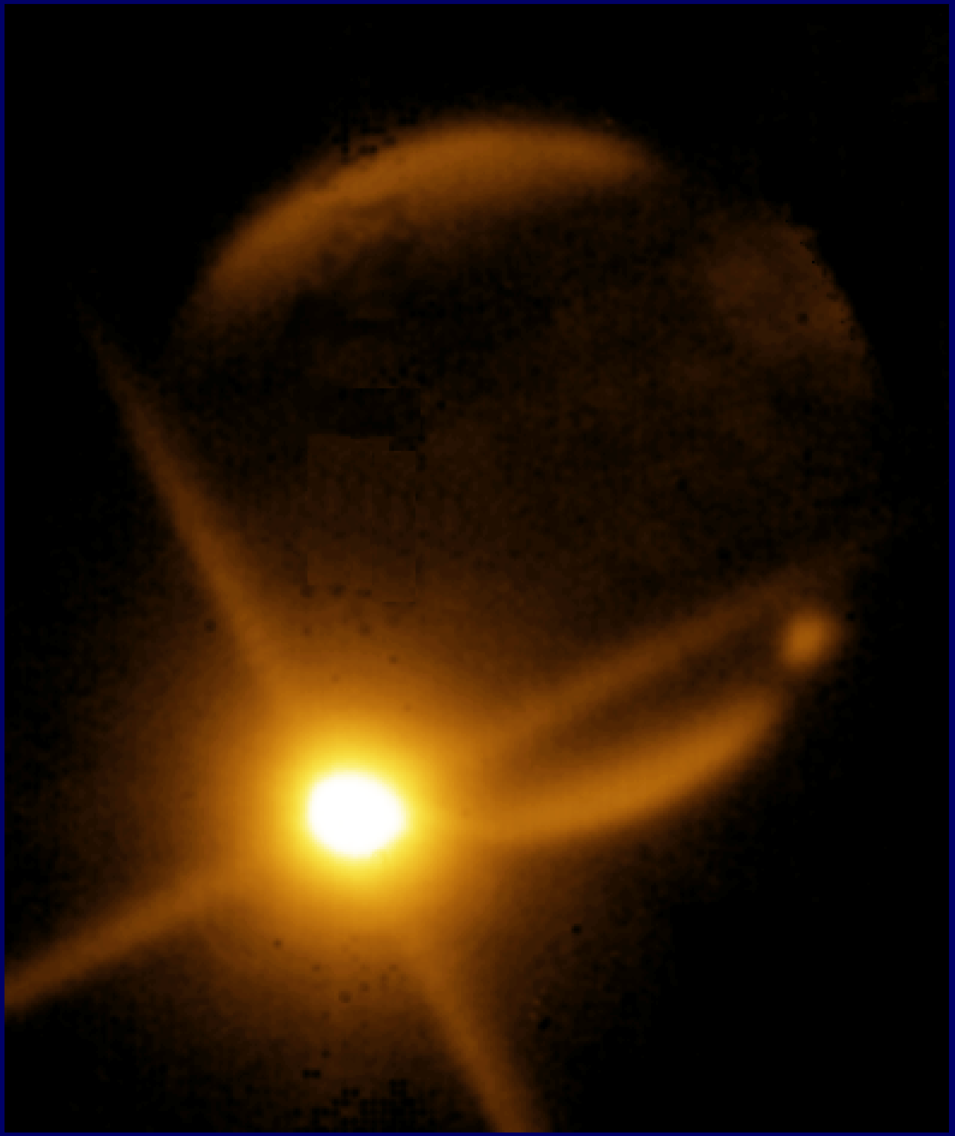
Jon Lomberg


THE NEMESIS THEORY
A faint star in an elliptical orbit around the sun passes through the Oort cloud of comets, hurling some of them toward the inner solar system.
CLOSEST APPROACH TO SUN (BETWEEN 5 AND 13 MILLION YEARS AGO)
EARTH
SOLAR SYSTEM
ORBIT OF COMET
NEMESIS TAKES 26 MILLION YEARS TO COMPLETE ONE ORBIT
OORT CLOUD
NEMESIS (A DIM COMPANION STAR)
Source: Richard Muller
TIME Diagrams by Joe Lertola

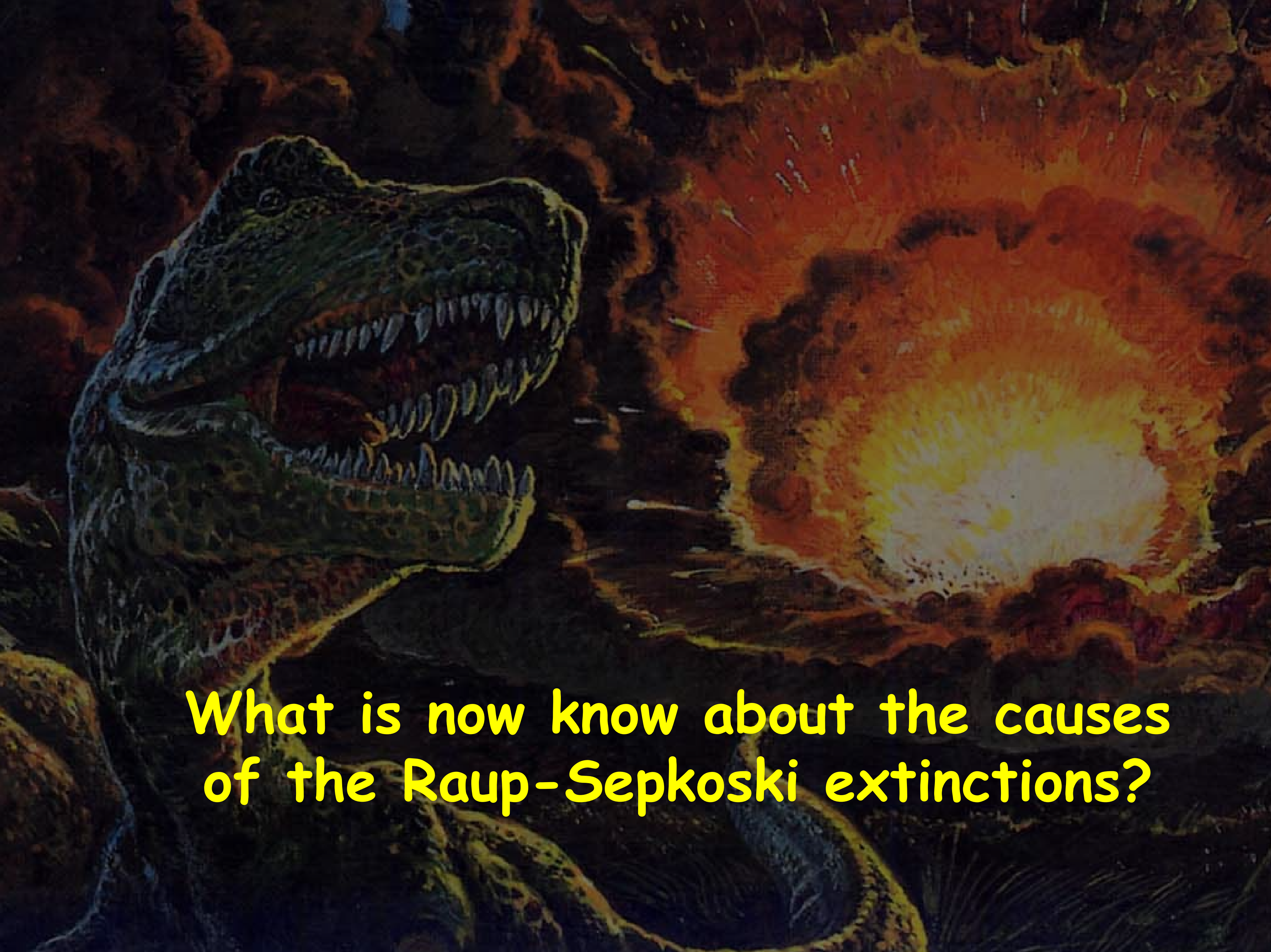
comet showers



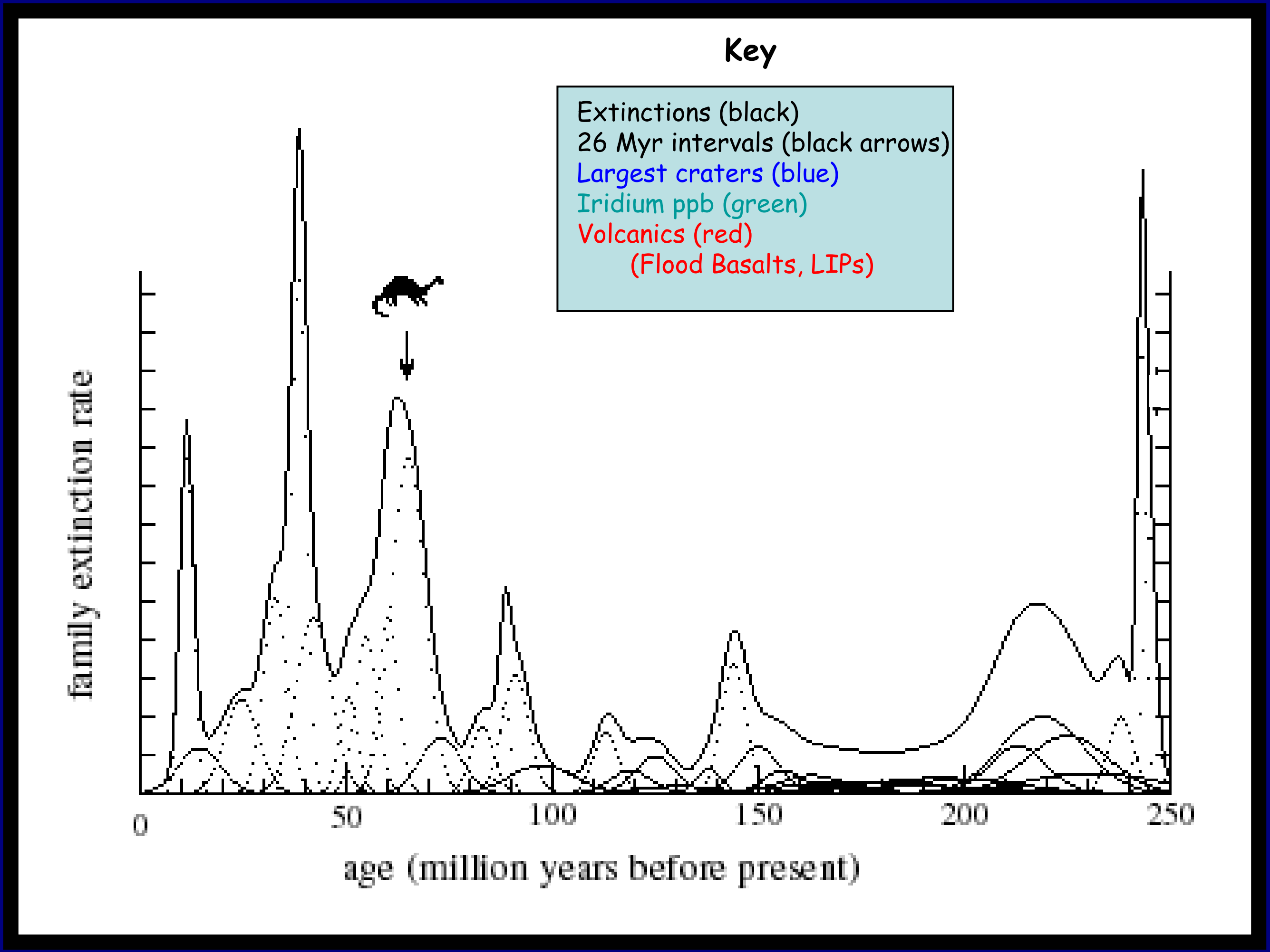
from “Nemesis” 1988 cover



comet Shoemaker-Levy 1994

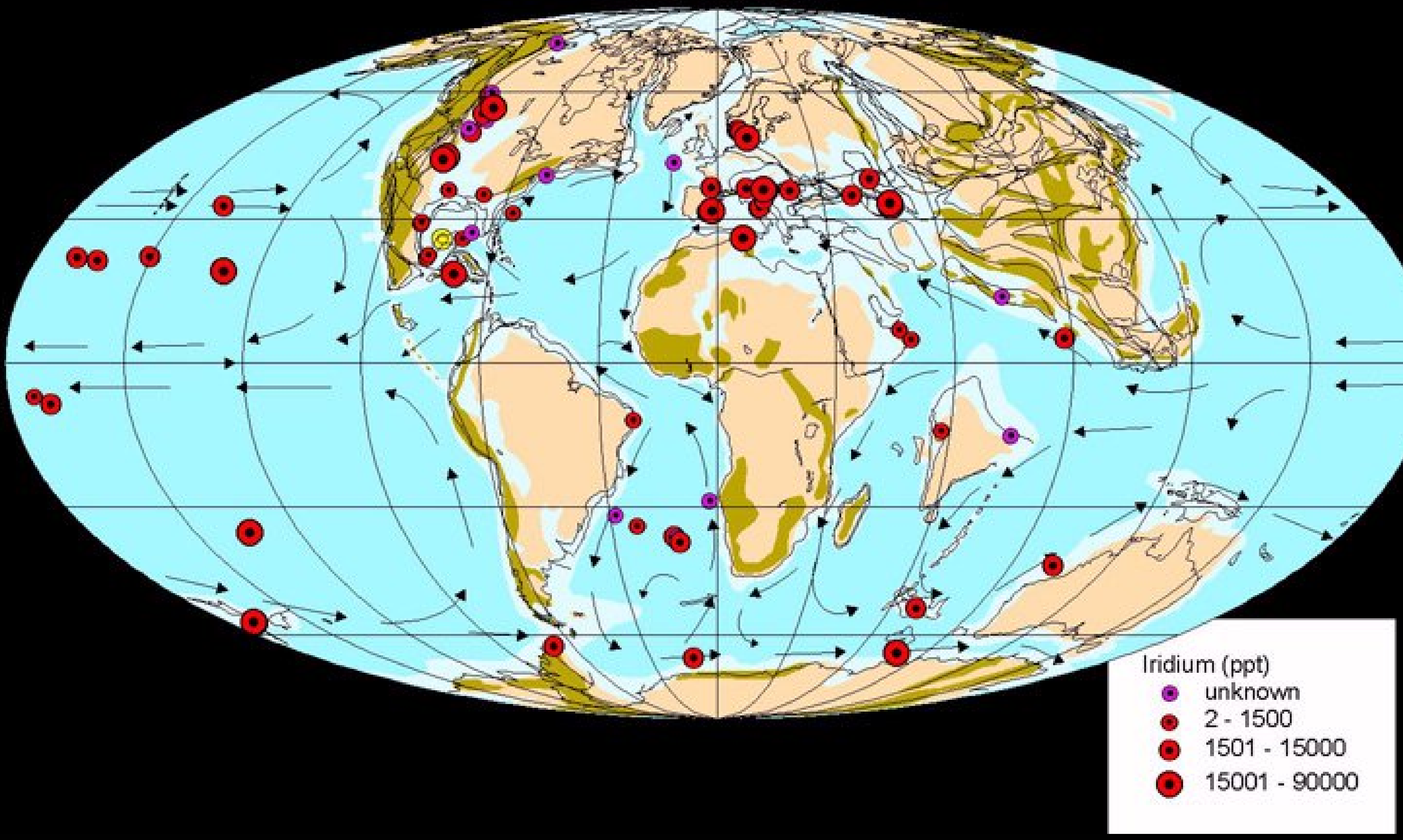

What is now know about the causes
of the Raup-Sepkoski extinctions?

Extinctions (and other things) for the last 250 million years

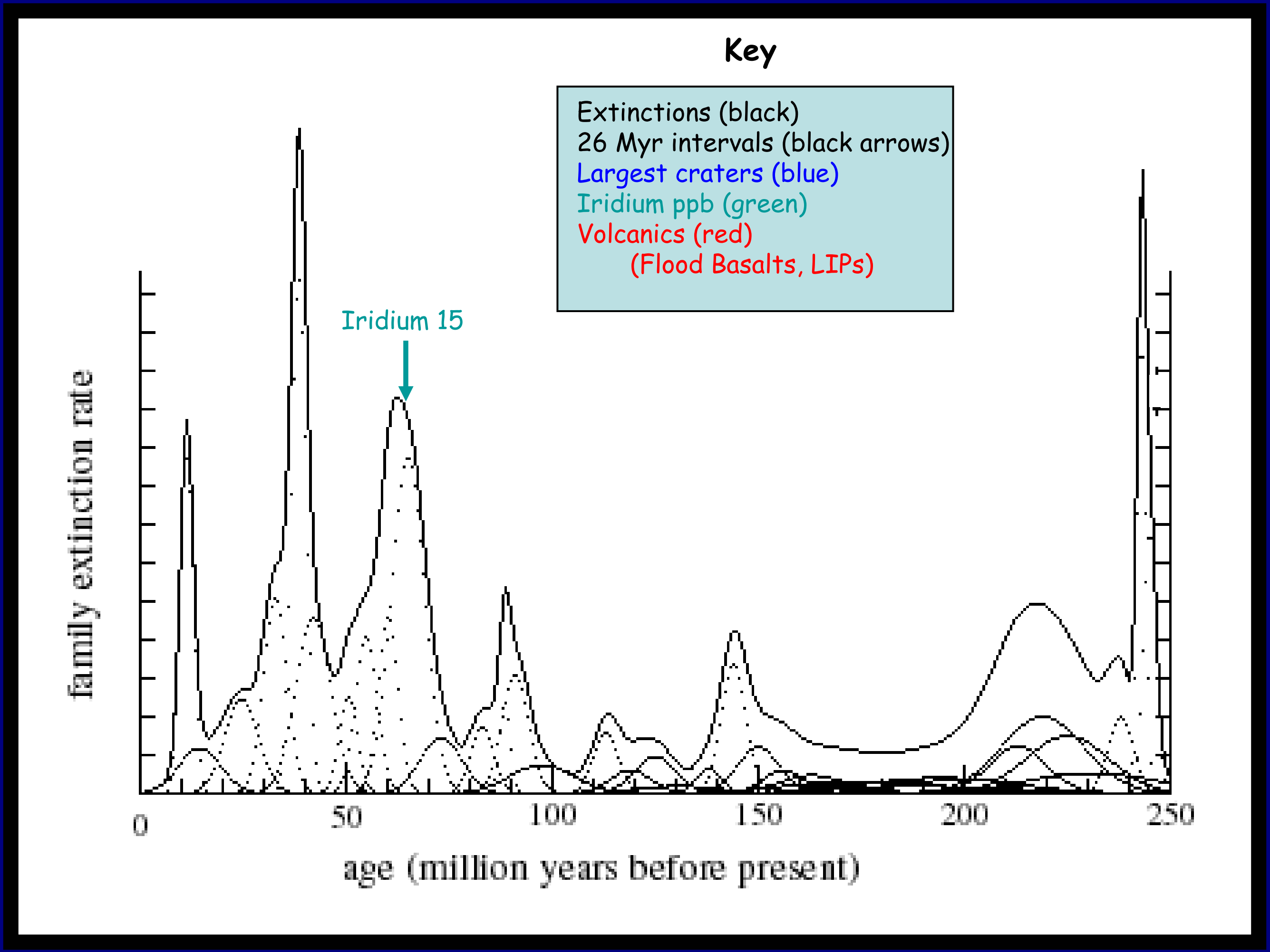


Extinctions: Sepkoski, Muller   Craters: Koeberl   Iridium: Asaro, Orth, others   Volcanism: Ernst & Buchan

65 Myr
Cretaceous-Tertiary
Iridium Anomalies



Iridium Anomaly and mass extinctions



Extinctions: Sepkoski, Muller   Craters: Koeberl   Iridium: Asaro, Orth, others   Volcanism: Ernst & Buchan

Possible comet shower
35 Million years ago

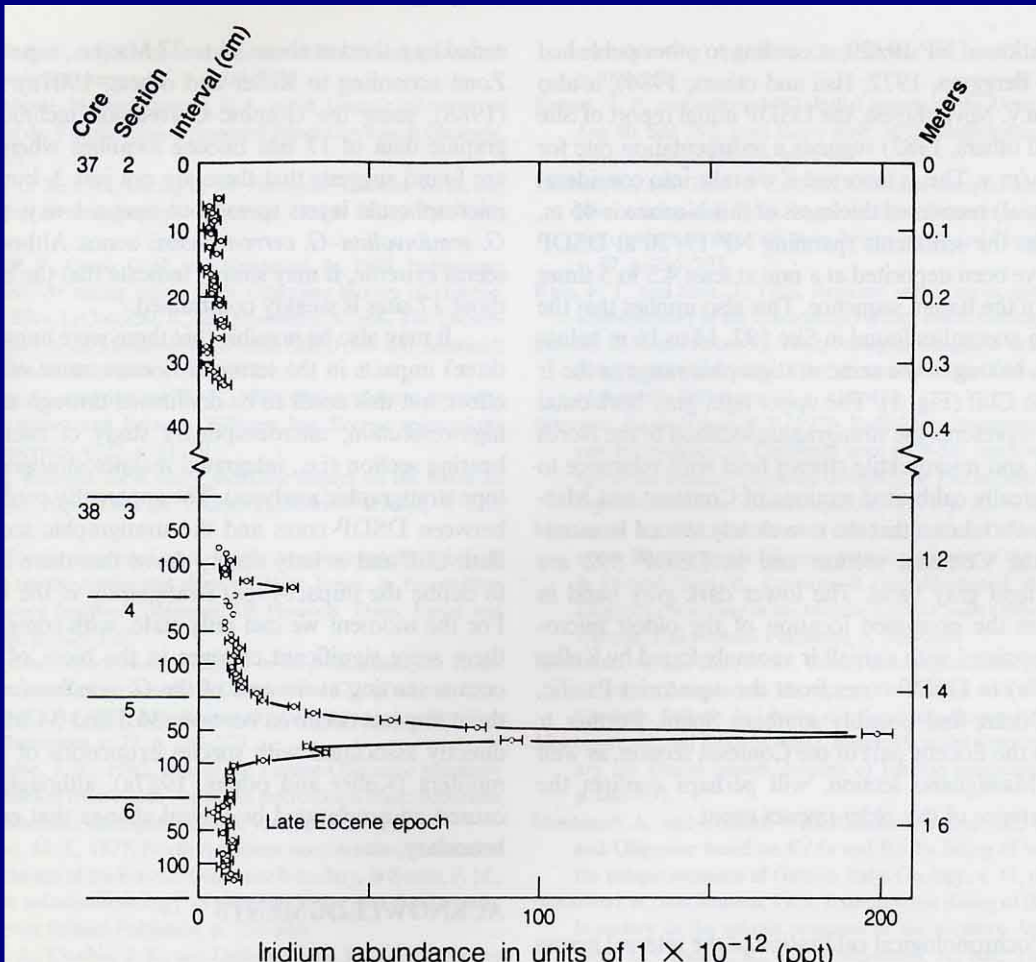
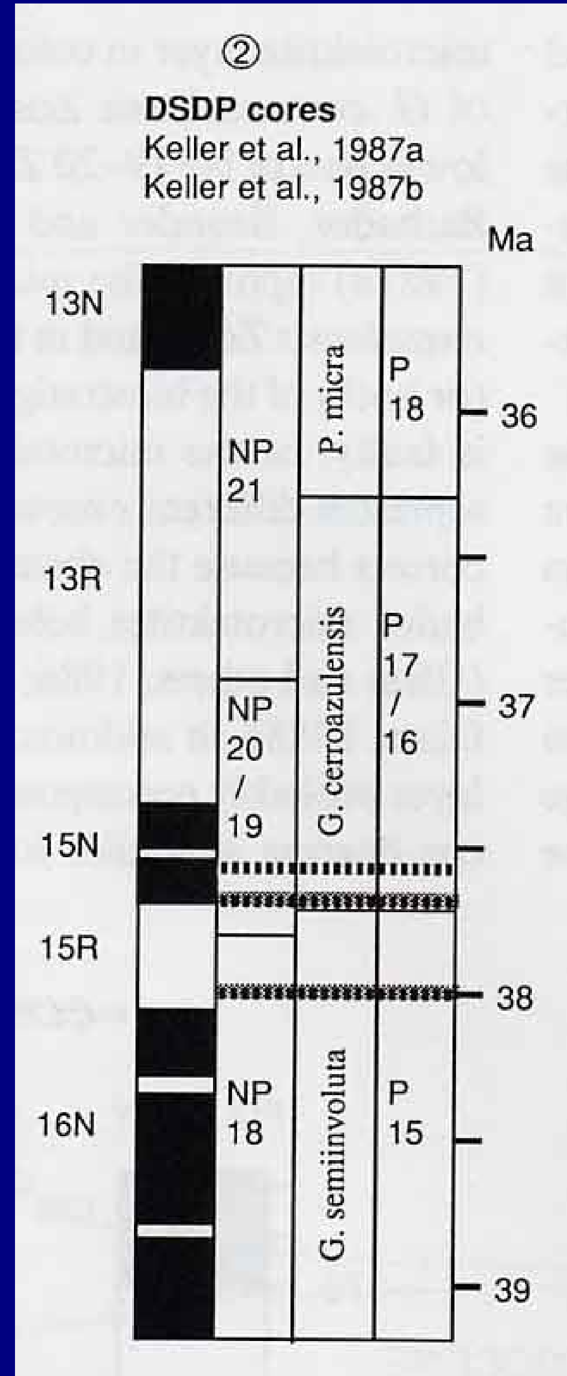
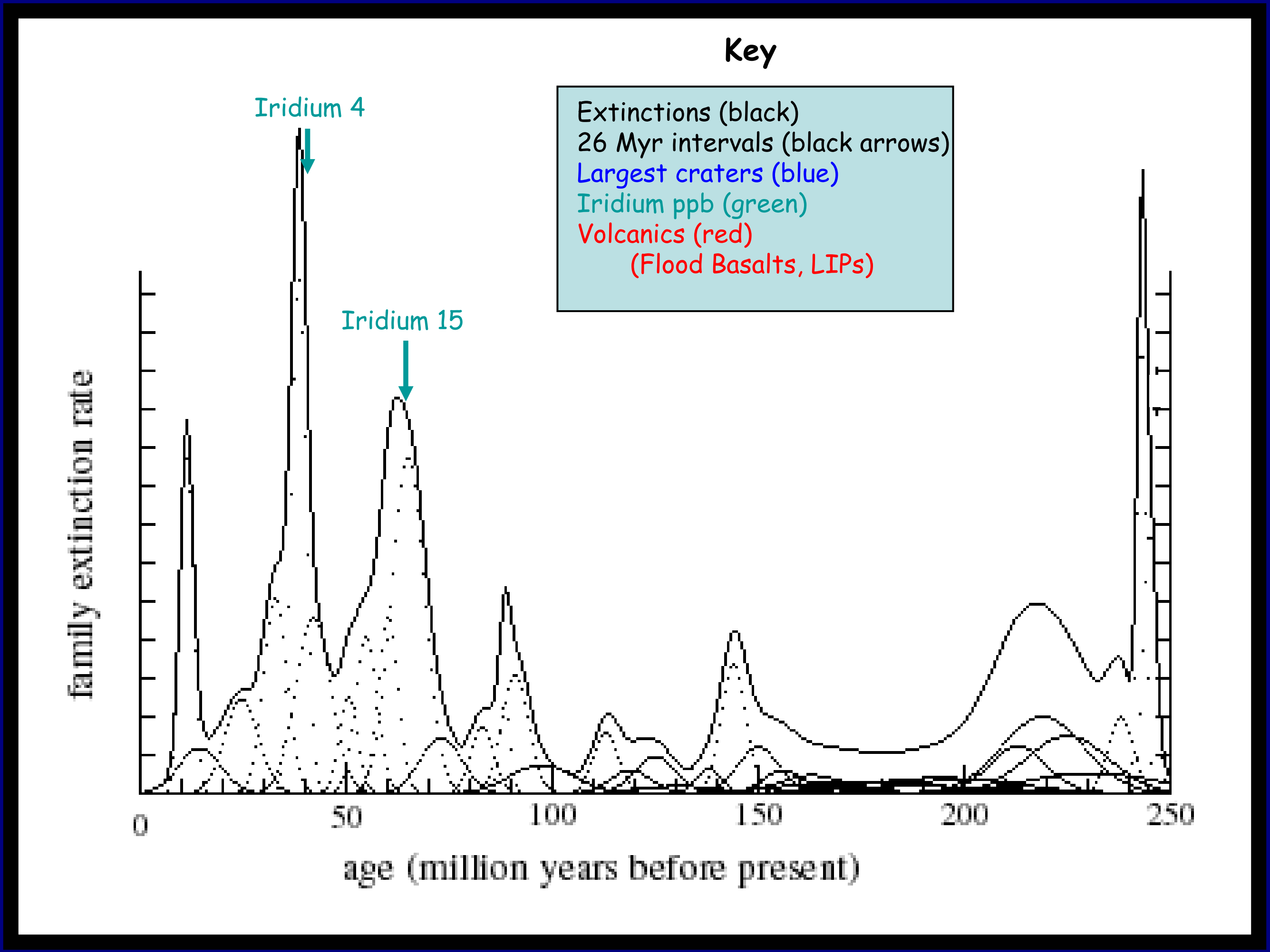


Figure 5. Occurrence of two small Ir anomalies in the upper part of NP 19/20 nannofossil range zone (upper Eocene) from DSDP Site 592 (Tasman Sea), core 38 (courtesy of Frank Asaro).

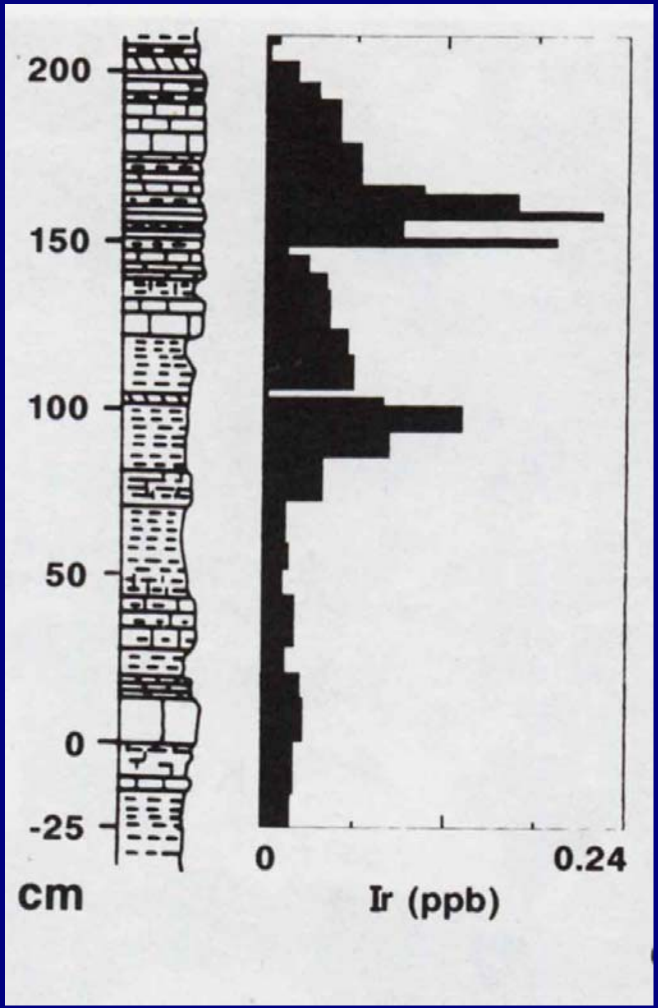


Another iridium anomaly



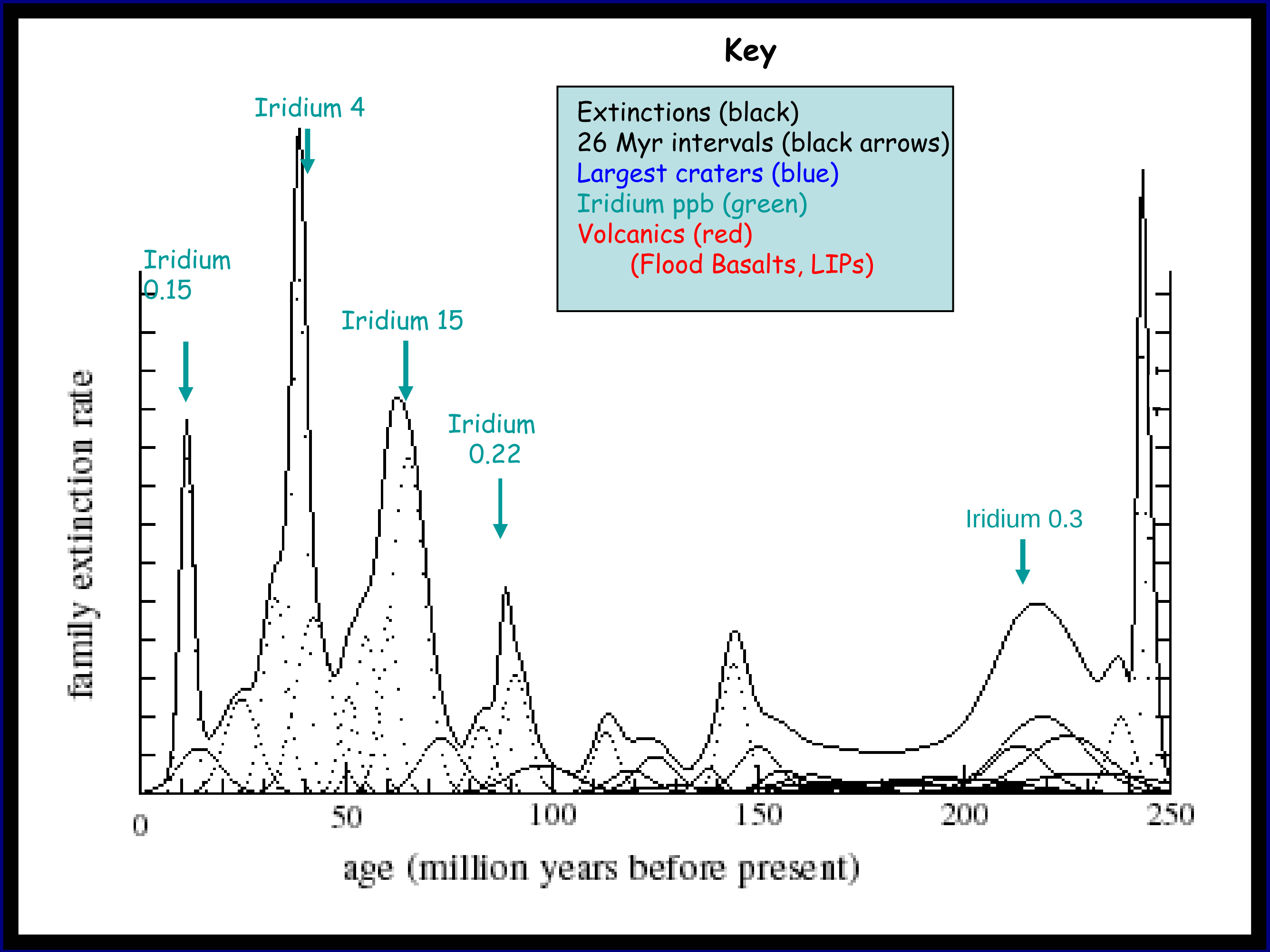
Extinctions: Sepkoski, Muller Craters: Koeberl Iridium: Asaro, Orth, others Volcanism: Ernst & Buchan

Iridium layer(s) at 91 Myr



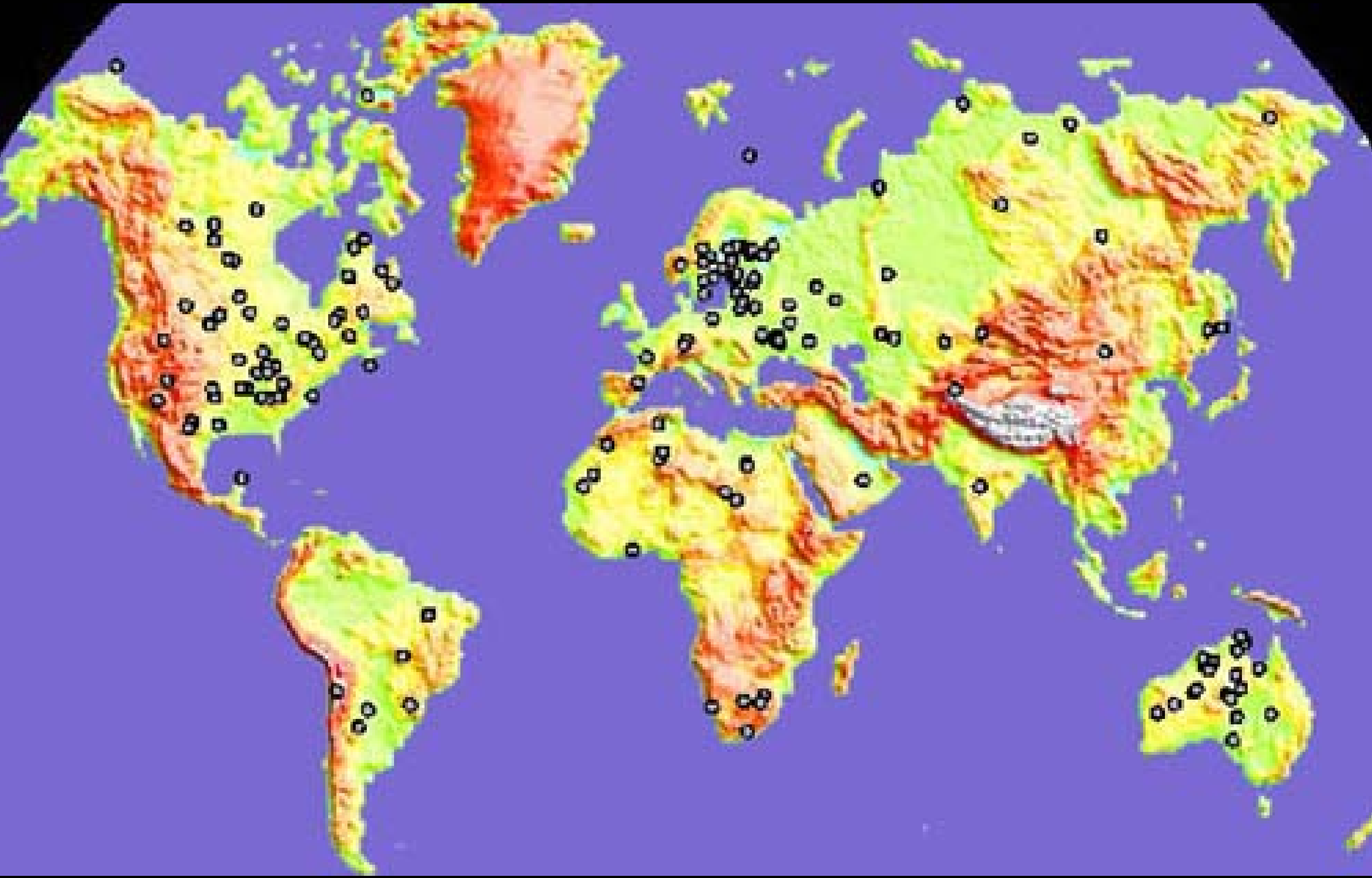
from Carl Orth et al.
Special Paper 247 p.55

more iridium anomalies



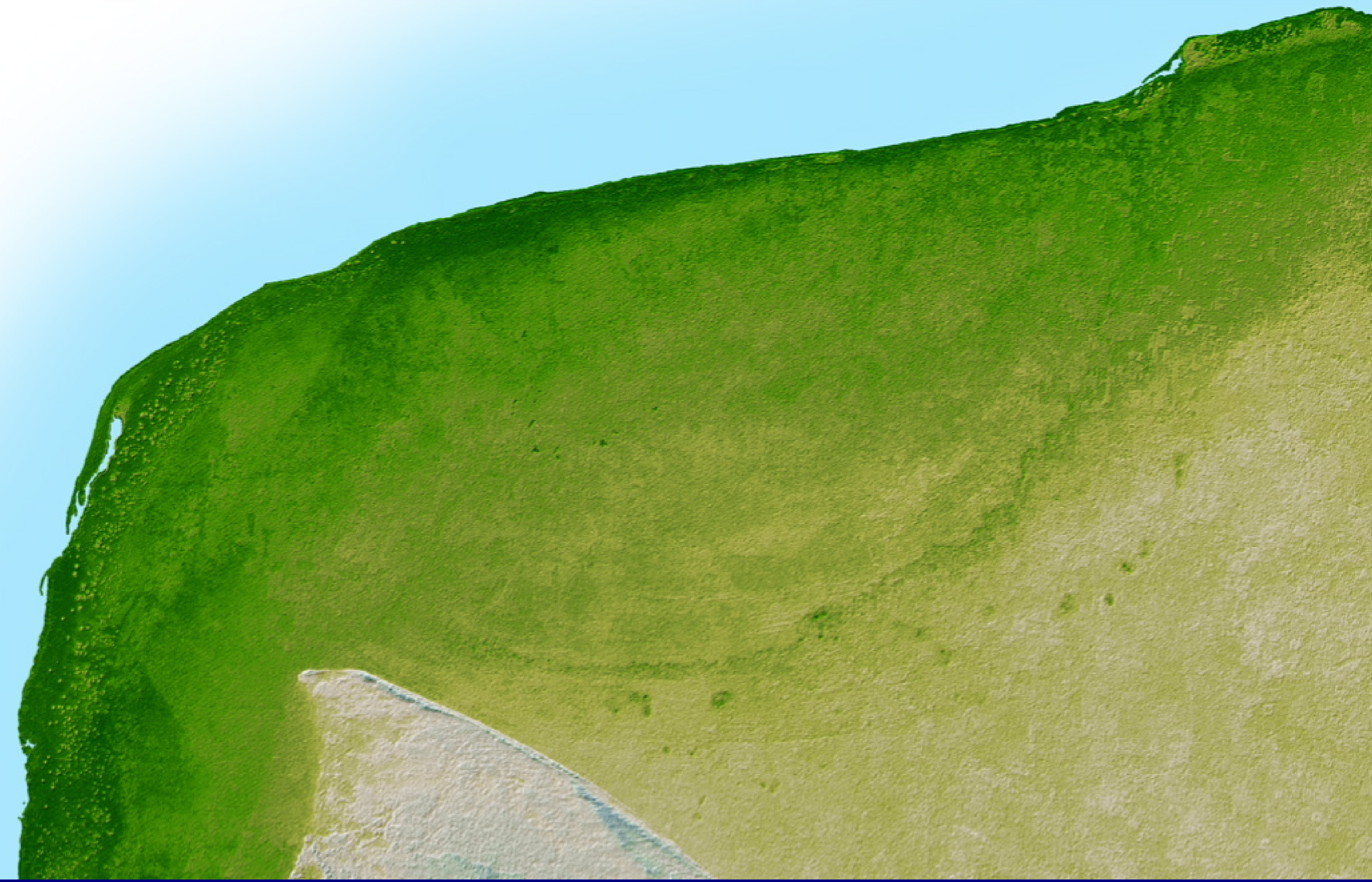
Extinctions: Sepkoski, Muller   Craters: Koeberl   Iridium: Asaro, Orth, others   Volcanism: Ernst & Buchan

known Earth craters



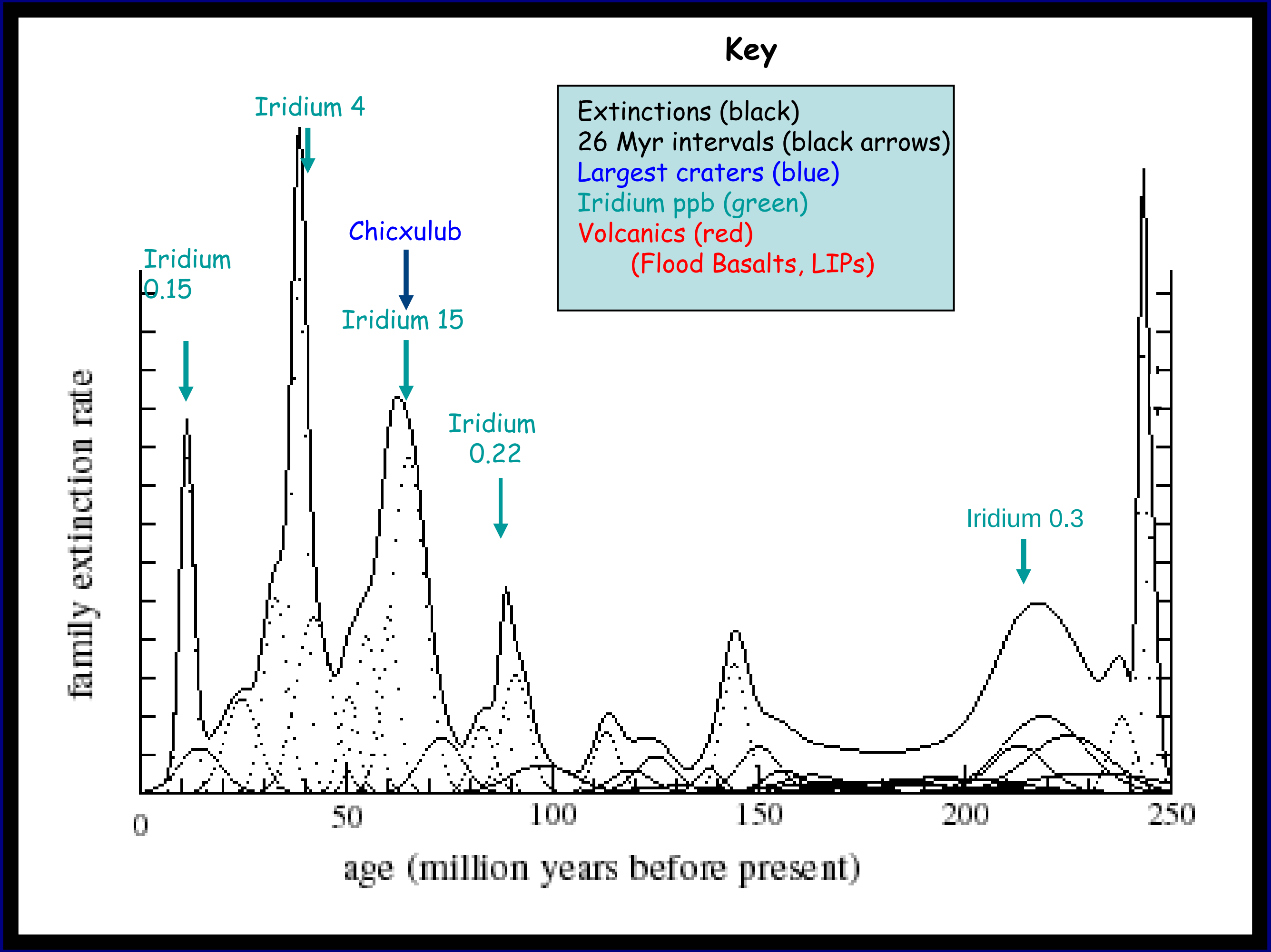
7 largest known impact craters on Earth

CRATER NAME	LOCATION	LAT	LONG	DIAMETER	AGE (Myears)	EXTINCTION
Chesapeake Bay	Virginia, U.S.A.	N 37 17'	W 76 1'	90 km	35.5 ± 0.3	Eocene-Oligocene
Acraman	South Australia	S 32 1'	E 135 27'	90 km	~ 590	pre-Phanerozic
Manicouagan	Quebec, Canada	N 51 23'	W 68 42'	100 km	214 ± 1	Triassic-Jurassic
Popigai	Russia	N 71 39'	E 111 11'	100 km	35.7 ± 0.2	Eocene-Oligocene
Chicxulub	Yucatan, Mexico	N 21 20'	W 89 30'	170 km	64.98 ± 0.05	Cretaceous-Tertiary
Sudbury	Ontario, Canada	N 46 36'	W 81 11'	250 km	1850 ± 3	pre-Phanerozic
Vredefort	South Africa	S 27 0'	E 27 30'	300 km	2023 ± 4	pre-Phanerozic



Yucatan Penninsula North
(NASA Radar Topography Mission)

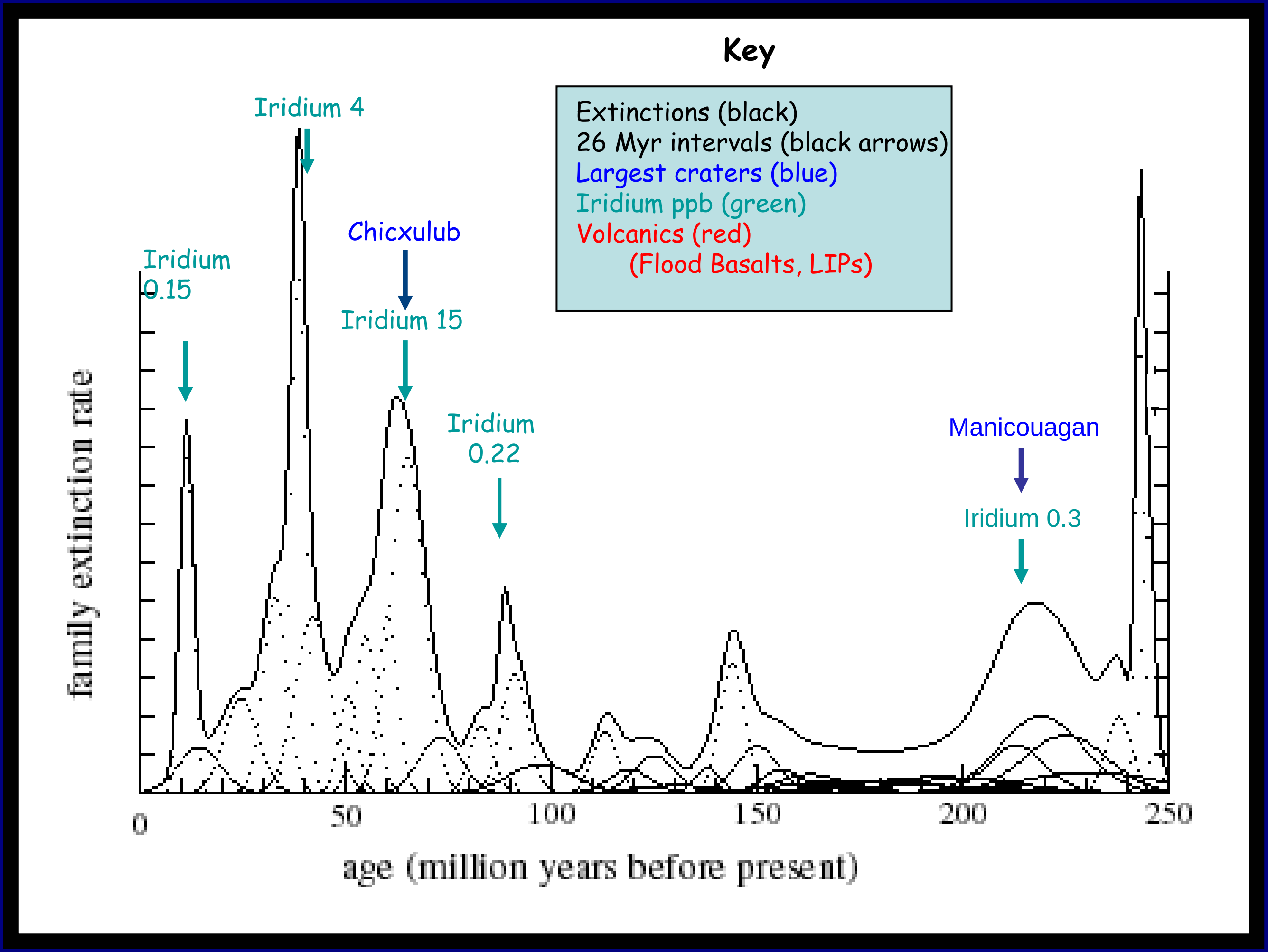
The largest impact craters



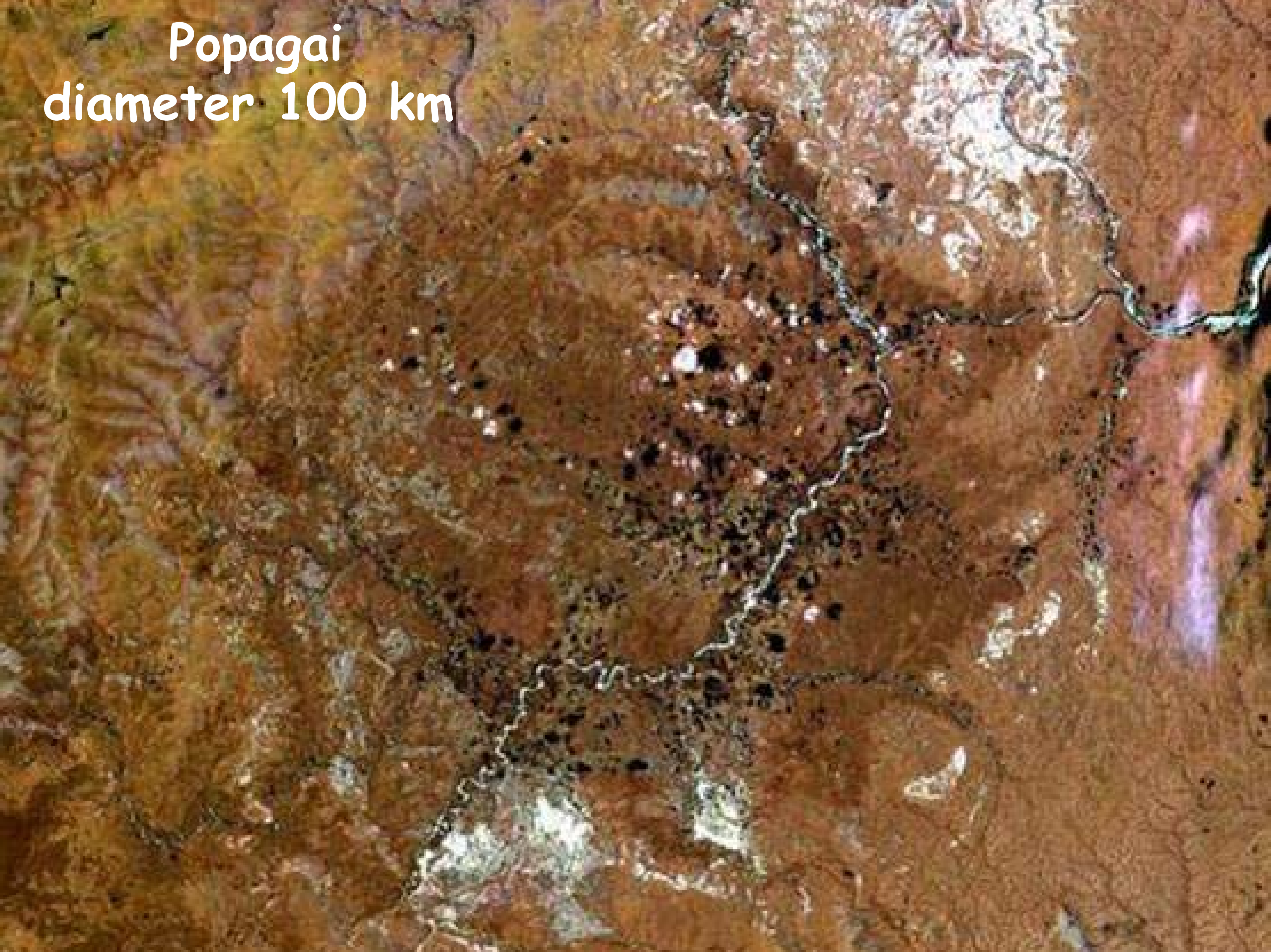
Extinctions: Sepkoski, Muller Craters: Koeberl Iridium: Asaro, Orth, others Volcanism: Ernst & Buchan


Manicouagan Crater (Canada)
diameter 45 miles

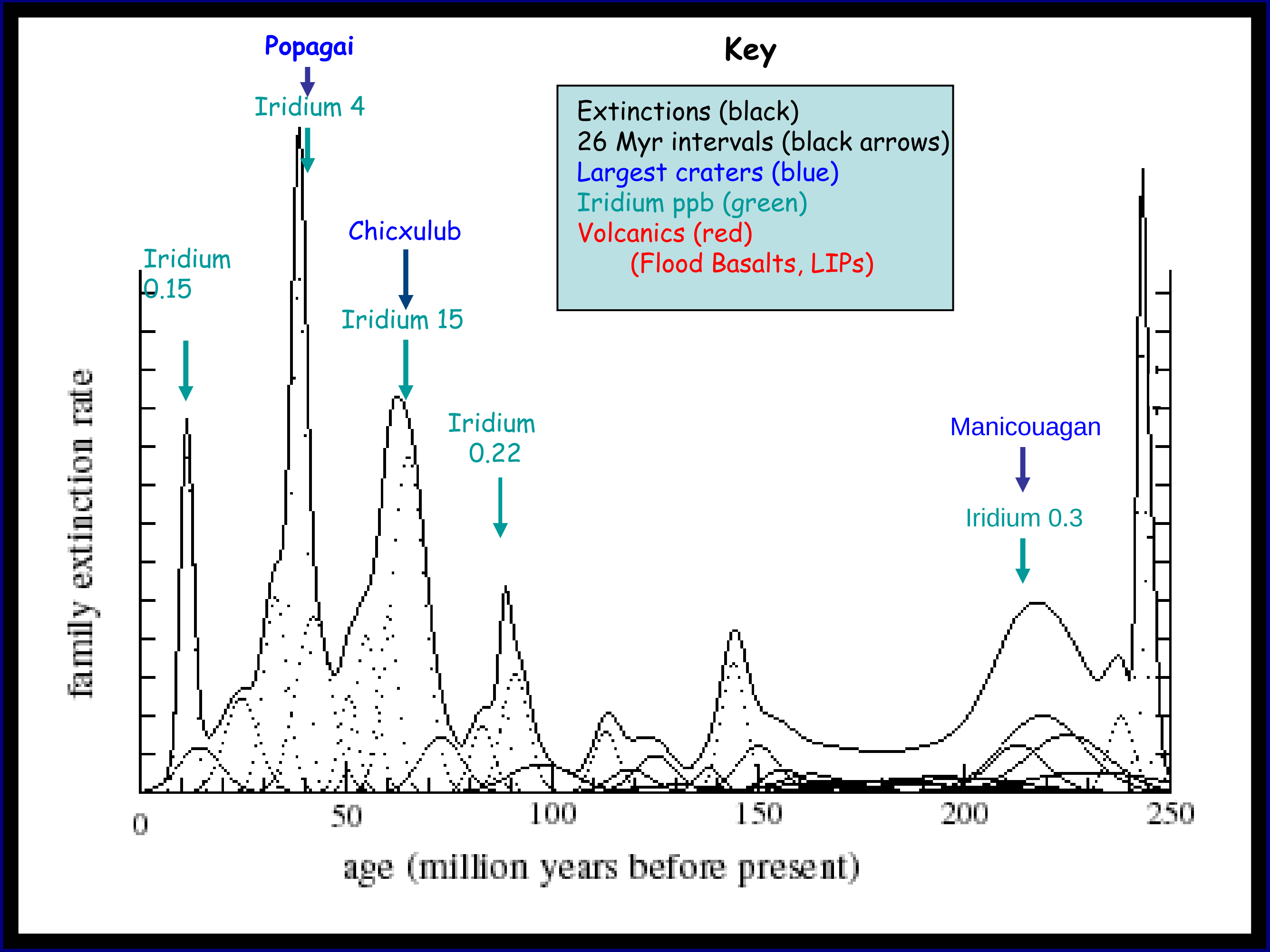
The largest impact craters



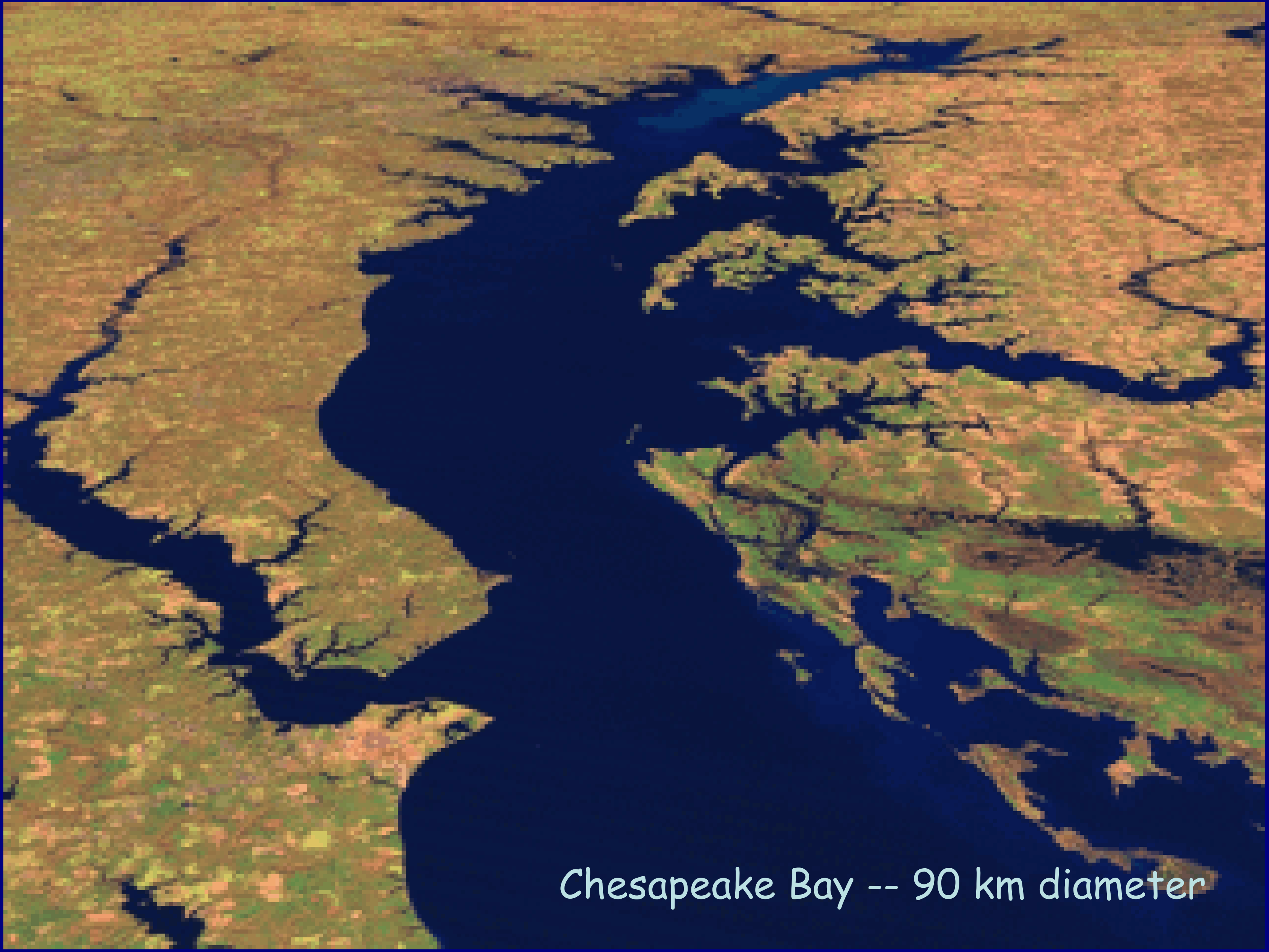
Extinctions: Sepkoski, Muller Craters: Koeberl Iridium: Asaro, Orth, others Volcanism: Ernst & Buchan


Popagai
diameter 100 km

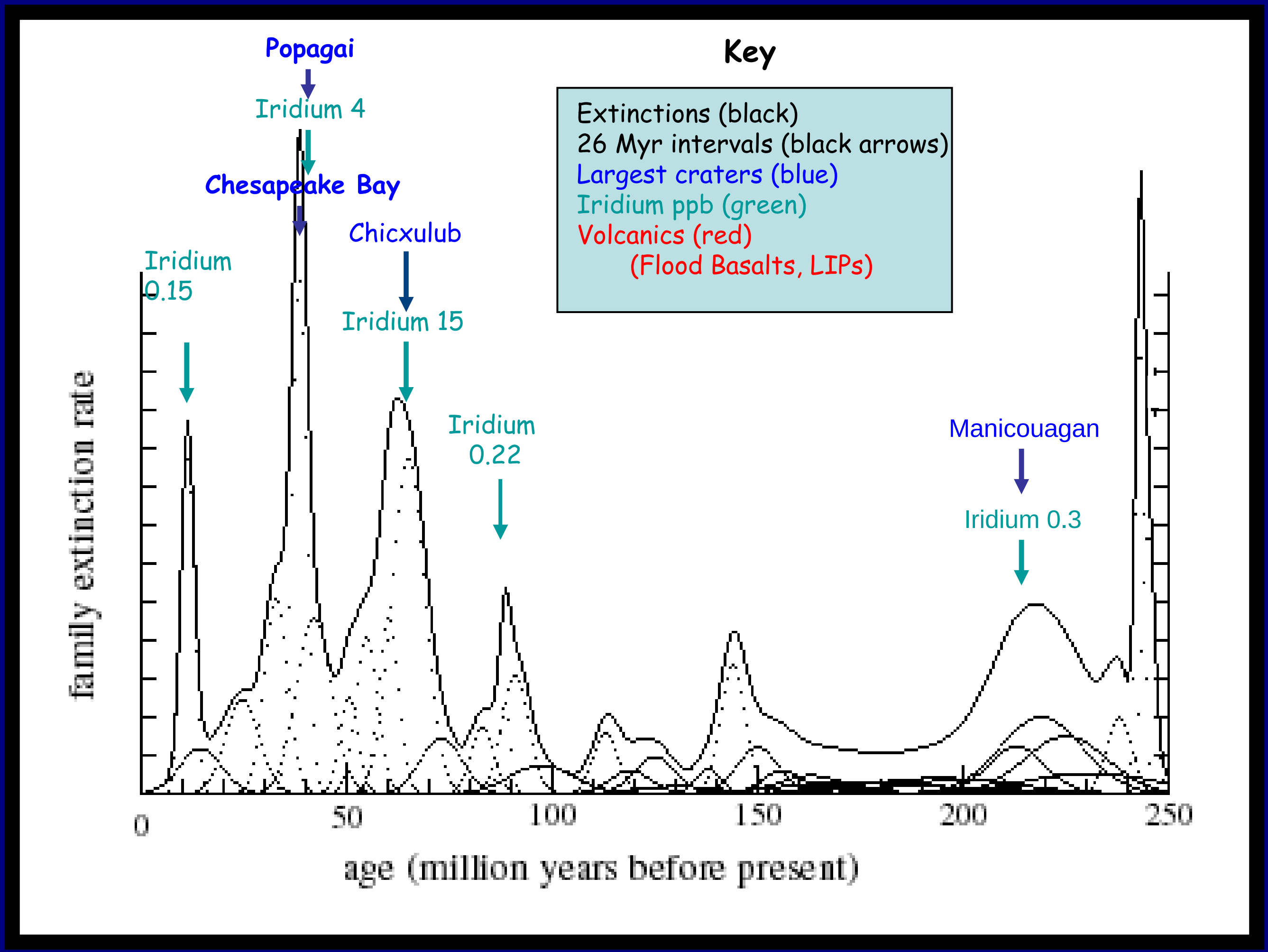
The largest impact craters



Extinctions: Sepkoski, Muller Craters: Koeberl Iridium: Asaro, Orth, others Volcanism: Ernst & Buchan


Chesapeake Bay -- 90 km diameter

The largest impact craters

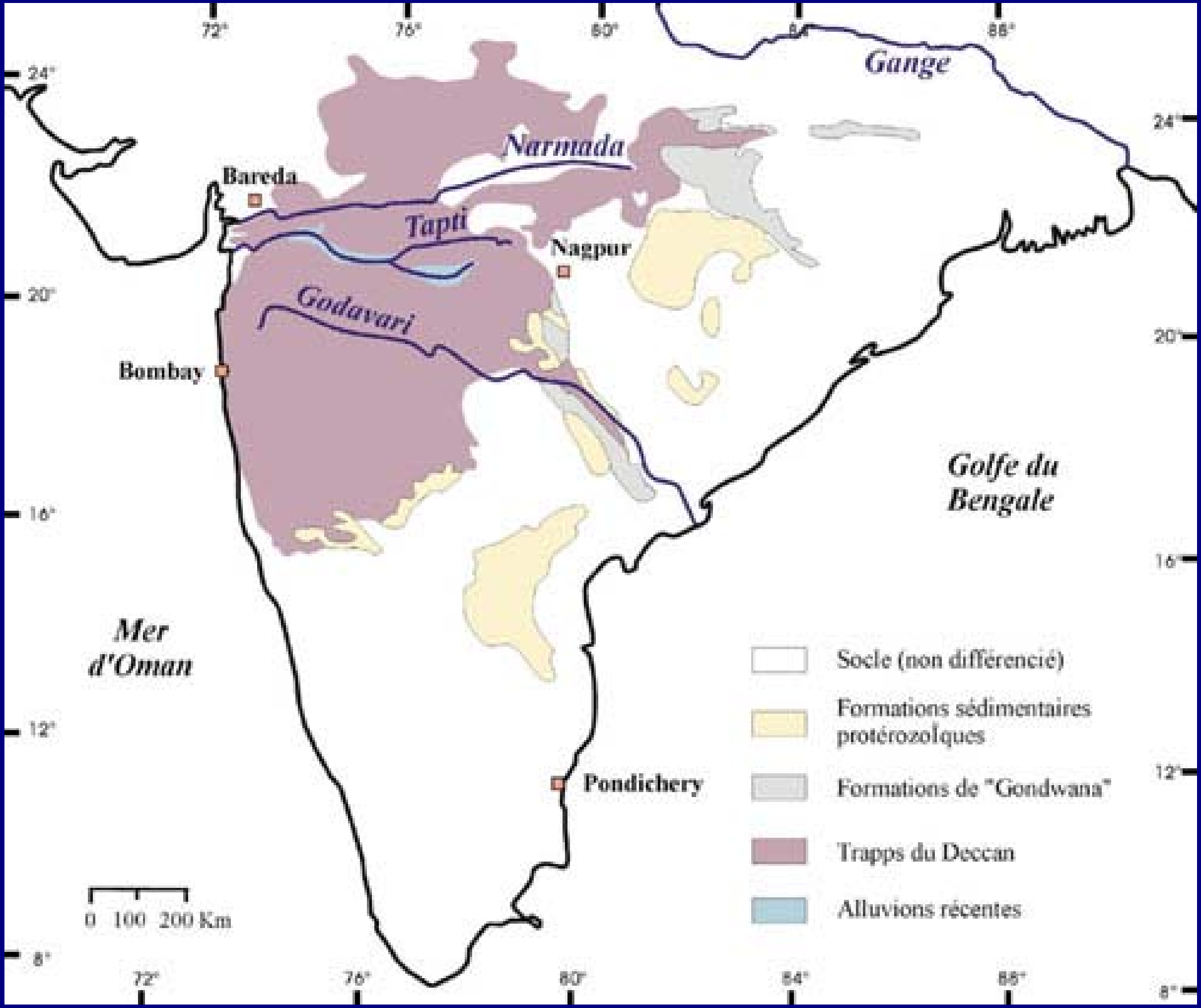


Extinctions: Sepkoski, Muller Craters: Koeberl Iridium: Asaro, Orth, others Volcanism: Ernst & Buchan

Deccan India Lava Flows

Deccan Flood Basalts

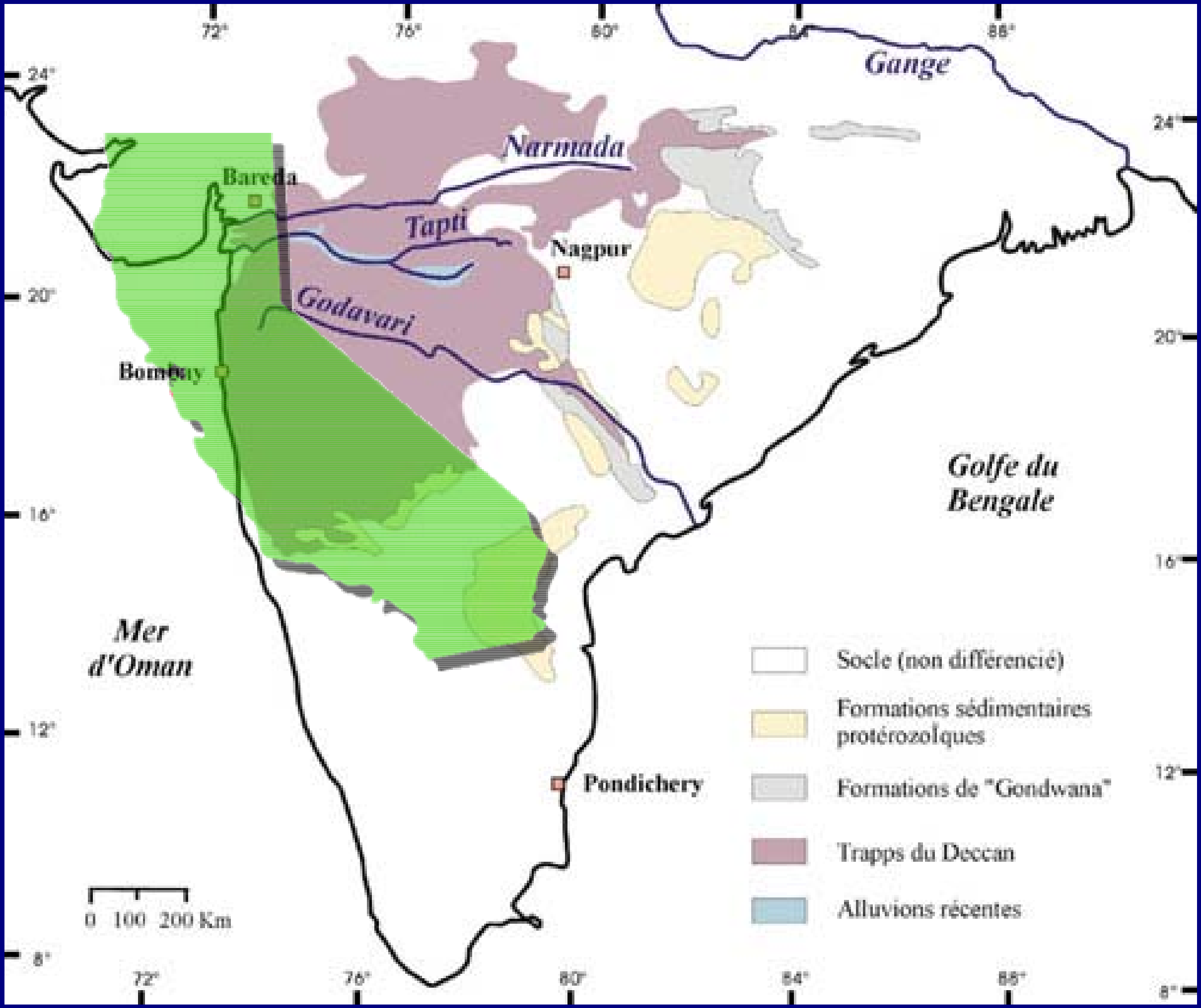
The greatest eruption on Earth in the last 100 million years



1.8 million square kilometers

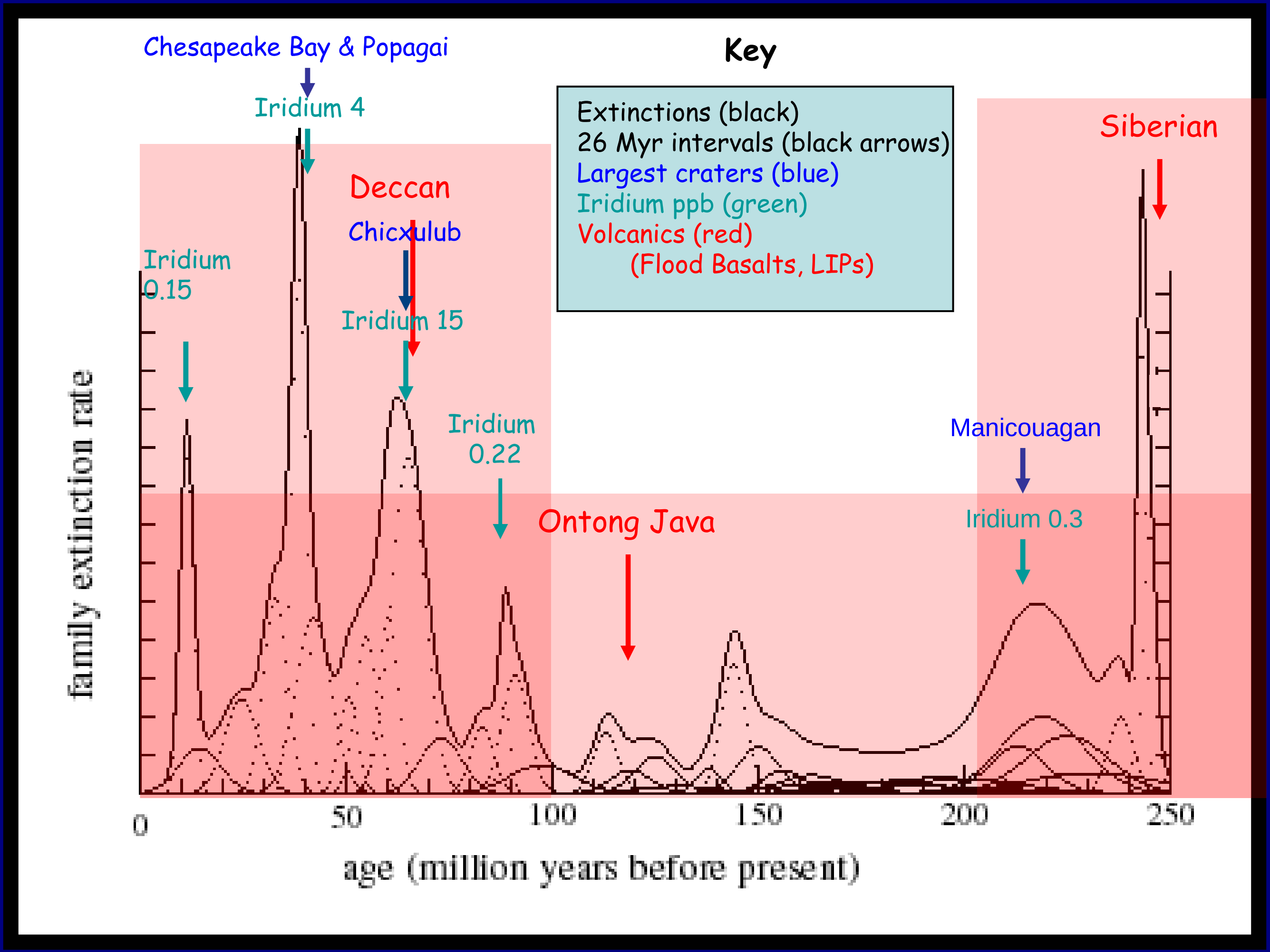
Deccan Flood Basalts

The greatest eruption on Earth in the last 100 million years



1.8 million square kilometers

Large Igneous Provinces (Volcanic eruptions)



Extinctions: Sepkoski, Muller   Craters: Koeberl   Iridium: Asaro, Orth, others   Volcanism: Ernst & Buchan

so --

Are all extinctions attributed to impacts?

Is the Nemesis theory now accepted?

And what about those volcanic eruptions?

Nemesis for Nemesis?

Nature **311**, Oct 18, 1984

Mark Bailey (page 602) “*Nemesis for Nemesis*”

periodicity not perfect [as in original Nemesis paper: Nature 308 *715-717, 1984]*

lifetime only 1 Gyr (ref to Clube and Napier) [aioNp]

Hut paper amounts to a “a near retraction” *(words not those of Bailey!)*

[so don’t bother reading it?]

Jack G. Hills (page 636)

supports Nemesis hypothesis -- remaining lifetime ≈ 1 Gyr [aioNp]

Nemesis may have perturbed orbit of Pluto

Piet Hut (page 638)

lifetime of orbit is not constant, but decreasing linearly [aioNp]

Simulations show 1 Gyr left. Began with 5 Gyr [aioNp]

plane of orbit ≈ that of Milky Way

Torbett and Smoluchowski (page 641)

Giant molecular clouds disrupt orbit

but they mistakenly assumed such clouds were compact

error pointed out by Muller and Morris*, Icarus* v. 65, p. 1-12.

“The trouble with most folks isn't so much their ignorance…

It's know'n so many things that ain't so.” -- J. Billings

How can we get a better history of impacts?

Answer:

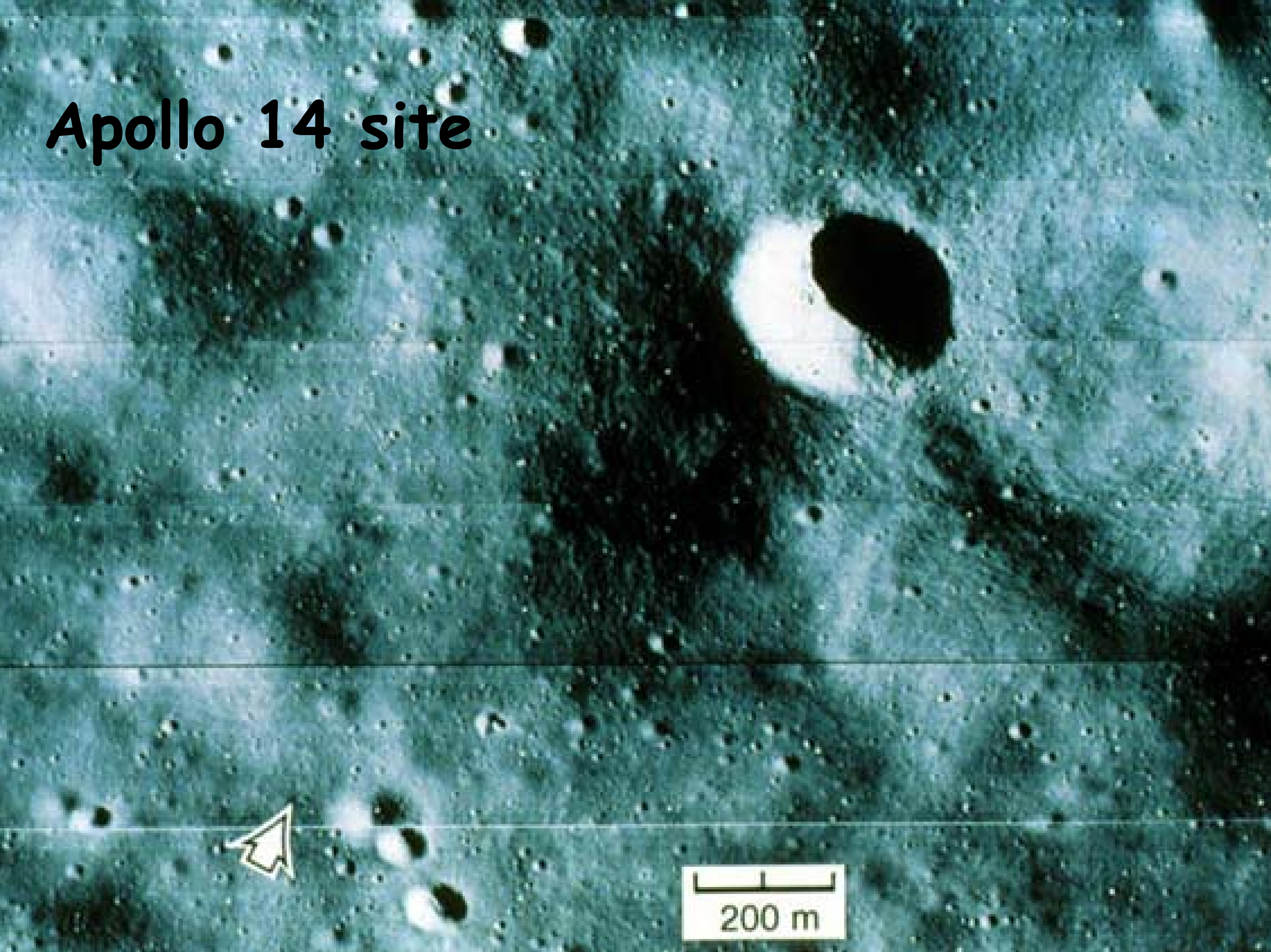
The Moon!

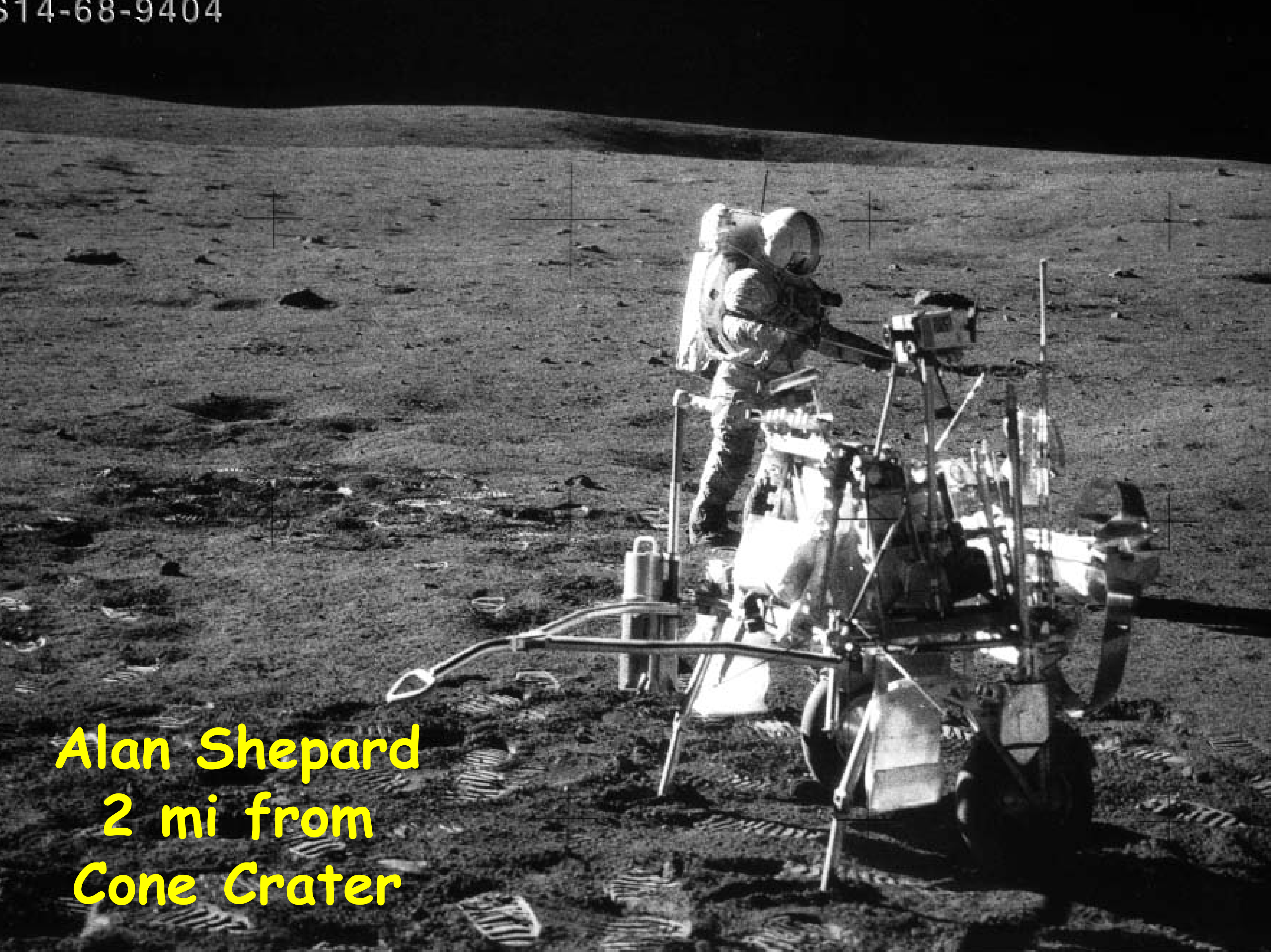
But -- only 3 craters have known ages

And -- trips to the moon are expensive!

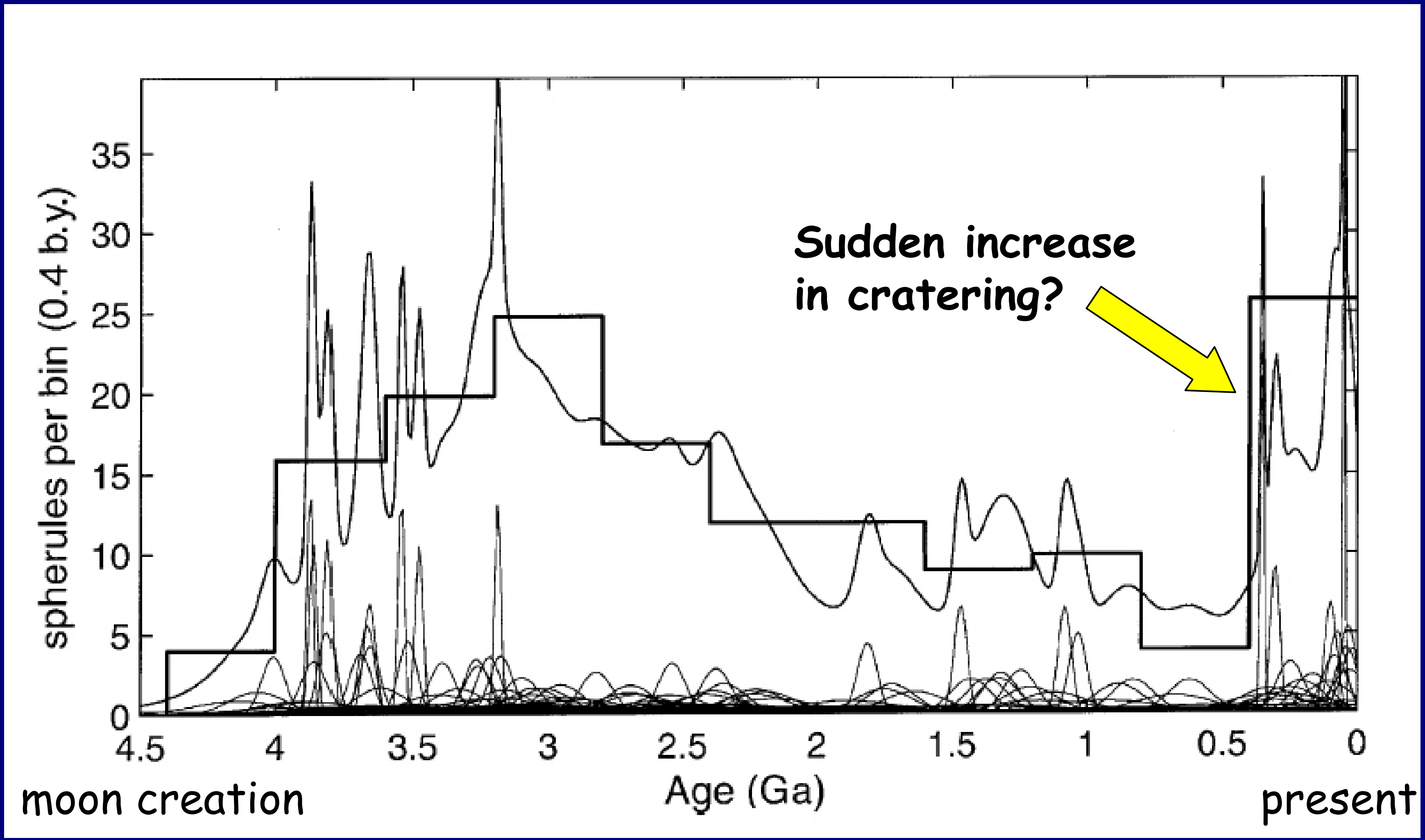
Glass droplets (spherules) created by impact

diameter 100 microns (4 human hairs)


Apollo 14 site
200 m


AS14-68-9404
Alan Shepard
2 mi from
Cone Crater

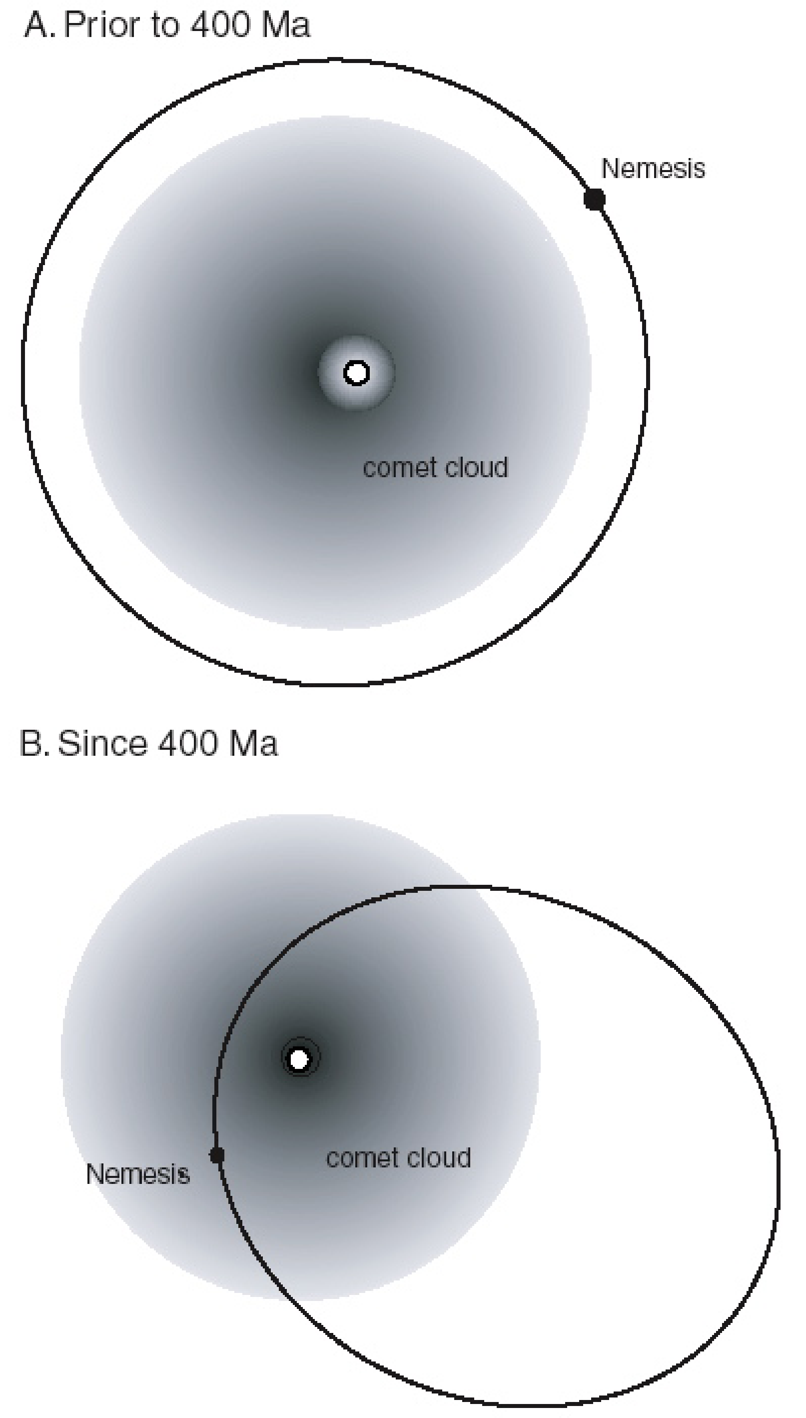
138 Apollo 14 glass droplet ages



Culler, Becker, Muller, Renne, Science **287**, 1785-1788 (2000)

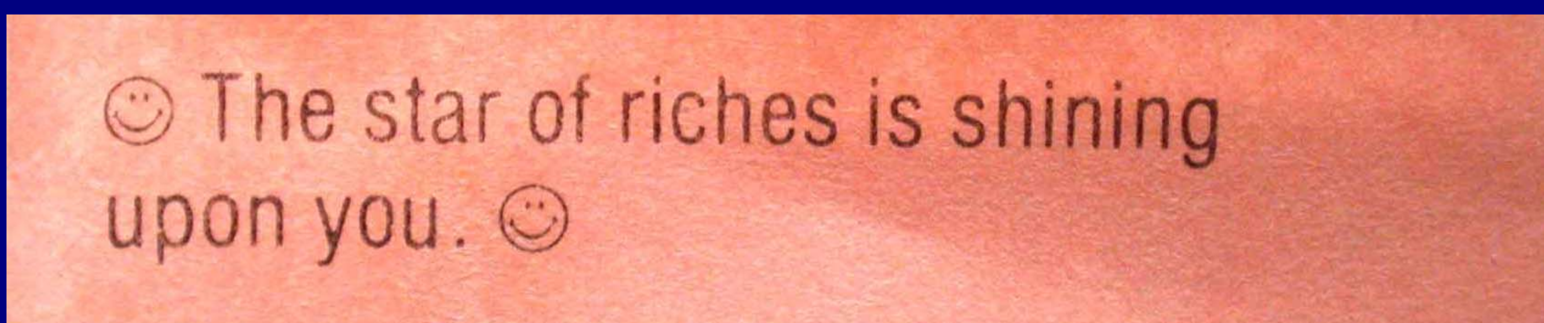
postulated
Nemesis
orbit
change

in the
"recent" past
(400 Ma)



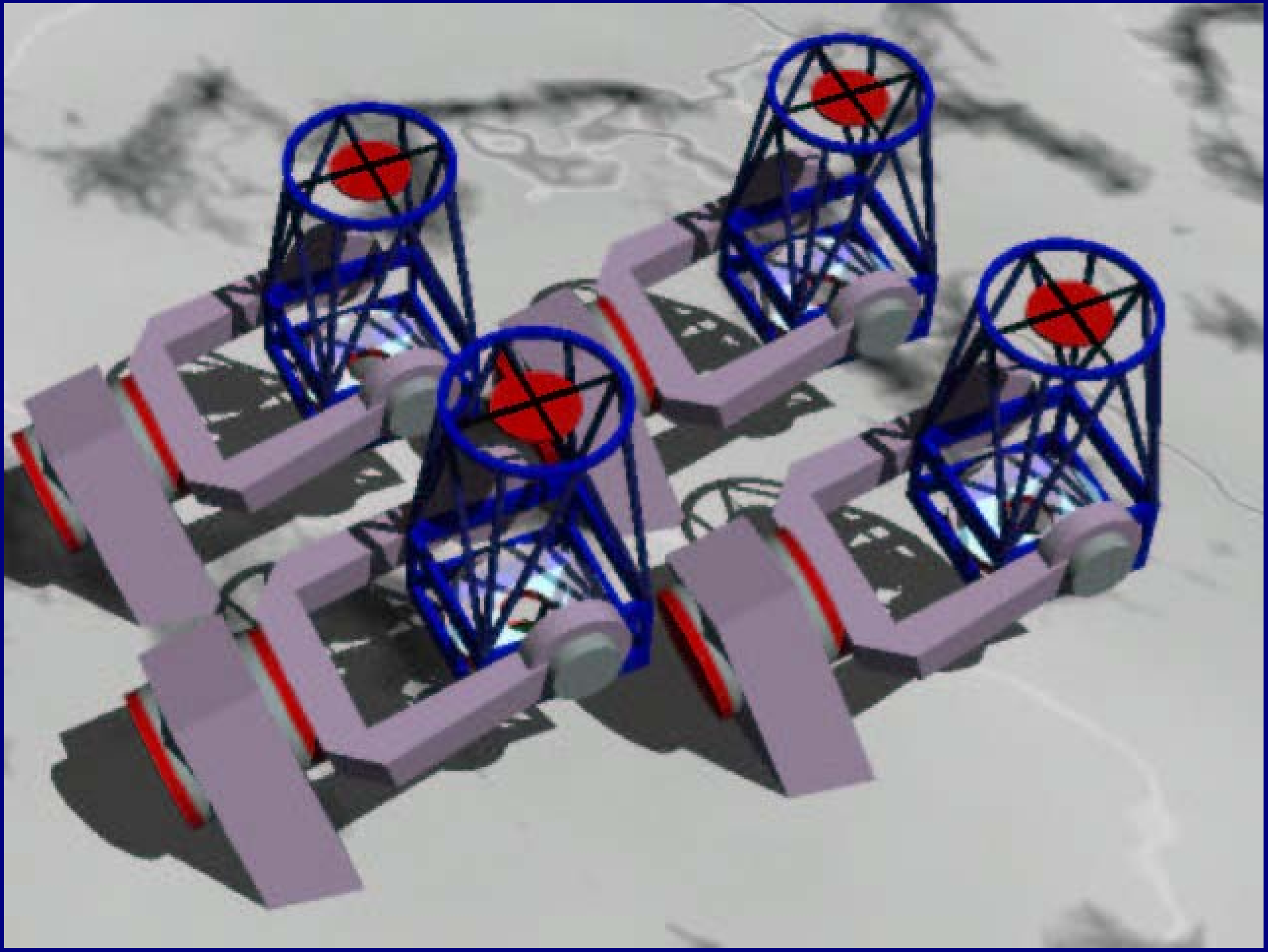
Walter Alvarez has dinner with Gene Shoemaker

According to Walter, they discussed Rich's star, Nemesis. Then, after dinner, Walter got his fortune cookie.



Better than fortune cookie: Pan-Starrs

(Panoramic Survey Telescope and Rapid Response System)



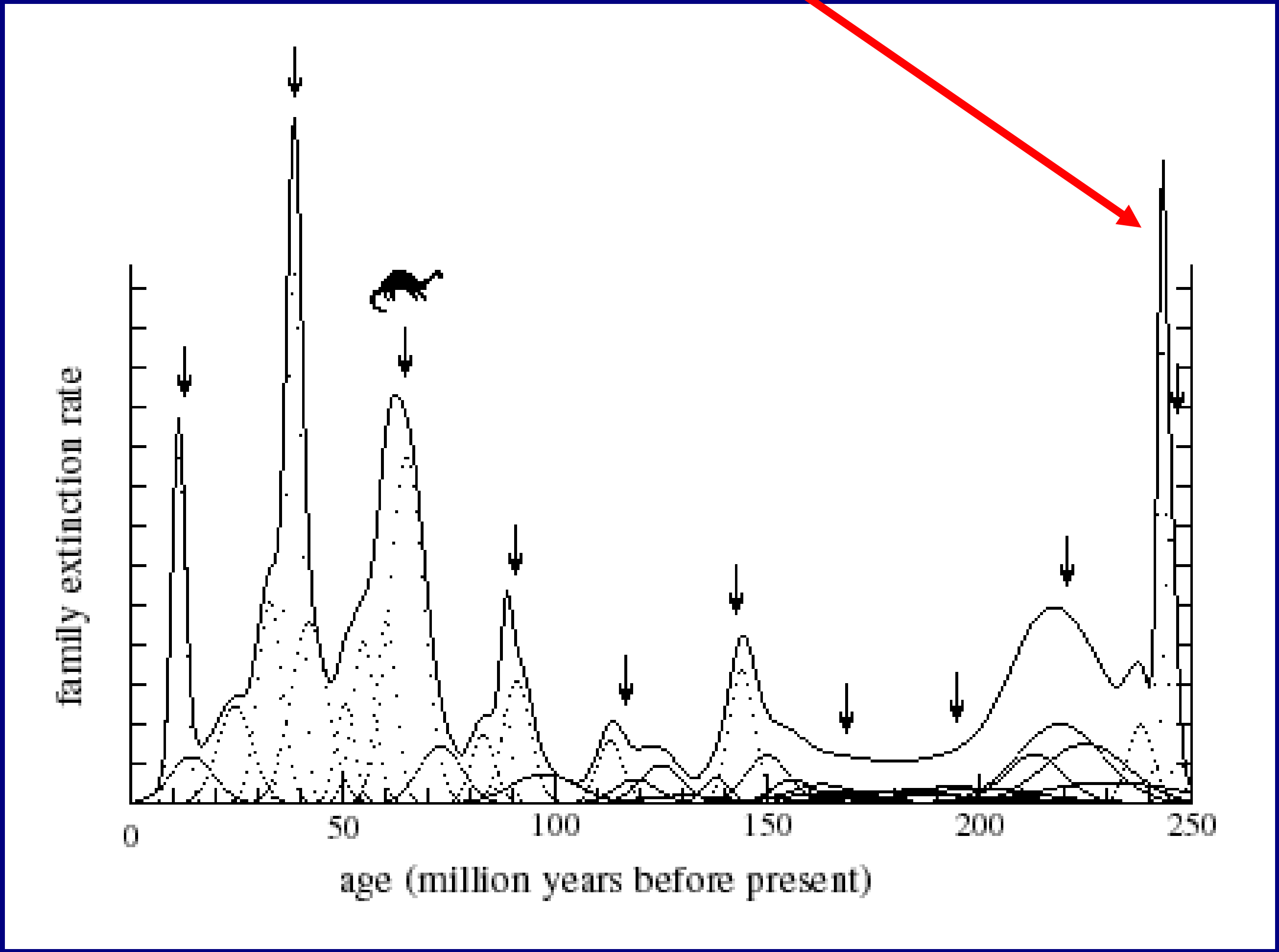
U. Hawaii, MIT Lincoln Labs, Maui High Perf. Comp Center, SAIC

LSST OBSERVATORY

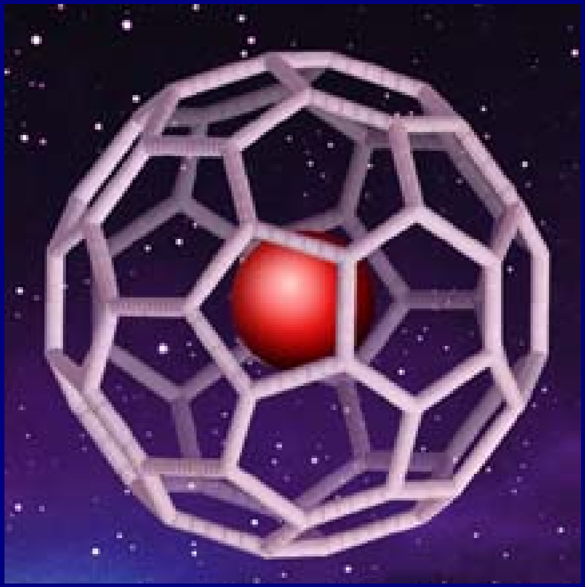
The Large-aperture Synoptic Survey Telescope, often called the Dark Matter Telescope, is a proposed 8.4 meter, 7 square-degree field, synoptic survey telescope. The product of collecting area and field of view will be 20 times more powerful than any observatory now operating or under construction. Its effective aperture is 6.9 meters. The possibility of repeatedly surveying large portions of the sky to unprecedented depth opens a range of unique opportunities, from detecting Earth-threatening asteroids to probing the nature of dark energy.

By 2010, we will either find Nemesis, or prove it doesn't exist.

What about the Permian-Triassic?



Luann Becker: Buckyballs at the Permian Triassic



with extraterrestrial argon!

but: Ken Farley contradicts

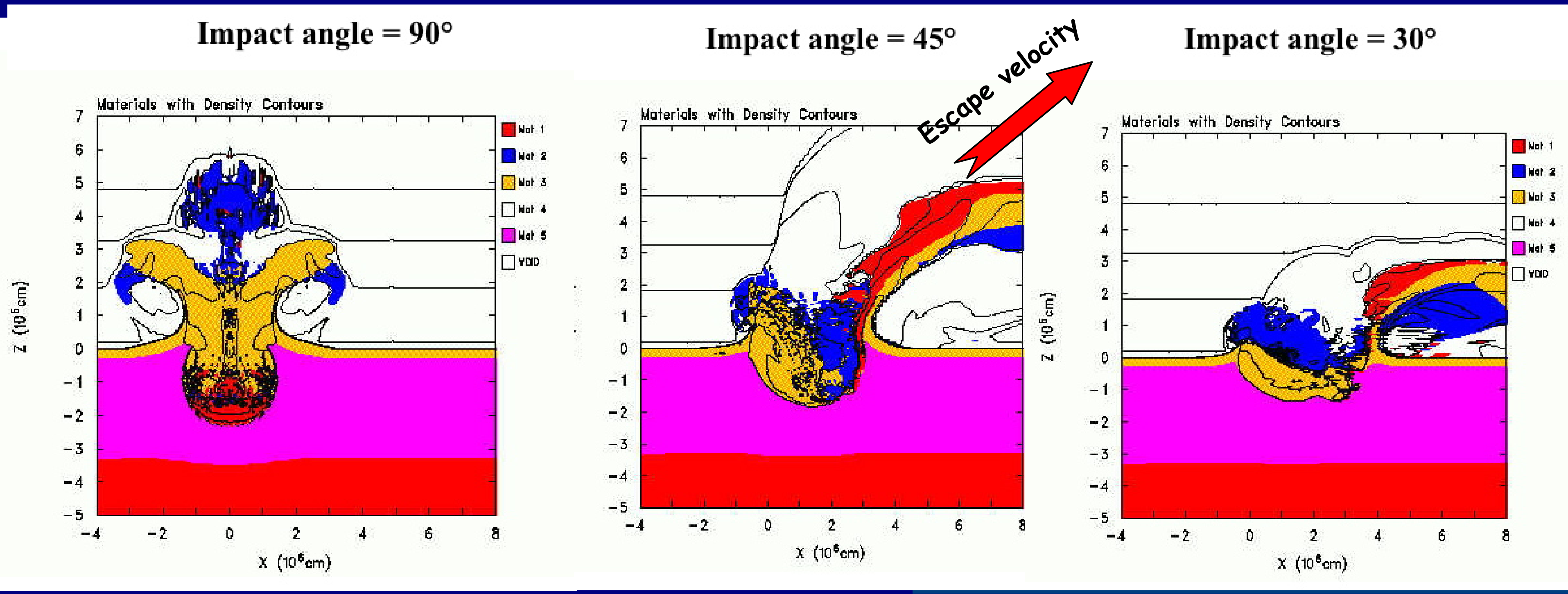
Nagging Puzzles at the Permian-Triassic (250 Million years ago)

- **why no iridium layer?**

solution: vertical impact

- **why huge vulcanism (Siberia)?**

Normal vs. Oblique Impacts



caveat: simulations done
at low velocities

E. Pieraxzo and H. J. Melosh

Nagging Puzzles at the Permian-Triassic (250 Million years ago)

- **why no iridium layer?**

  solution: vertical impact

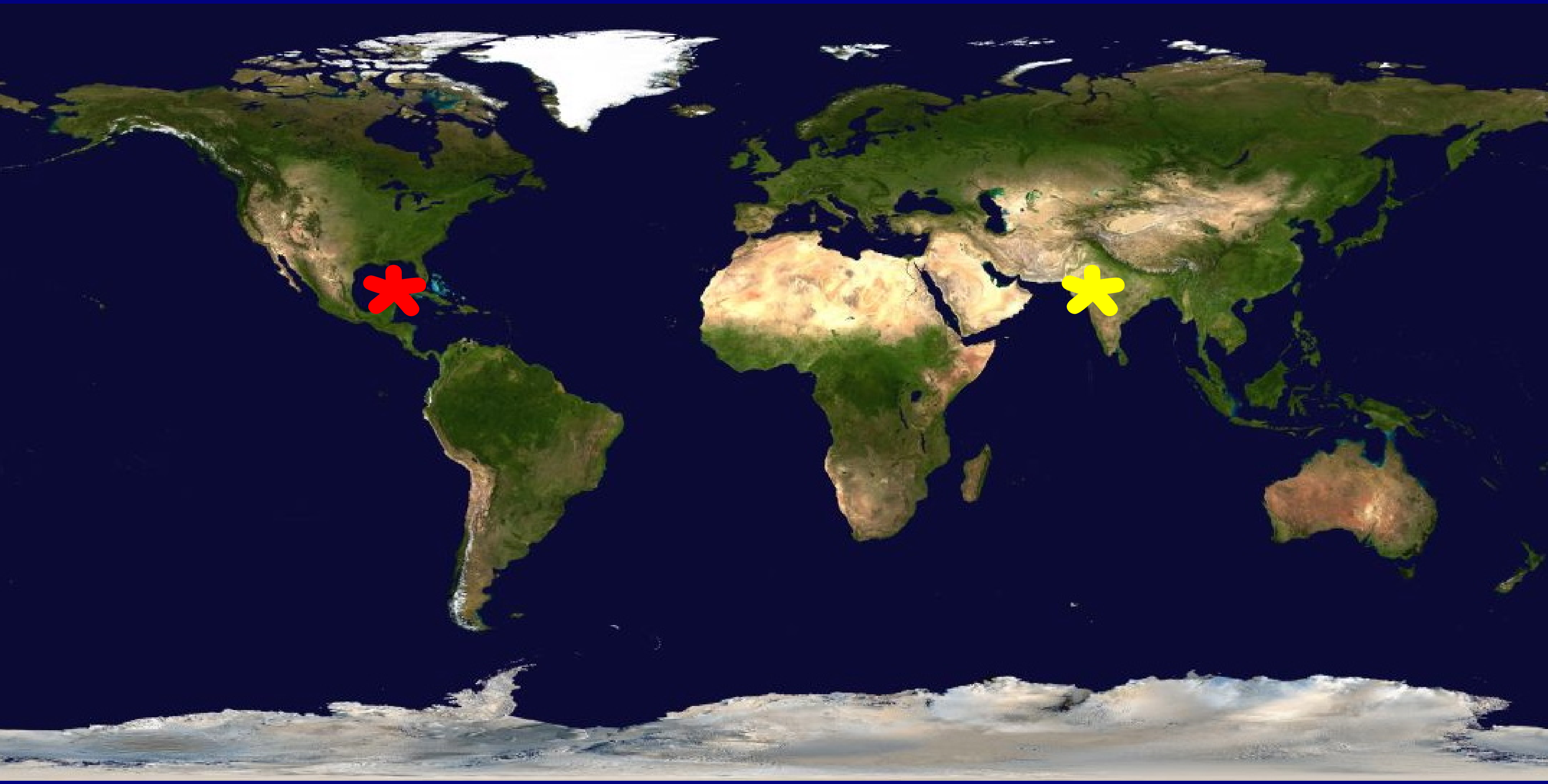
- **why huge vulcanism (Siberia)?**

  possible solution:
  triggered by impact

recall the vulcanism at the dinosaur extinctions

Deccan Traps

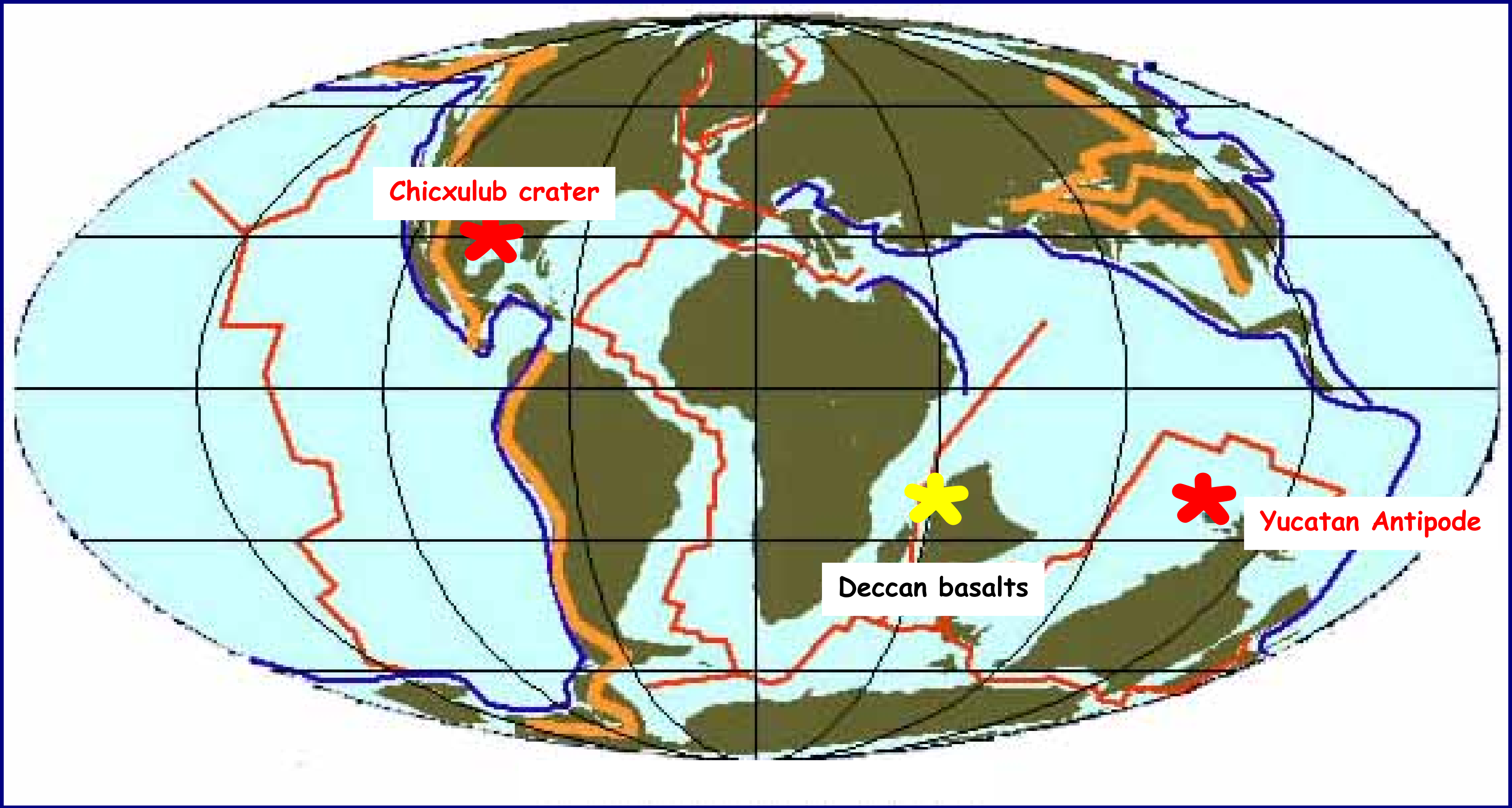
Antipodes?



Chicxulub

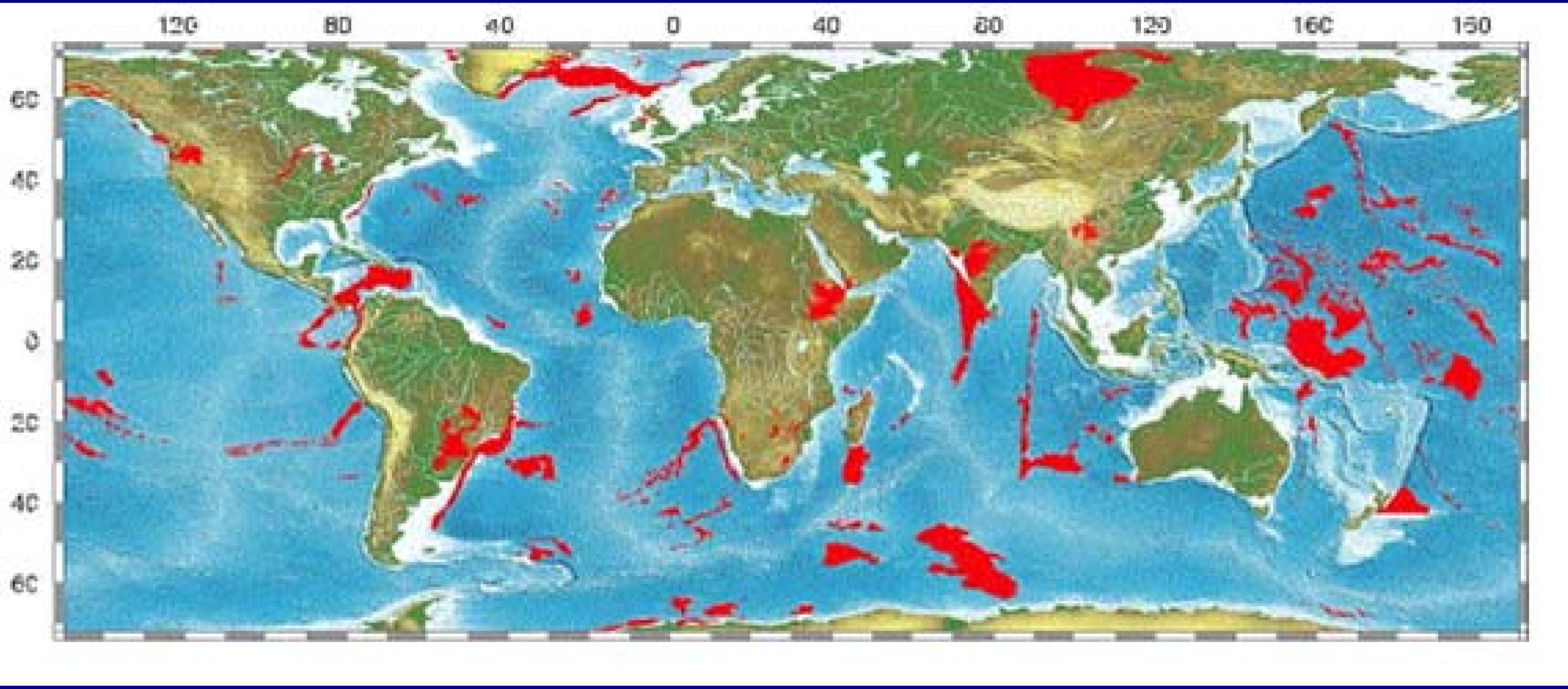
Deccan

Walter Alvarez: Deccan and Chicxulub NOT antipodes



Nevertheless, someone proposes the idea of antipodes every year

Large Igneous Provinces (flood basalts)

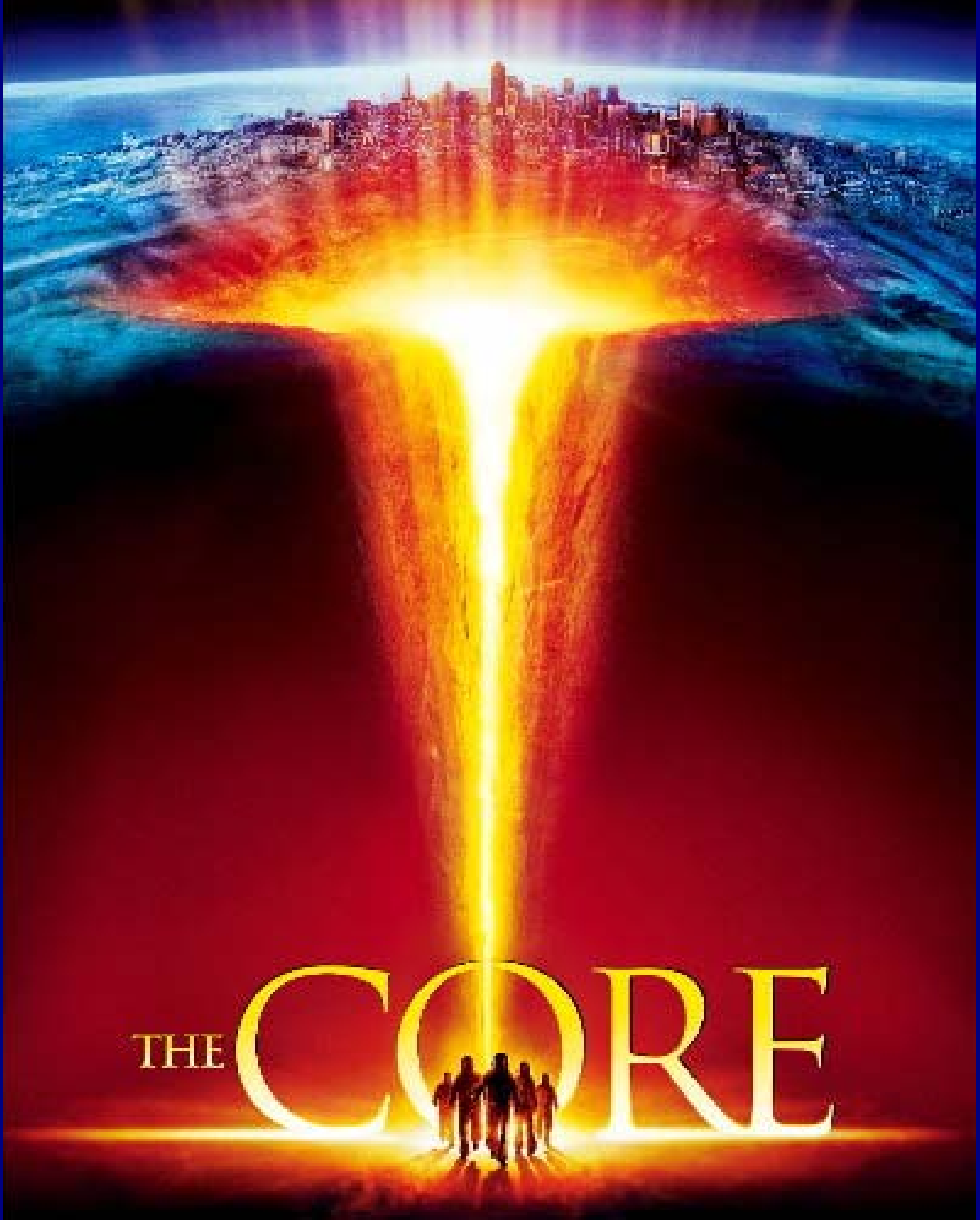


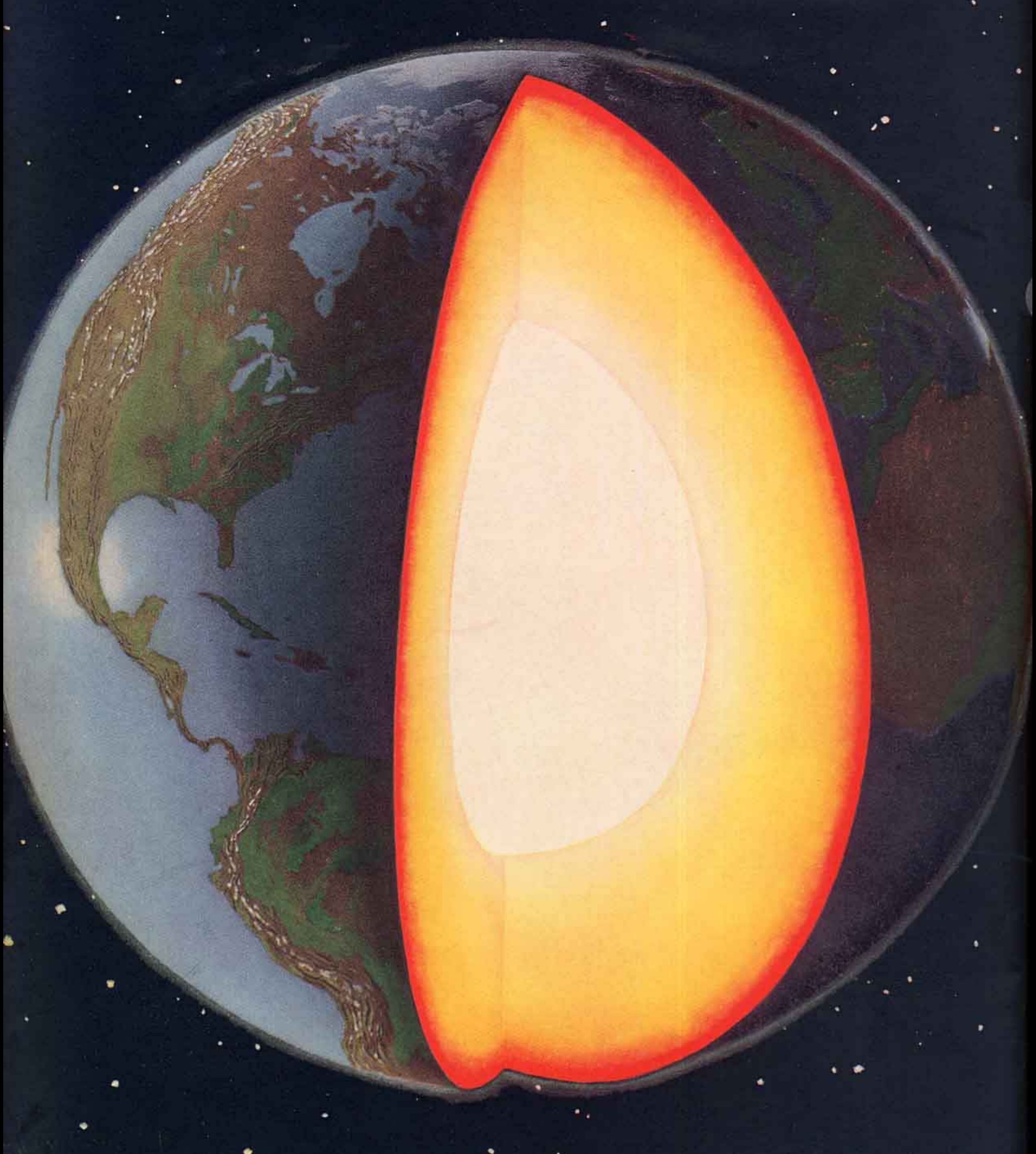
When the Earth bleeds, it bleeds basalt.

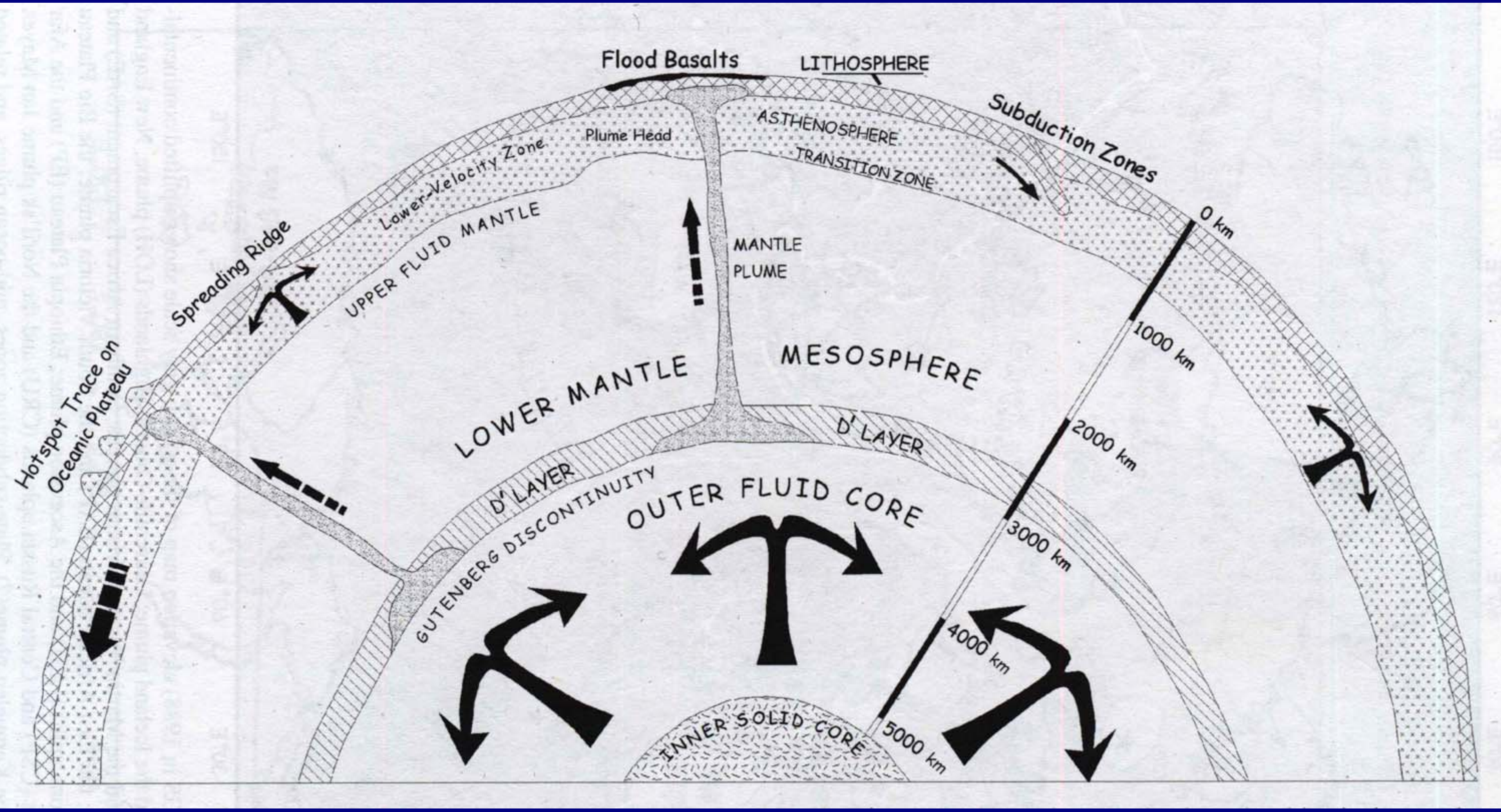
1984-2002

How could an impact trigger a flood basalt?

2002 -- a possible answer:

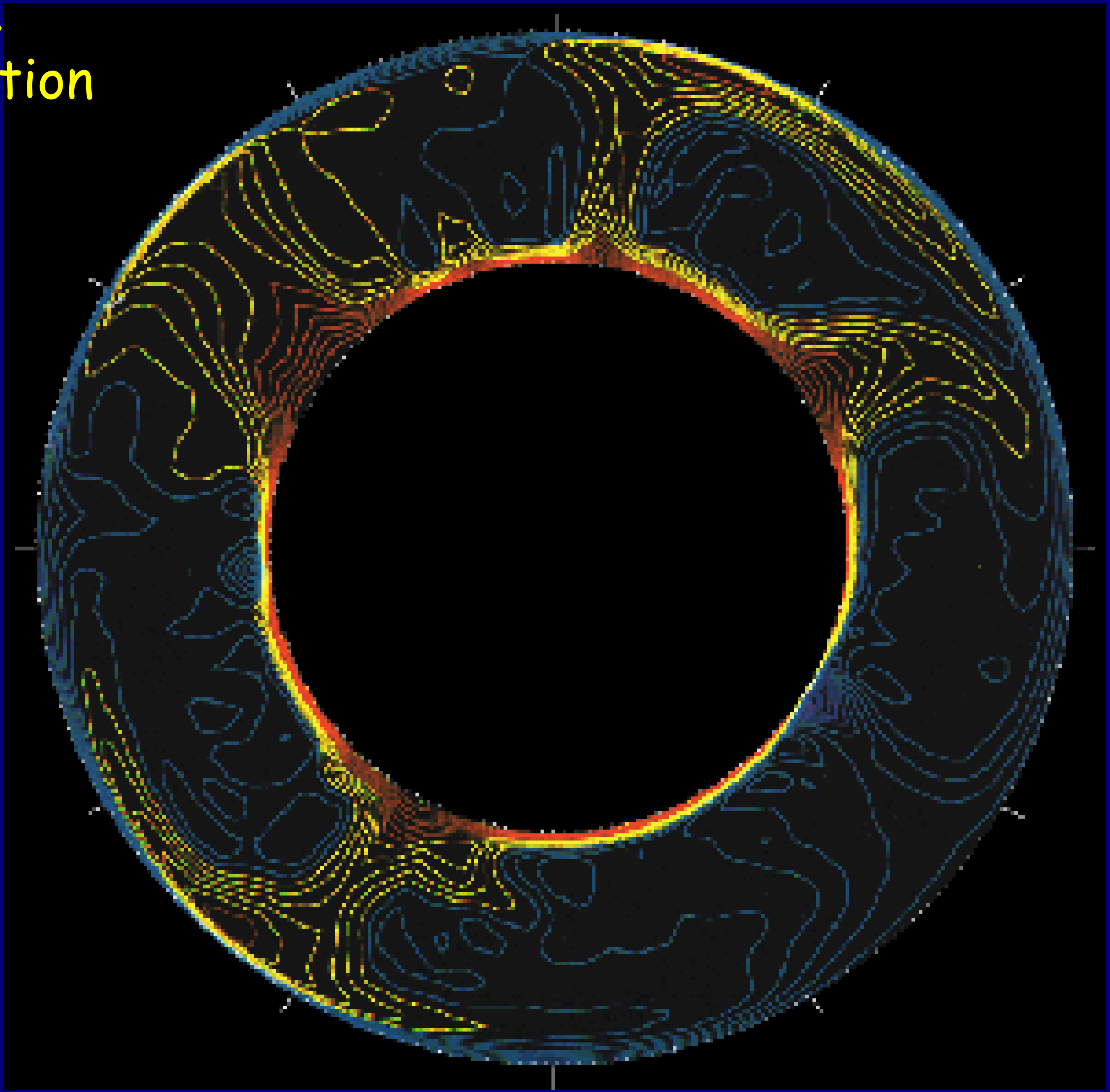

THE CORE





from Shissell

Mantle convection



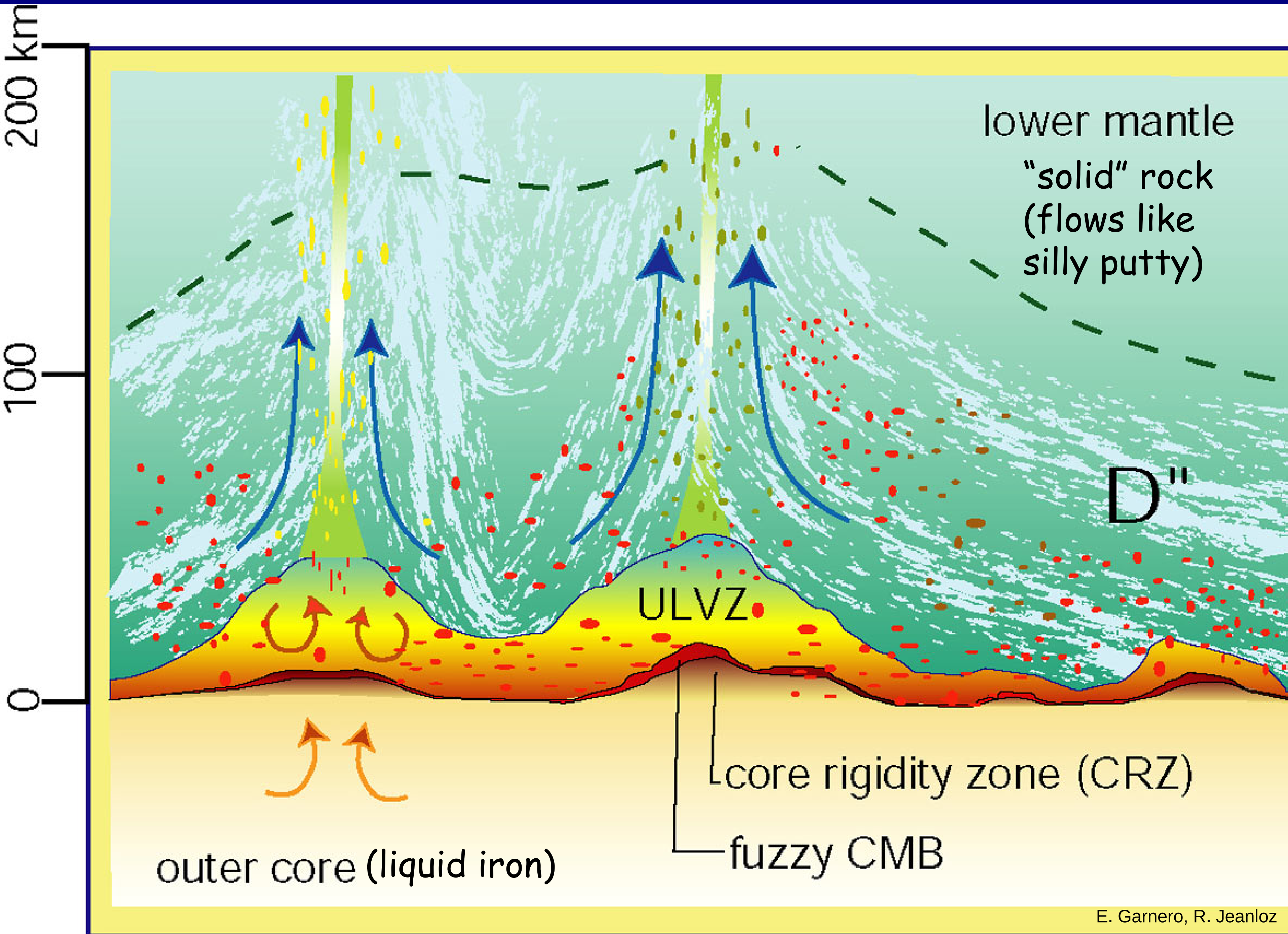
simulation by
Burkavici

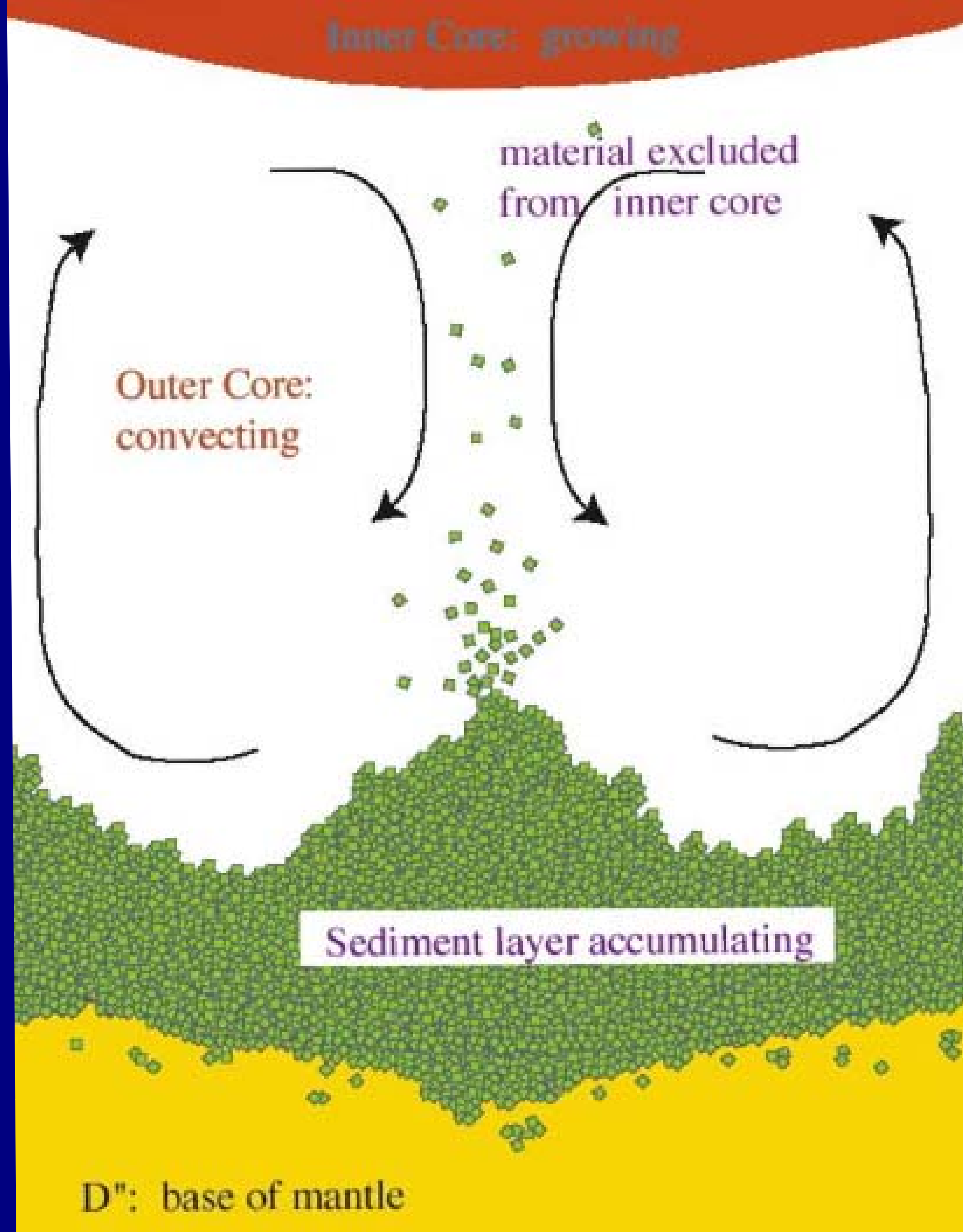
Plume simulation movie

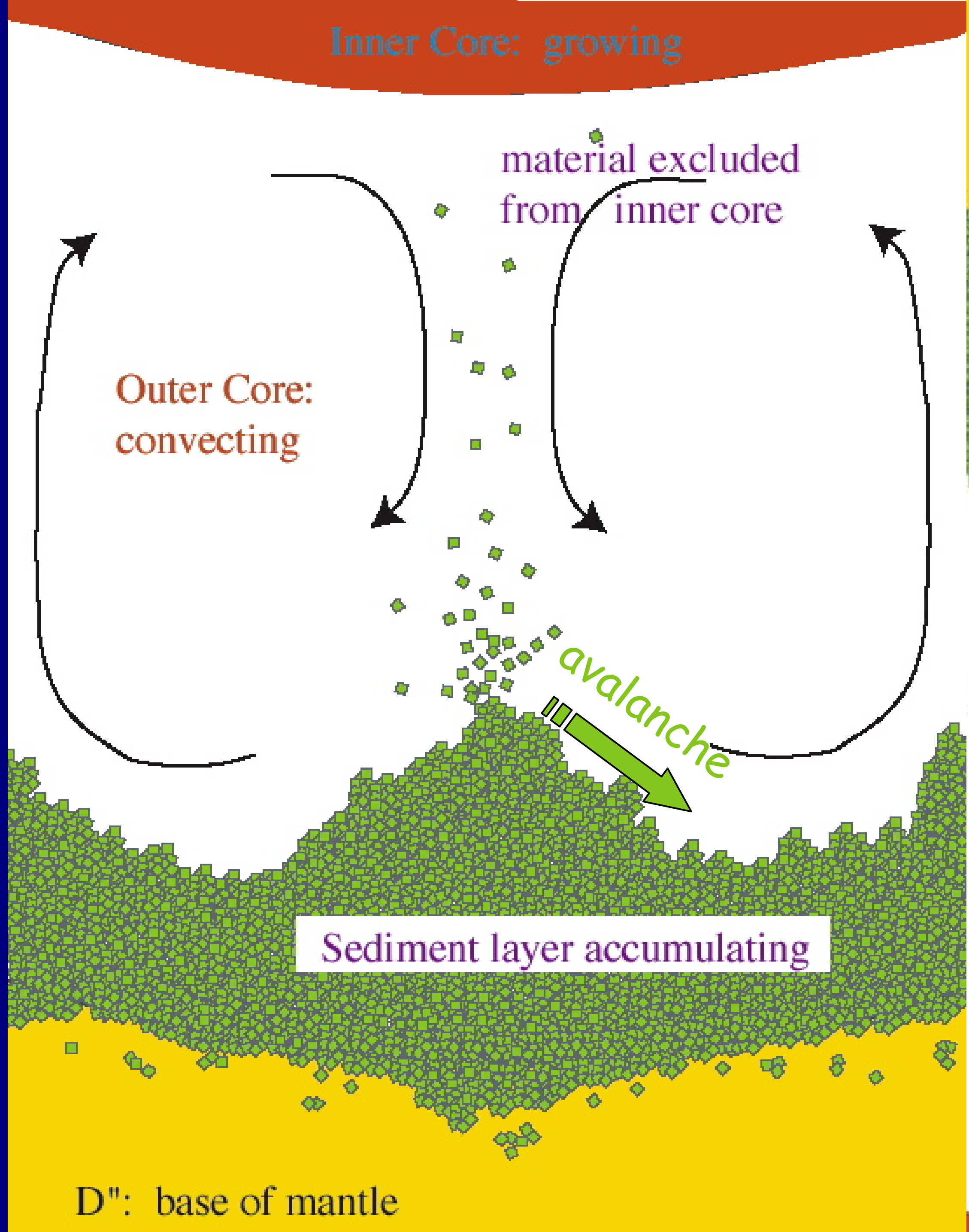
Convective Instability

Thunderstorm
or
Atomic Bomb
or
Heated oil (sautéing)
or
Lava lamp
or
Mantle Plume

simulation by
Paul Tackley, UCLA


200 km
100
0
lower mantle
"solid" rock
(flows like
silly putty)
D"
ULVZ
core rigidity zone (CRZ)
fuzzy CMB
outer core (liquid iron)
E. Garnero, R. Jeanloz

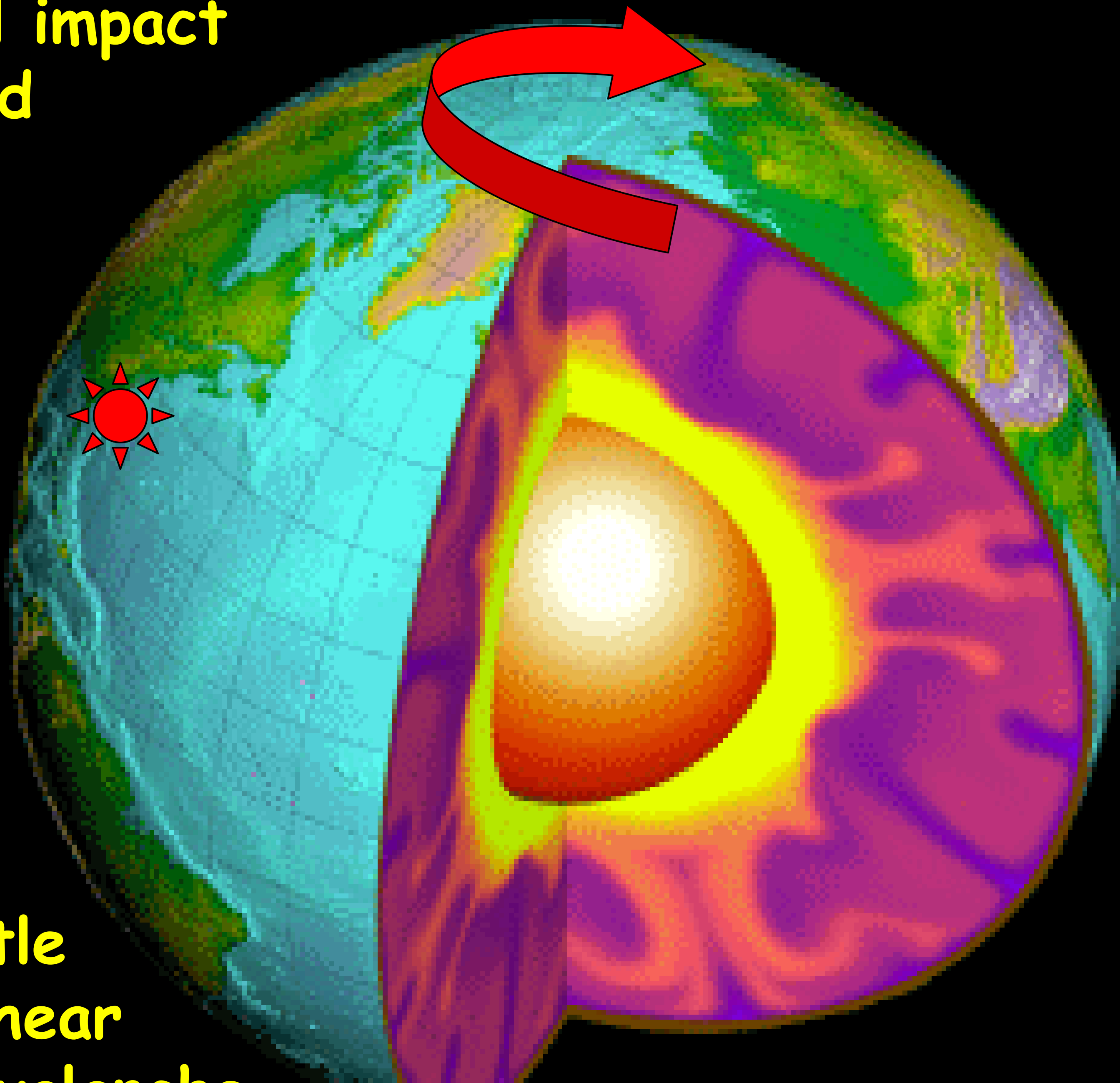

Inner Core: growing
material excluded
from inner core
Outer Core:
convecting
Sediment layer accumulating
D": base of mantle


Inner Core: growing
material excluded
from inner core
Outer Core:
convecting
avalanche
Sediment layer accumulating
D": base of mantle

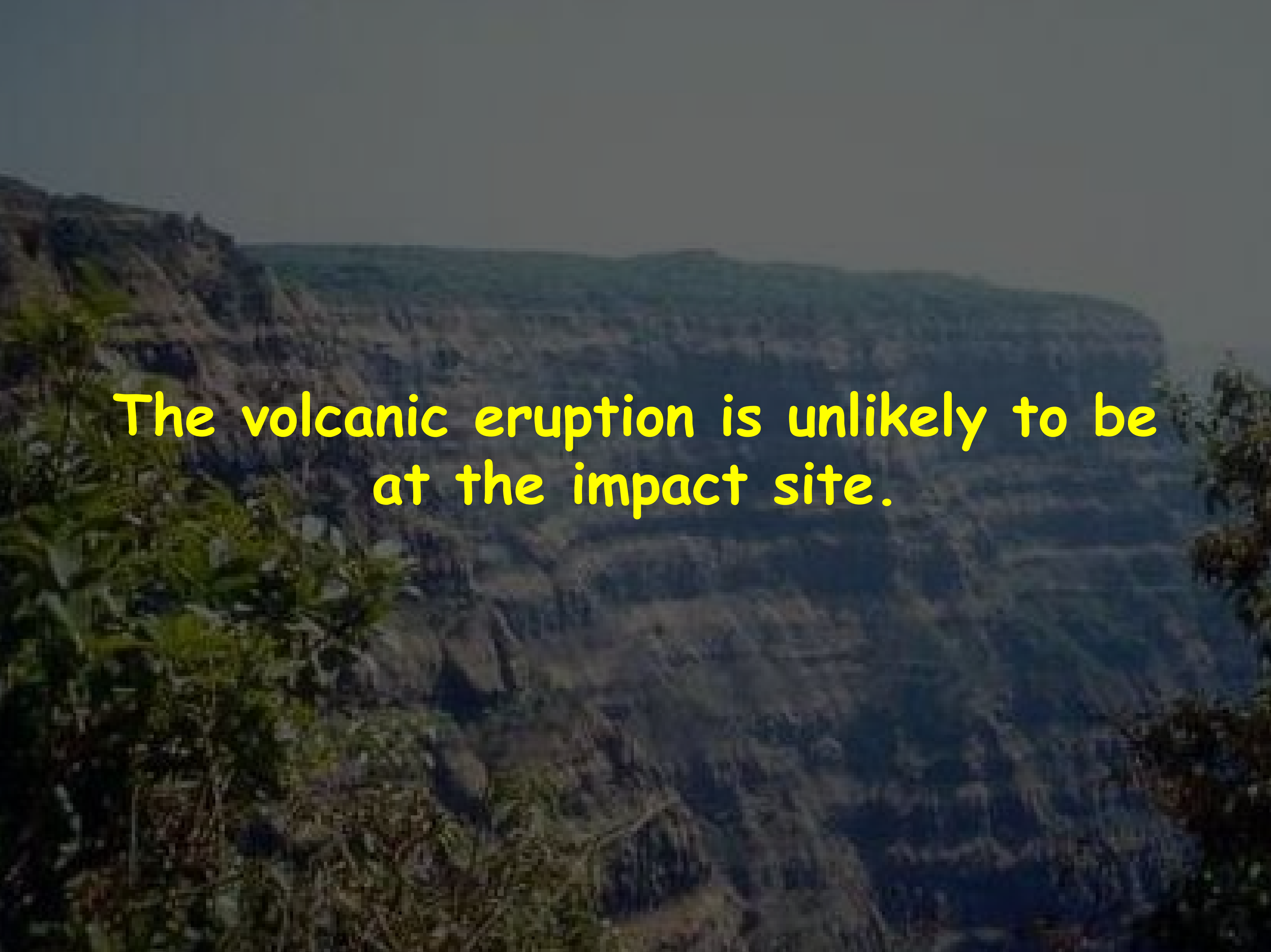
Tangential impact
of asteroid

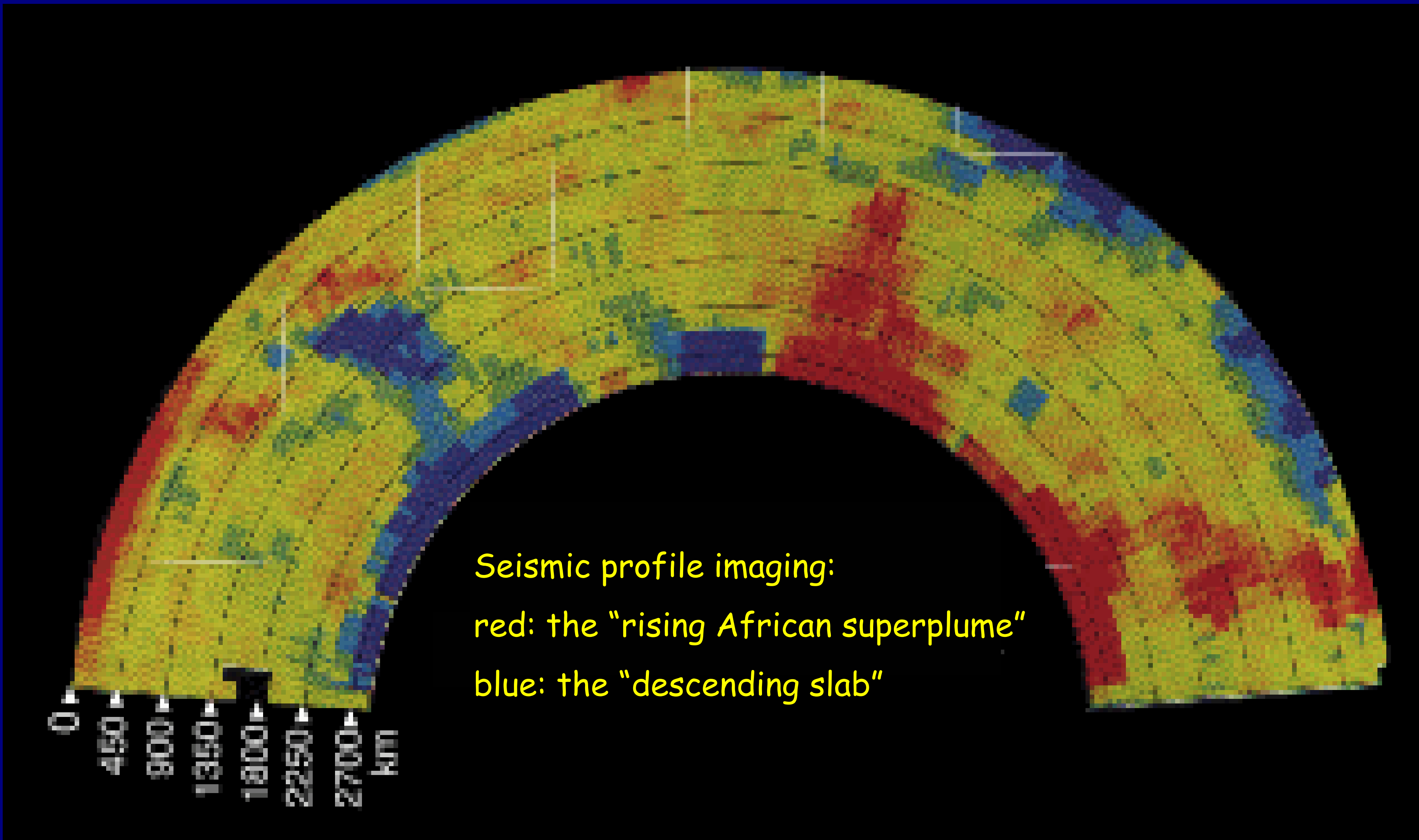
spins the
mantle

but not
the core!



Core-mantle
slippage shear
triggers avalanche, mantle plume, and vulcanism


The volcanic eruption is unlikely to be
at the impact site.



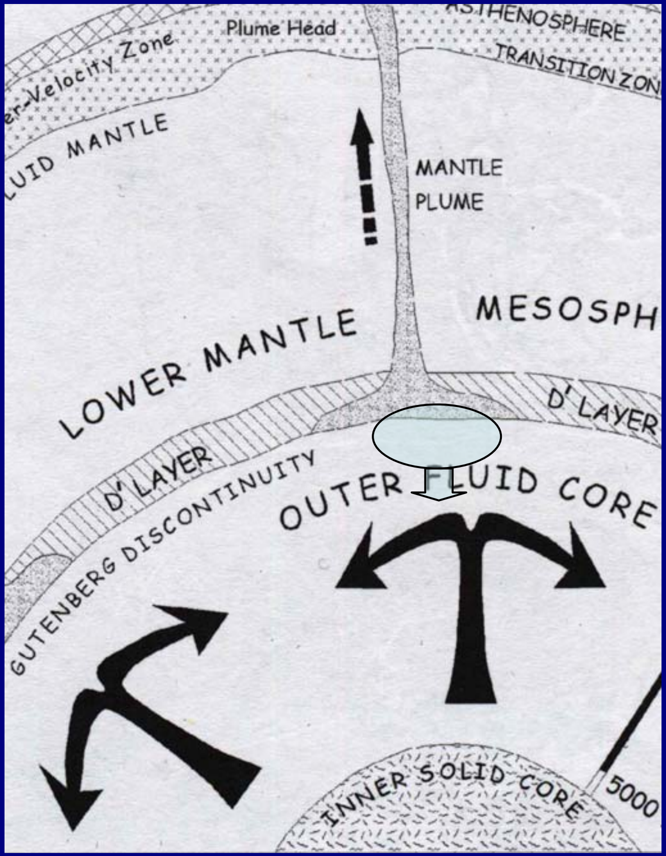
Seismic profile imaging:

red: the “rising African superplume”

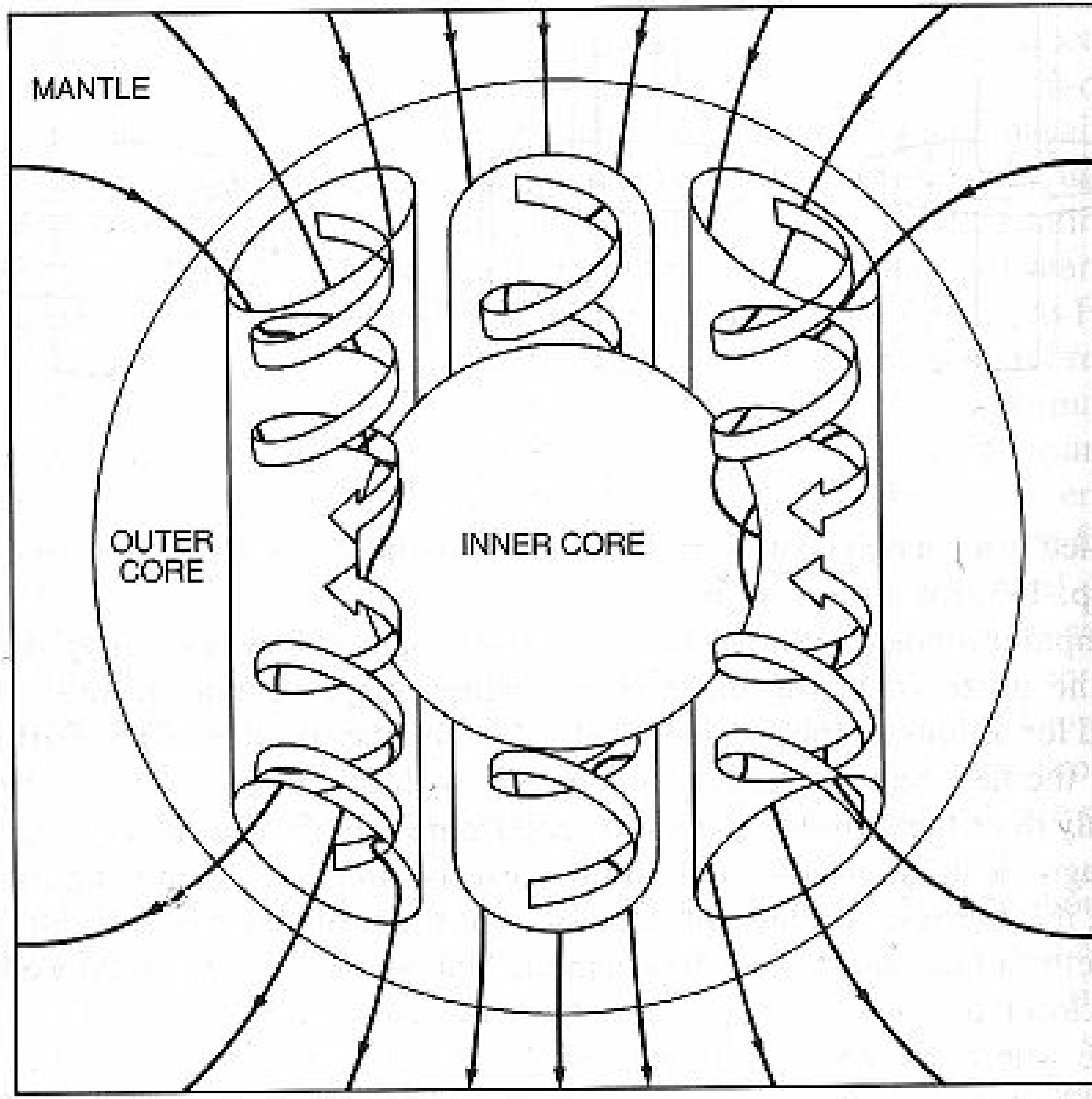
blue: the “descending slab”

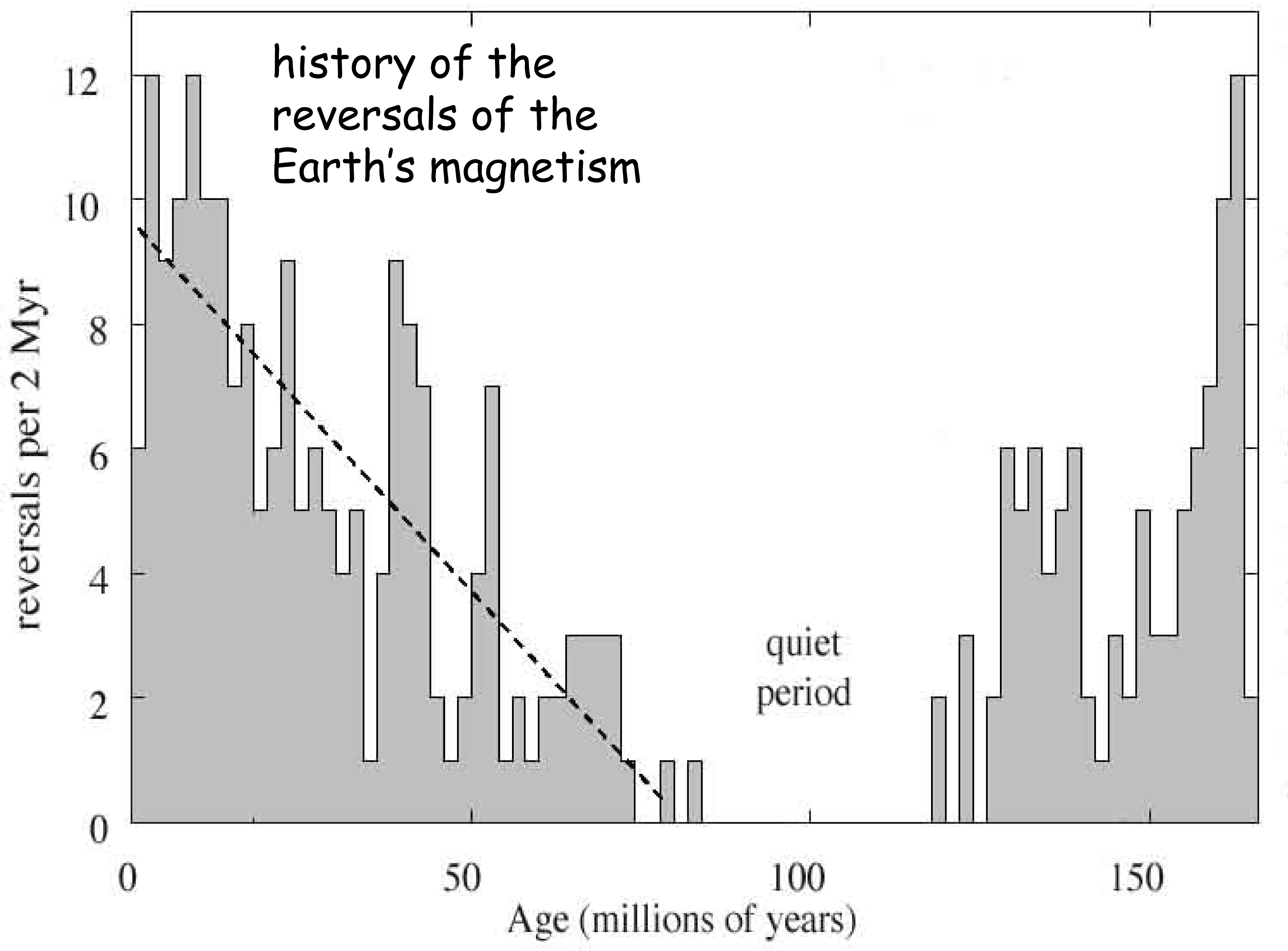
diagram by John Mutter, LDEO

Downward plumes -- into the liquid core are even easier to trigger!



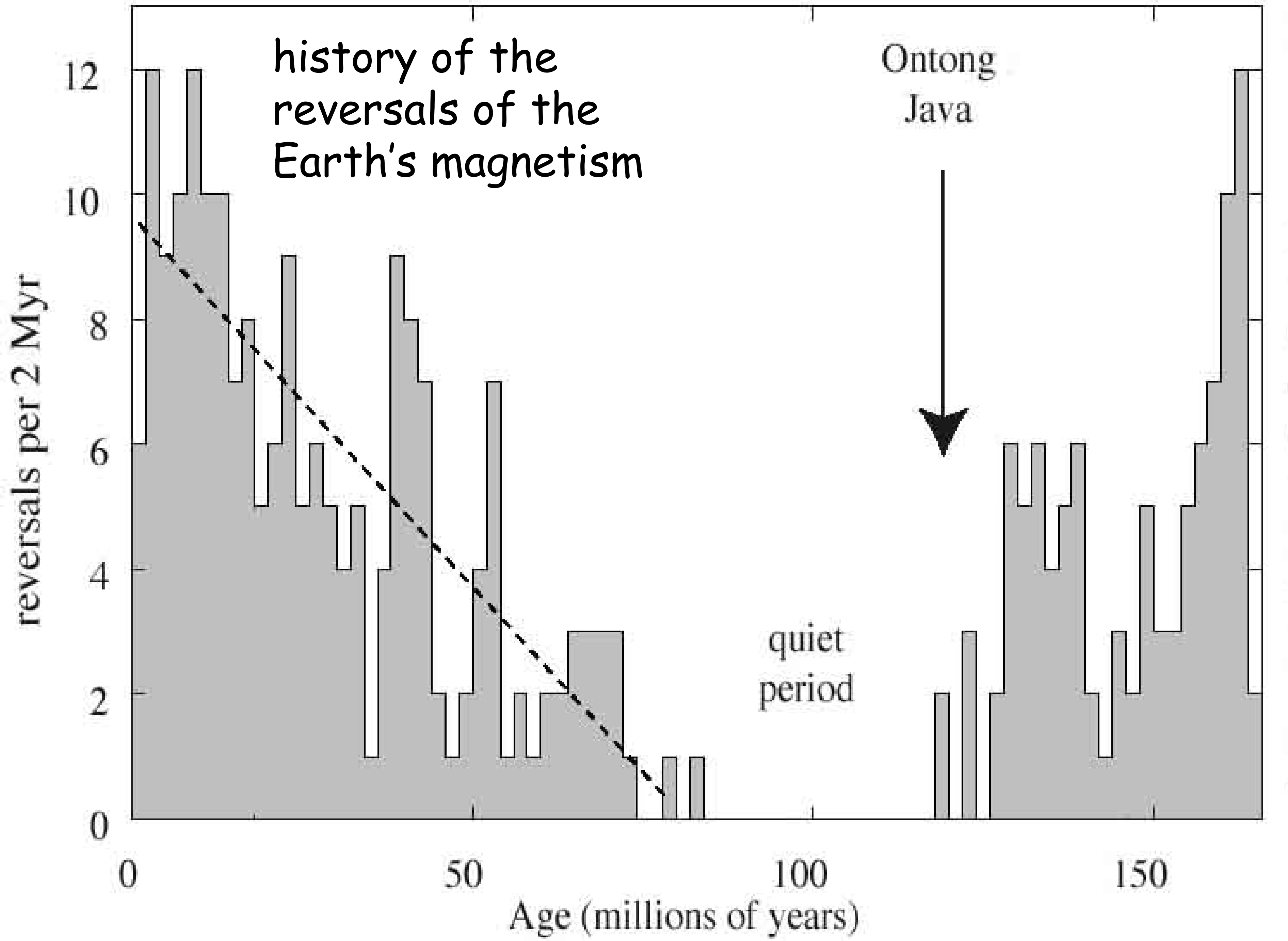
- avalanche cools the top of the liquid iron
- sinking iron disrupts the circulation
- dipole magnetism collapses
- magnetic field rebuilds (geomagnetic reversal or excursion)


MANTLE
OUTER CORE
INNER CORE


history of the reversals of the Earth's magnetism
reversals per 2 Myr
12
10
8
6
4
2
0
50
100
150
quiet period
Age (millions of years)

20 Jan 2002 draft of paper

- **GEOMAGNETIC QUIET PERIODS.** These are long periods when there are no geomagnetic reversals. The most recent such period spanned the time from about 120 Ma to 85 Ma. Could we find an explanation for such a quiet period, within the context of our model? The most obvious explanation is that such a quiet period is the consequence of a very large avalanche, perhaps spontaneous or perhaps triggered by a large impact. Such a large avalanche might destroy all sedimentary mounds, and give a general smoothing to the core-mantle boundary. It would then take a long time for the mounds to rebuild to their angle of repose. The gradual recovery of the rate of reversals (effectively a linear rise from 85 Ma to the present is observed) is consistent with this picture. However, we also expect to be able to observe a consequence of the event which started the quiet period. We might expect there to be a large plume (basaltic flow) near the beginning of the period, or at least evidence of a large cometary impact. As far as we know, this prediction is not verified. There is no evidence of strong flow at 120 Ma.



history of the
reversals of the
Earth's magnetism
Ontong
Java
quiet
period
reversals per 2 Myr
Age (millions of years)
0
2
4
6
8
10
12
0
50
100
150

published in Geophysical Research Letters, vol 29 pp 41-1 to 41-4 (2002)
[reference in new AGU format: 29(19), 1935, DOI 10.1029/2002GL015938, 2002]

Avalanches at the core-mantle boundary

Richard A. Muller

Department of Physics, University of California, Berkeley

Abstract. The partial collapse of topographic structure at the core-mantle boundary (CMB) in avalanches, slumps or turbidity flows, would cause sudden temperature changes in both the upper core and the lower mantle. Although such collapses are hypothetical, it is interesting to investigate the potential consequences. Downwelling from such events could disrupt core convection cells and trigger geomagnetic excursions and reversals. Buoyant sediment from the freezing of the inner core is hypothesized to rebuild the avalanched structures. Large avalanches could trigger Mantle plumes. Oblique extraterrestrial impacts impart high shear to the CMB, and can trigger one or more simultaneous avalanches, yielding observed coincidences between craters, tektite fields and reversals. A triggered avalanche can explain the coincidence between the formation of the largest known volcanic province (the Ontong-Java Plateau), the start of the 35 Myr Cretaceous geomagnetic quiet period, and reported coincidences between large flood basalts and extinctions.

Introduction

The core-mantle boundary (CMB) was once thought

Sediment accumulating on sloped surfaces at the CMB might flow immediately into valleys or it might adhere like snow until the surface exceeds the angle of repose and collapses in an avalanche. In this paper I explore the consequences of the assumption that the sediment is redistributed in discrete and abrupt avalanches.

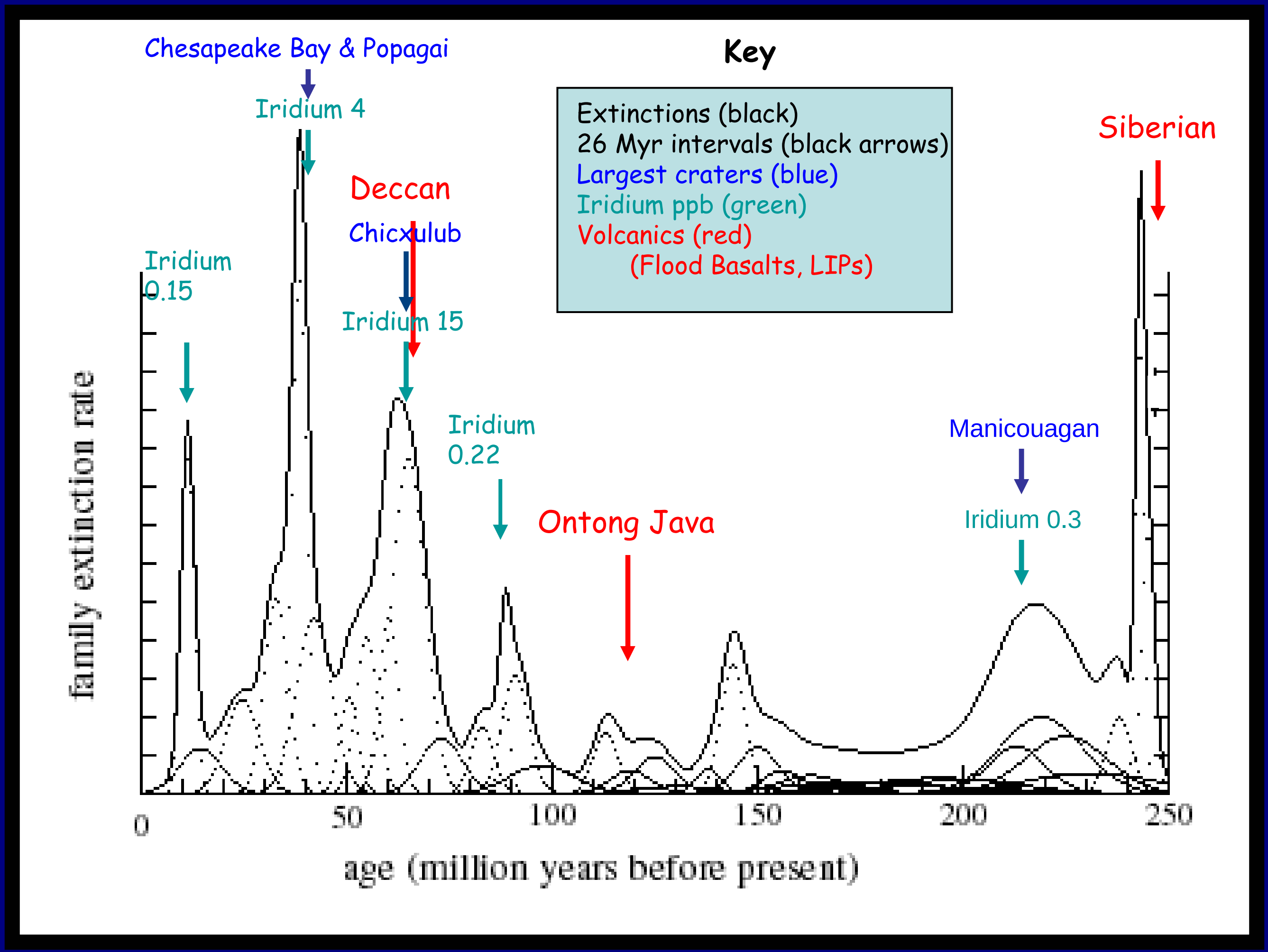
Avalanches

Avalanches at the CMB would entrain core liquid, and be similar in character to turbidity currents on the slopes of the ocean floor. Such flows can occur at relatively shallow slopes, less than a few degrees; thus the structure at the CMB need not be particularly steep prior to collapse. Except for the small angle, the topography of the structures might be similar to that of sand piles or dunes.

The most important effects of CMB avalanches may result from the redistribution of heat in the nearby upper core and lower mantle. For example, consider a 100-m thick avalanche, the amount of material that might accumulate in a few million years above a core upwelling region. The temperature gradient in the lower mantle is believed to be steep; Williams (1998) showed a “broad


Summary

Extinctions (and other things) for the last 250 million years

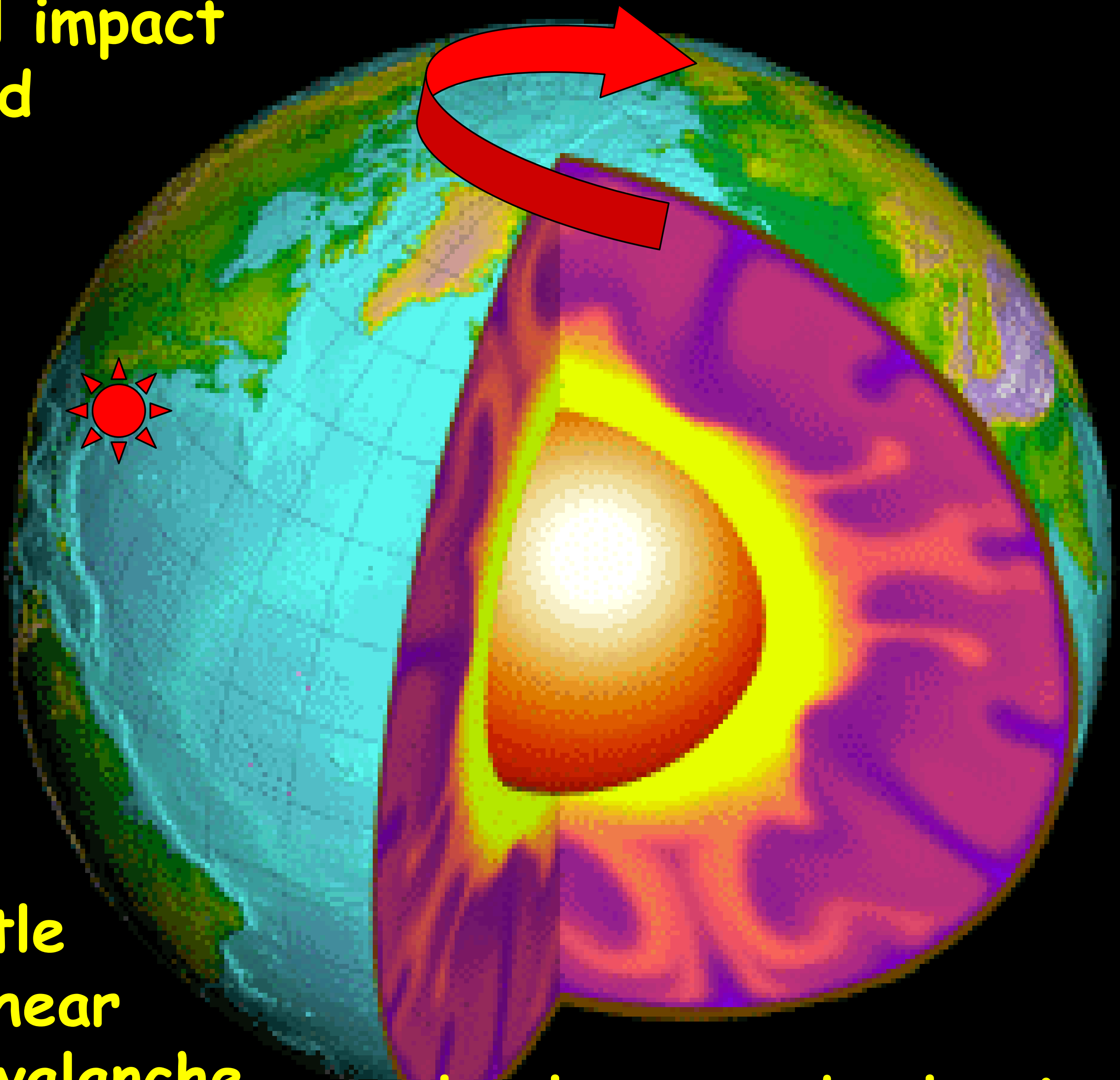


Extinctions: Sepkoski, Muller Craters: Koeberl Iridium: Asaro, Orth, others Volcanism: Ernst & Buchan

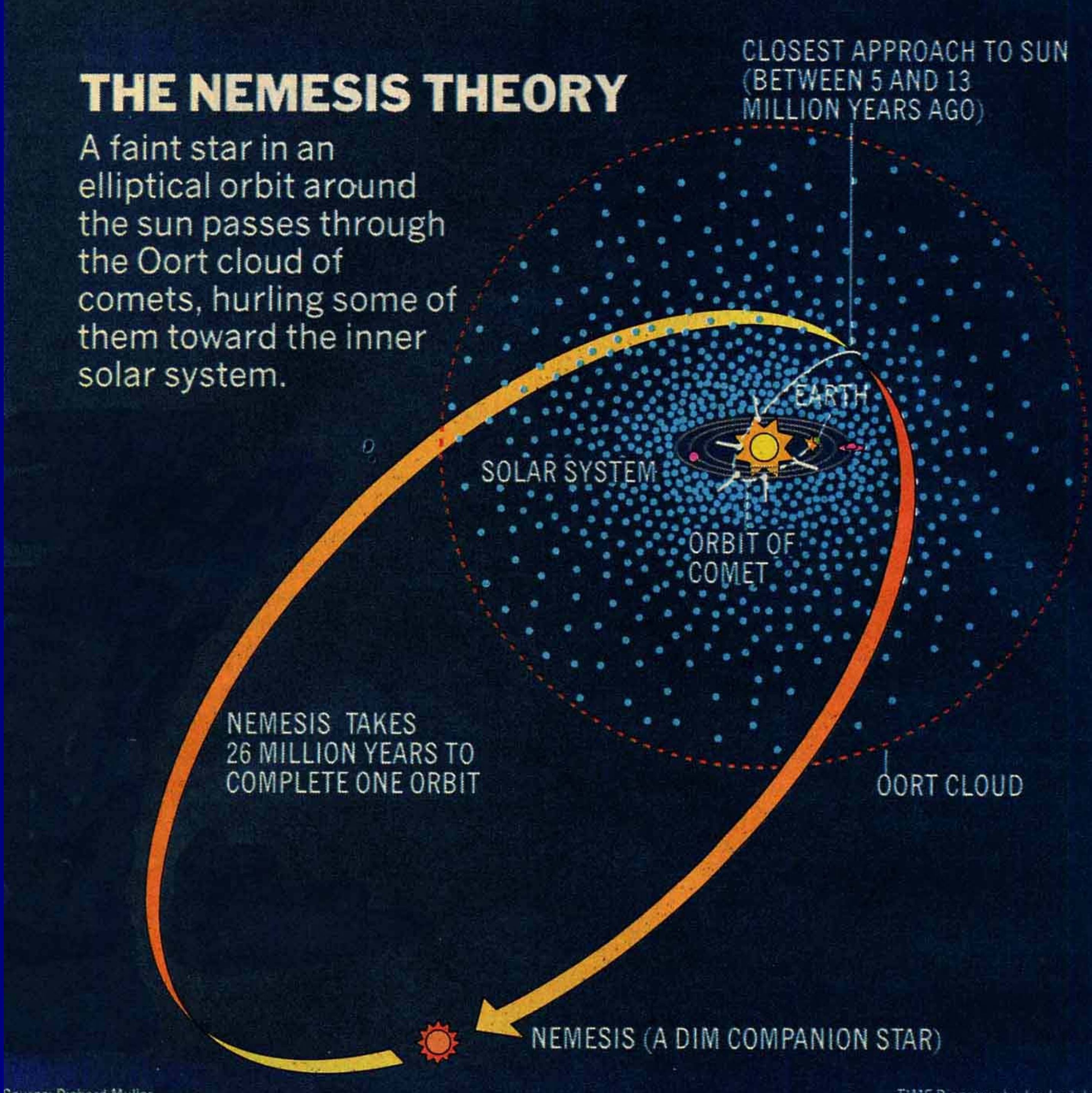
Tangential impact of asteroid

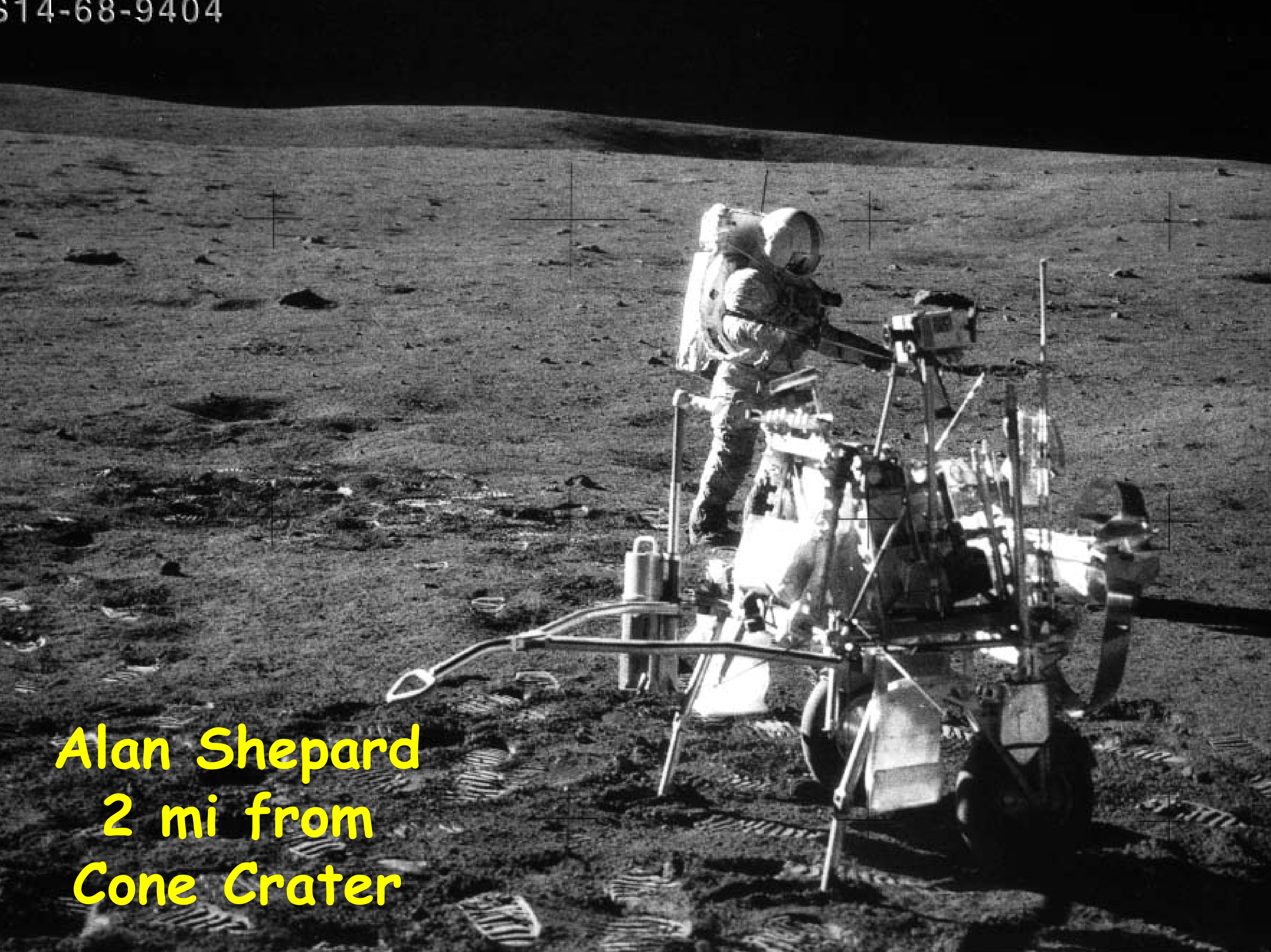
spins the mantle

but not the core!



Core-mantle slippage shear triggers avalanche, mantle plume, and vulcanism

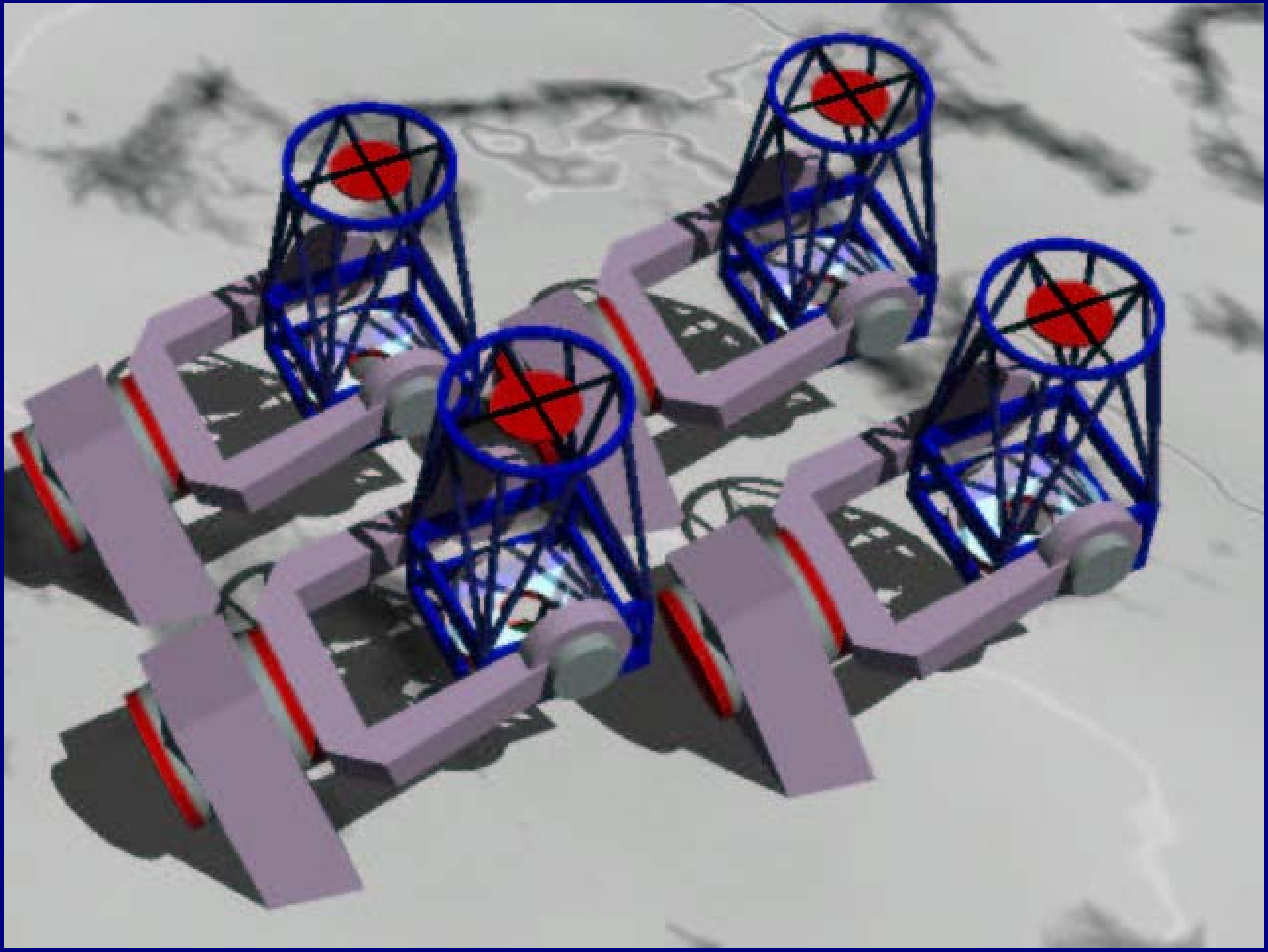

THE NEMESIS THEORY
A faint star in an elliptical orbit around the sun passes through the Oort cloud of comets, hurling some of them toward the inner solar system.
CLOSEST APPROACH TO SUN (BETWEEN 5 AND 13 MILLION YEARS AGO)
EARTH
SOLAR SYSTEM
ORBIT OF COMET
NEMESIS TAKES 26 MILLION YEARS TO COMPLETE ONE ORBIT
OORT CLOUD
NEMESIS (A DIM COMPANION STAR)


14-68-9404
Alan Shepard
2 mi from
Cone Crater

Pan-Starrs

(Panoramic Survey Telescope and Rapid Response System)

U. Hawaii, MIT Lincoln Labs, Maui High Perf. Comp Center, SAIC



By 2010 we'll know if Nemesis is there, or not there.

The paradox of science:

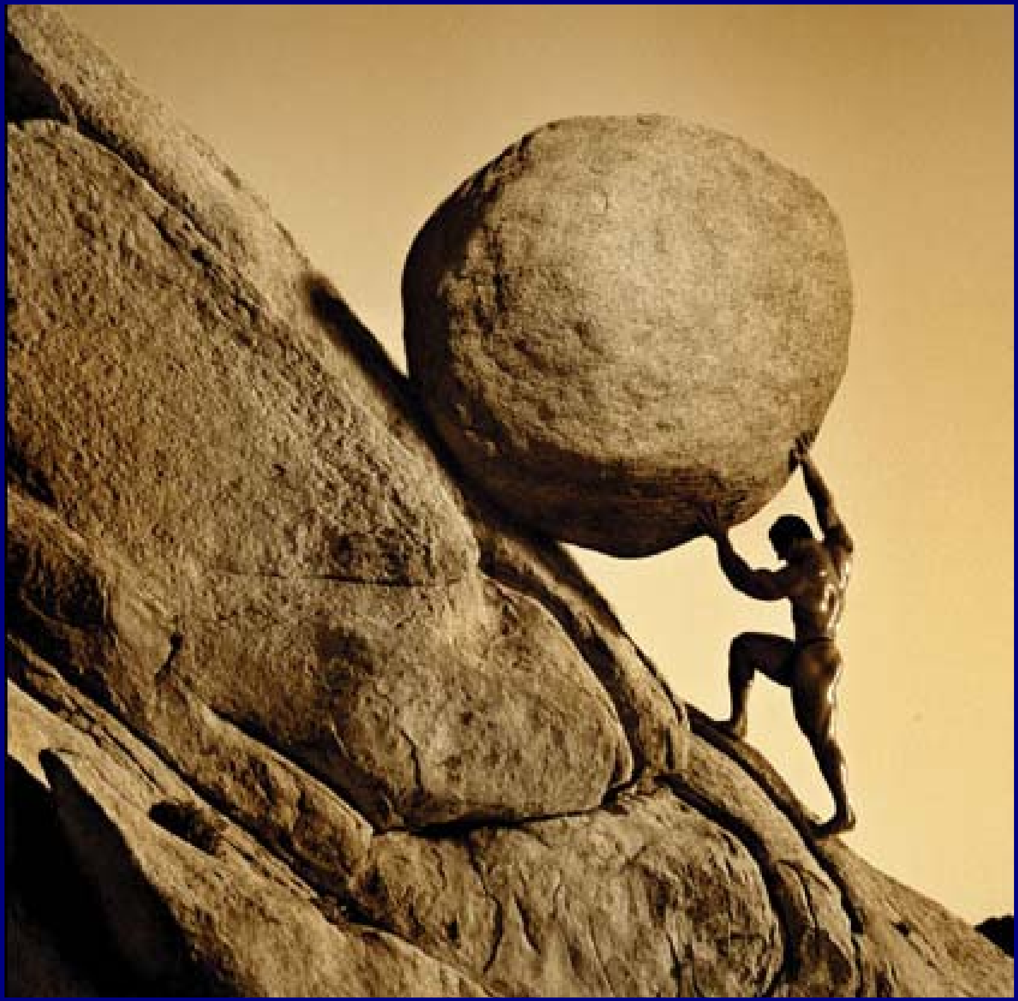
The more you learn, the more you don't know.

My favorite unanswered questions (and unproven hypotheses):

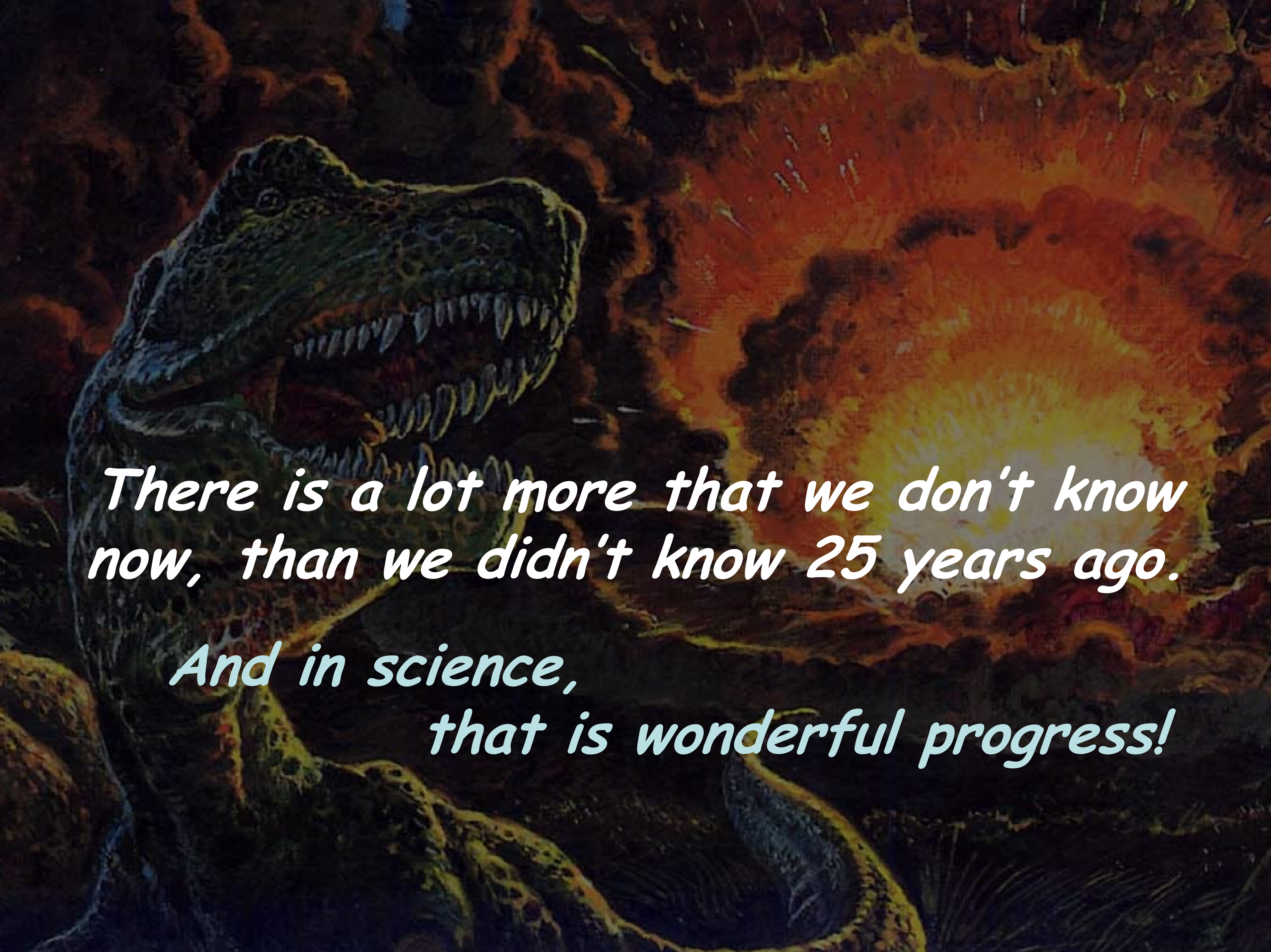
What happened 250 Myr ago?
Does Nemesis exist?
Role of volanic eruptions?
Deep underground avalanches?
Link to geomagnetic reversals?

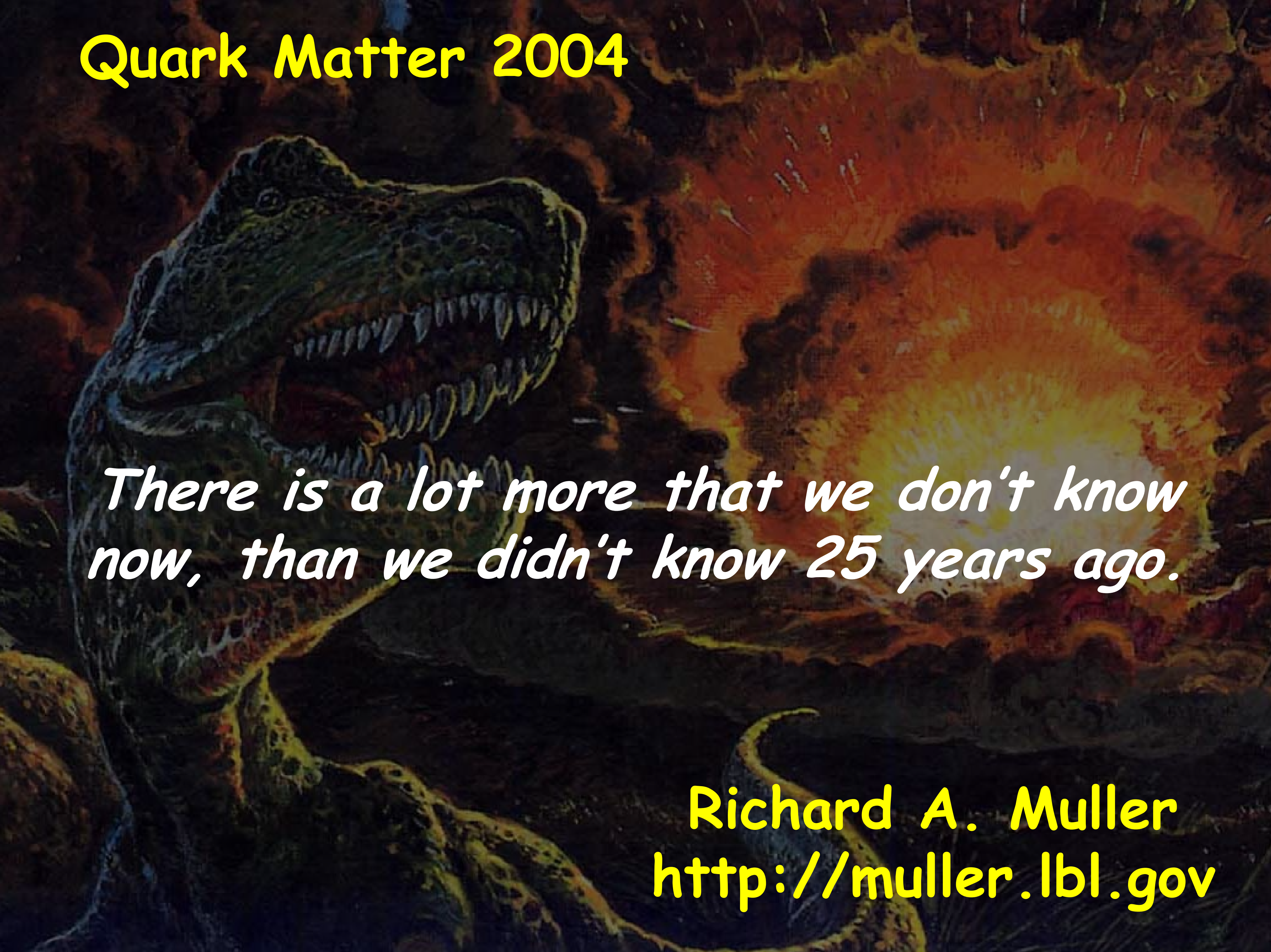
Scientific research and Sisyphus

The king of Corinth condemned forever to roll a hugh stone up a hill in Hades only to have it roll down again on nearing the top.



Albert Camus: Sisyphus is happy.


There is a lot more that we don't know now, than we didn't know 25 years ago.
And in science,
that is wonderful progress!


Quark Matter 2004
There is a lot more that we don't know now, than we didn't know 25 years ago.
Richard A. Muller
http://muller.lbl.gov

The End

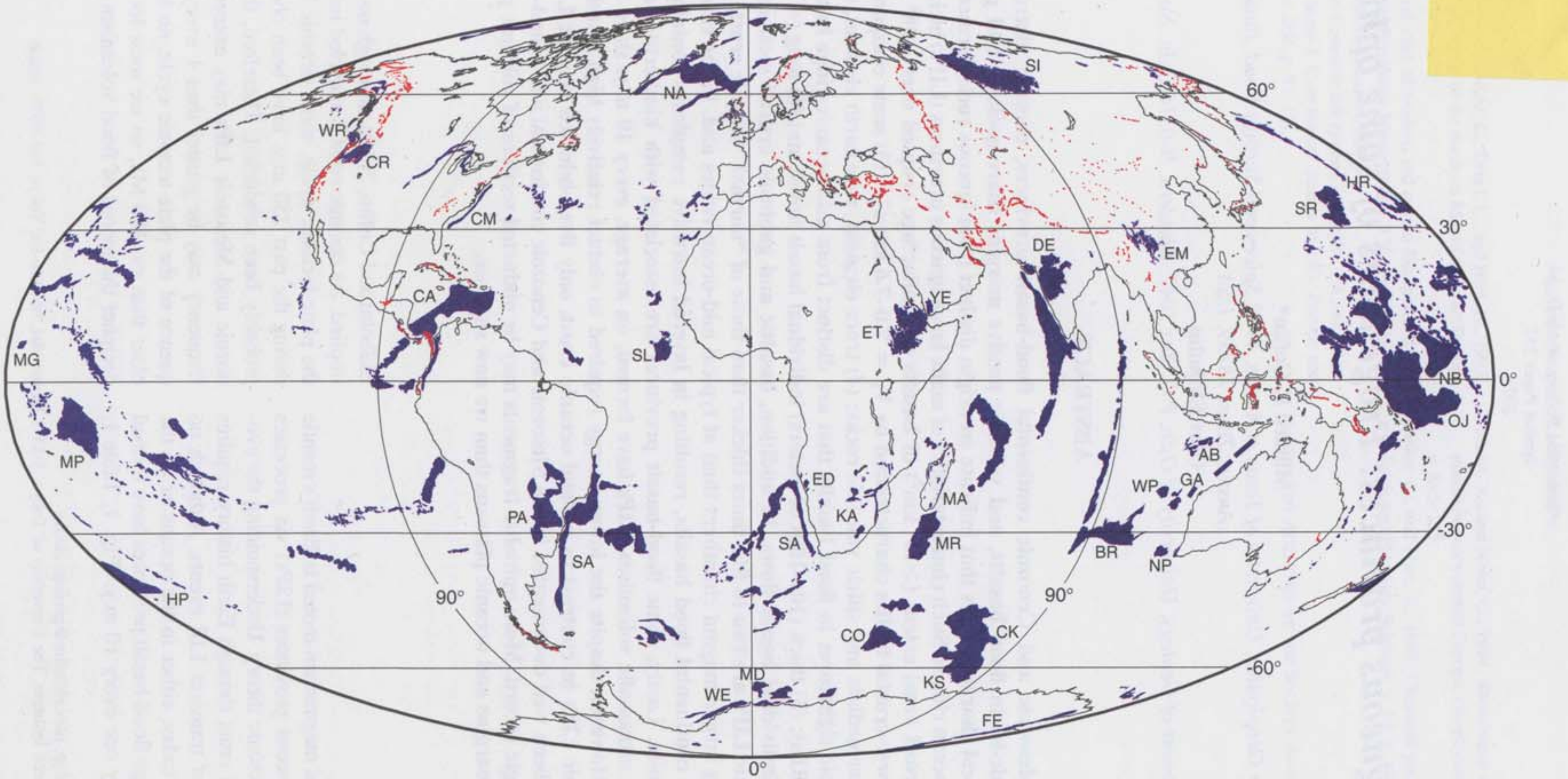
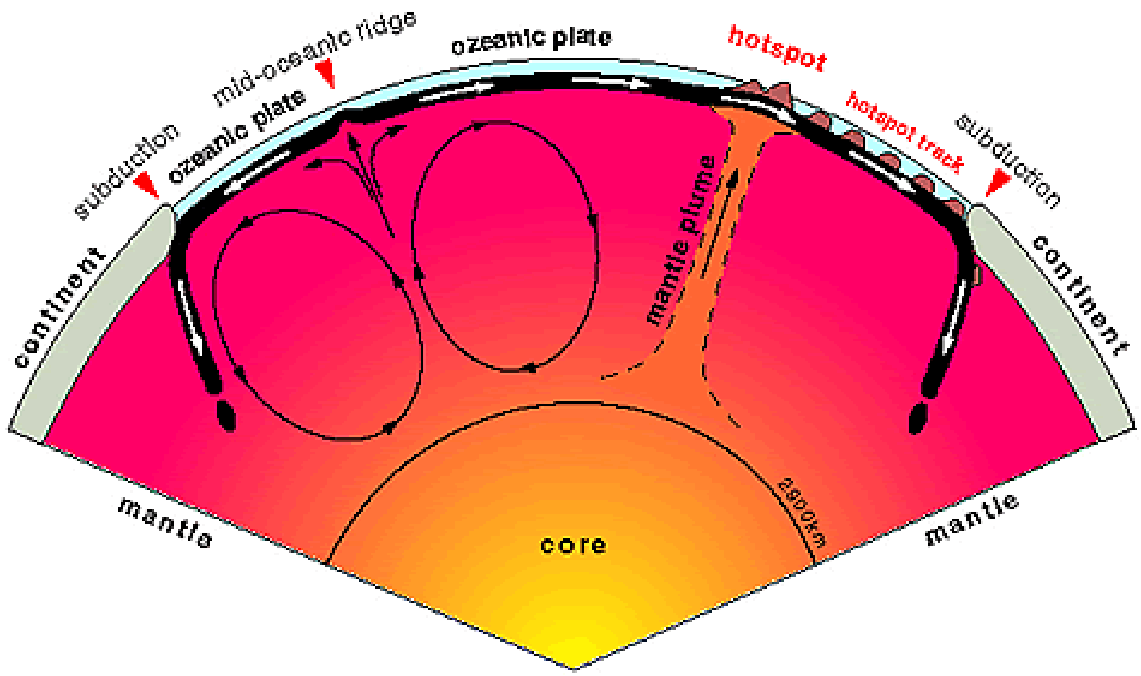
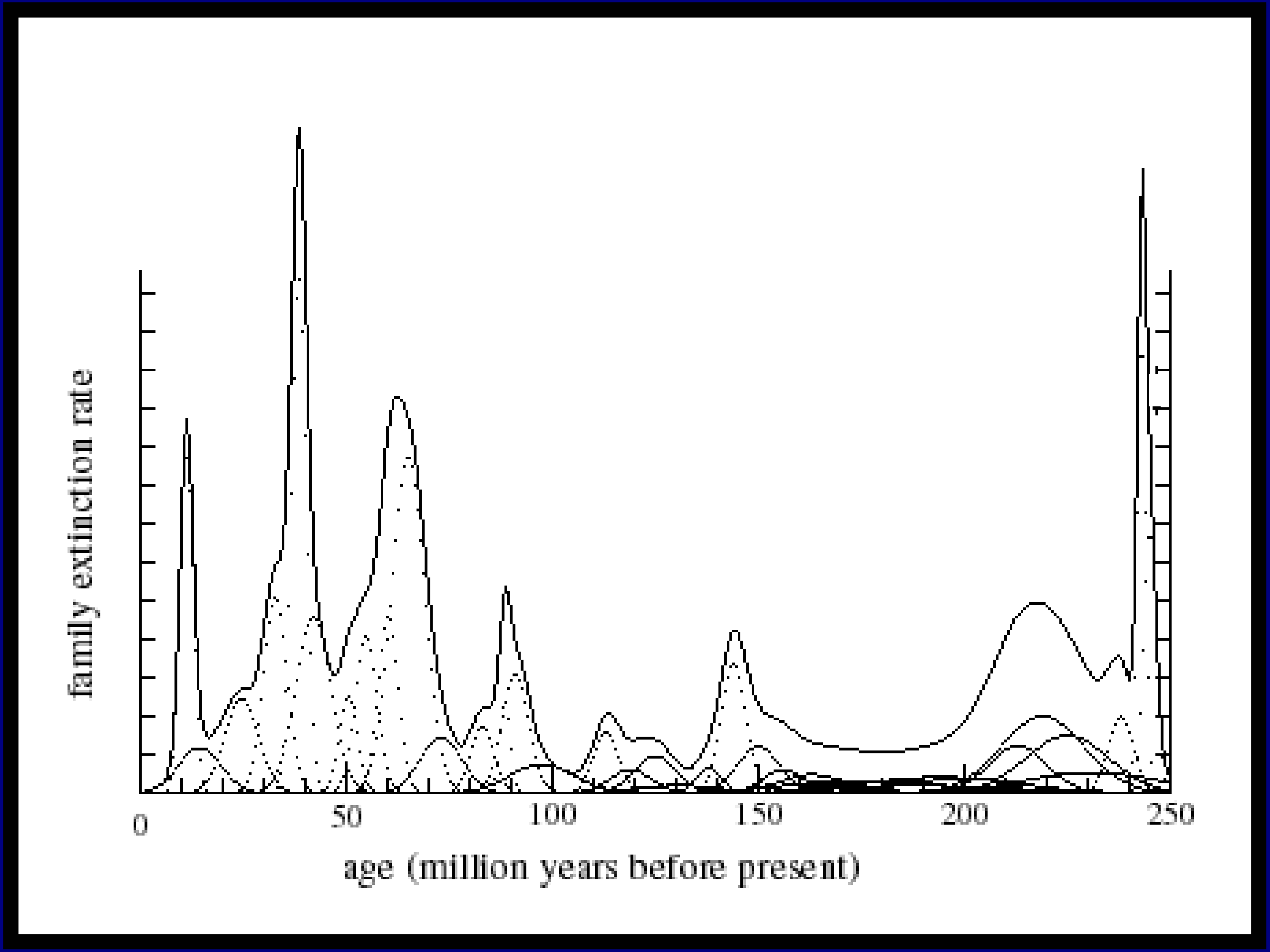


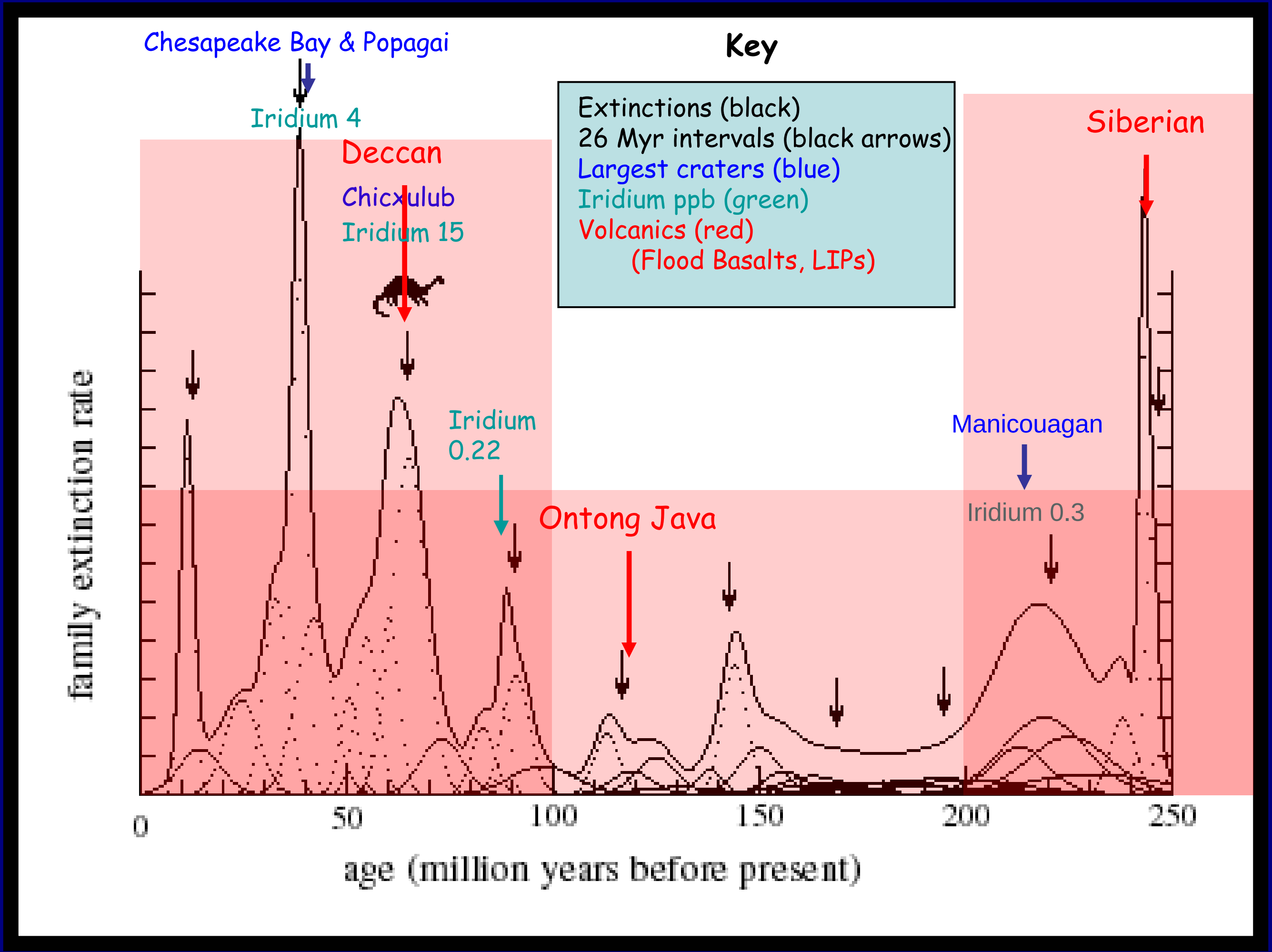
Figure 1. Predominantly Phanerozoic global LIP distribution (blue) (after Coffin and Eldholm, 1994), with Mesozoic and Cenozoic transient LIPs (labels explained in Table 1) and global distribution of ophiolites (red) (after Widmier et al., 1985).



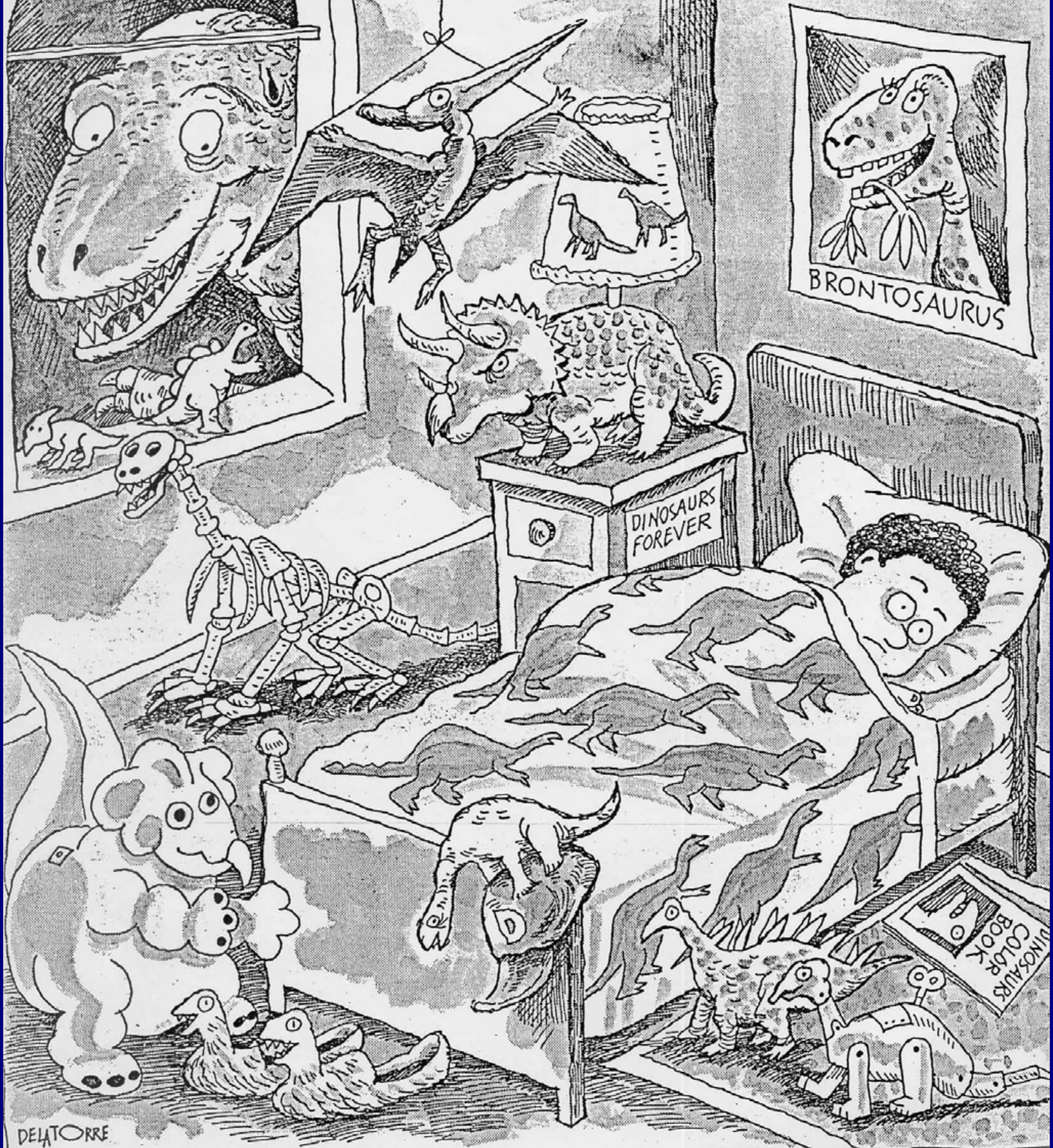
A sector through the earth, showing major tectonic and magmatic processes (plate boundaries are marked by red arrows)

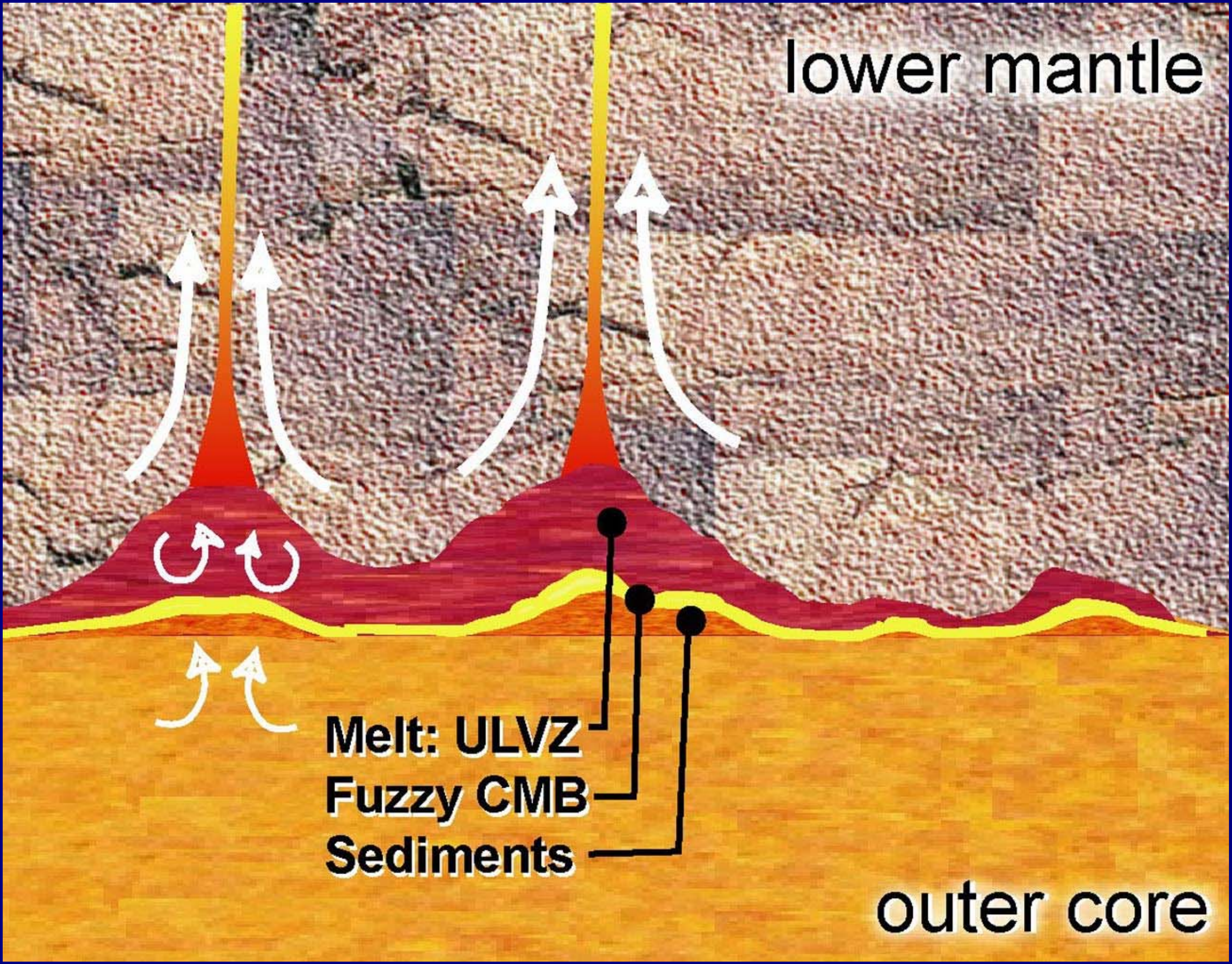

family extinction rate
0
50
100
150
200
250
age (million years before present)

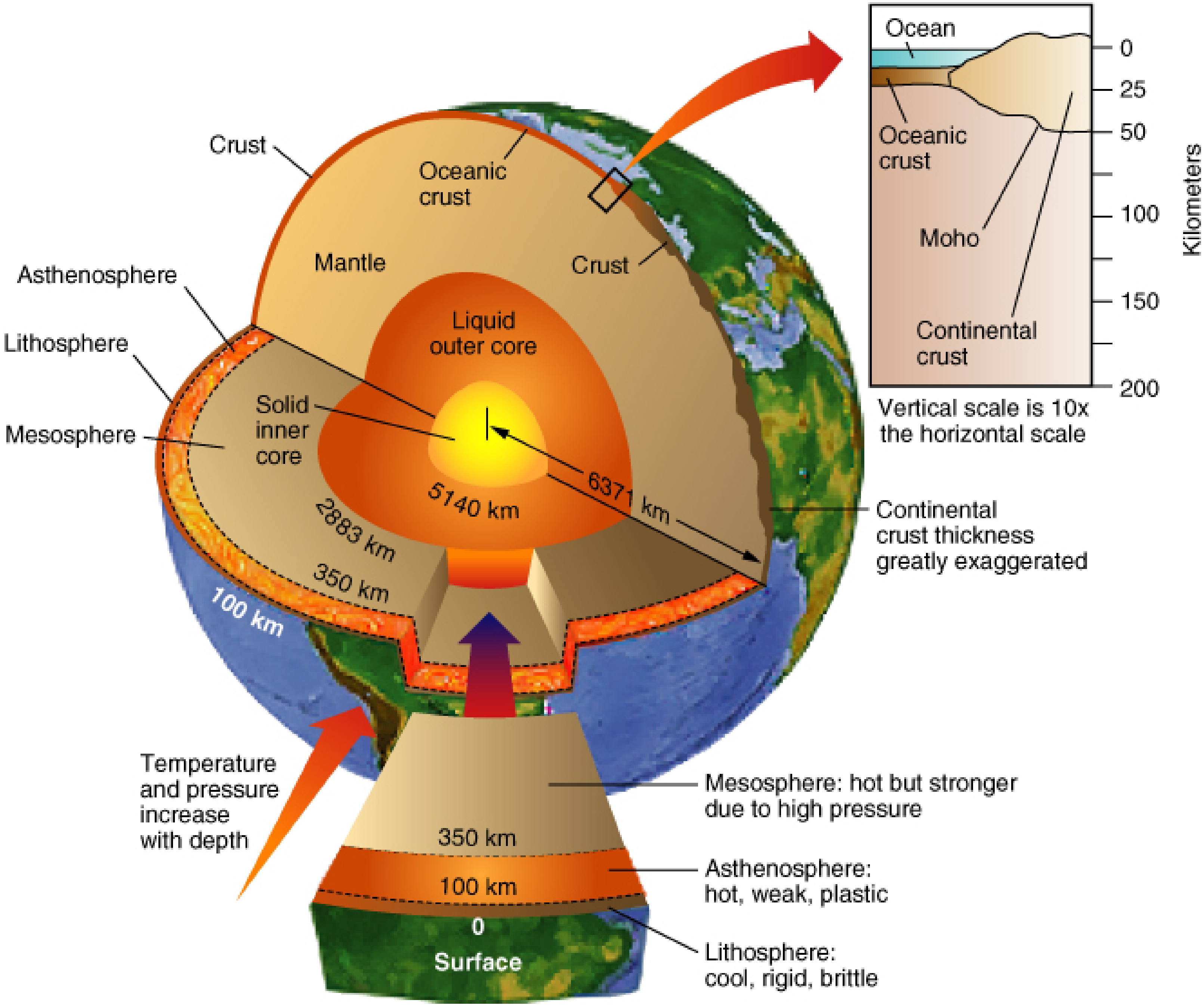
Extinctions (and other things) for the last 250 million years



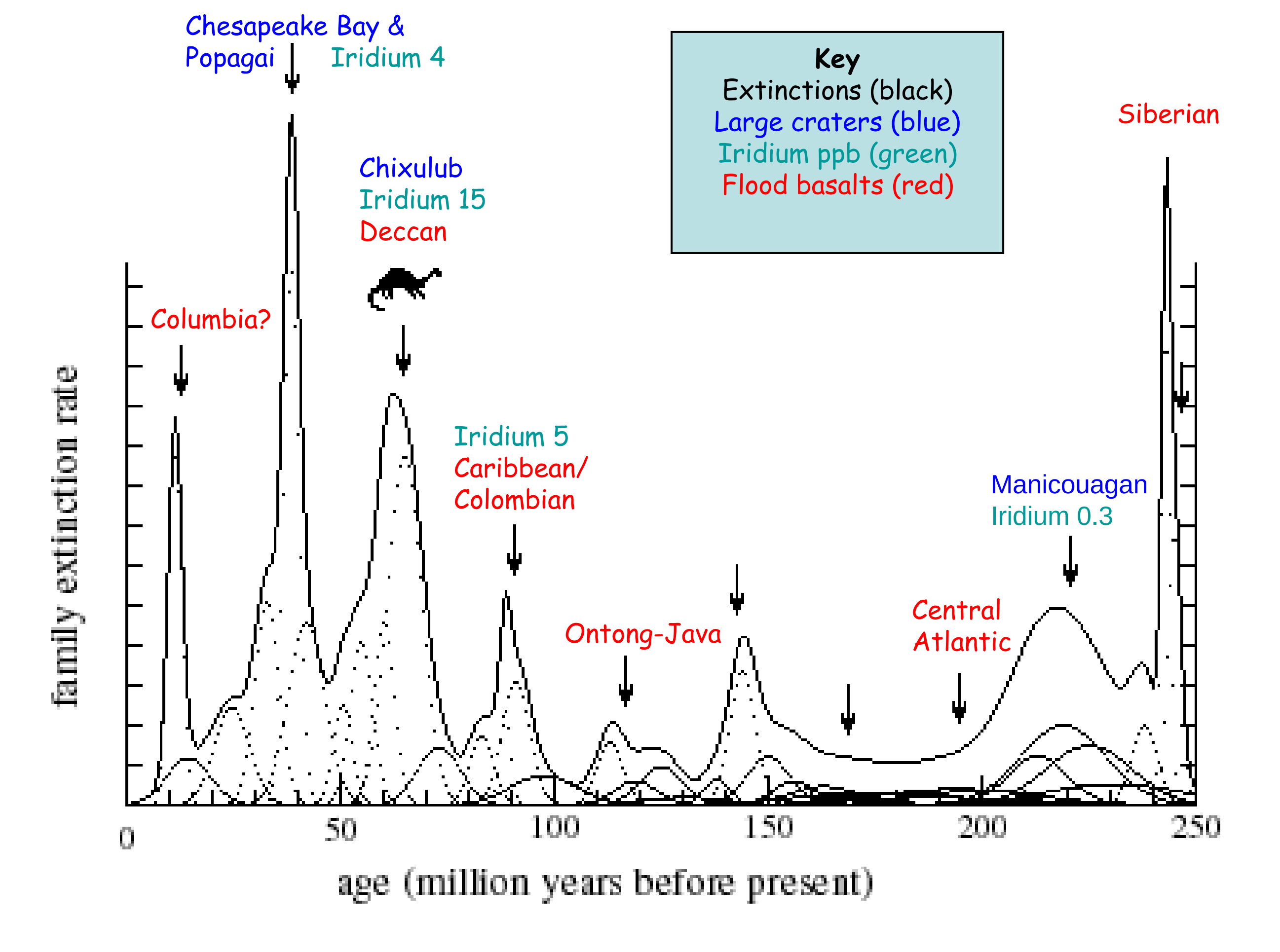
Extinctions: Sepkoski, Muller   Craters: Koeberl   Iridium: Asaro, Orth, others   Volcanism: Ernst & Buchan


BRONTOSAURUS
DINOSAURS FOREVER
DINOSAURS COLOR BOOK
DELATORRE


lower mantle
Melt: ULVZ
Fuzzy CMB
Sediments
outer core

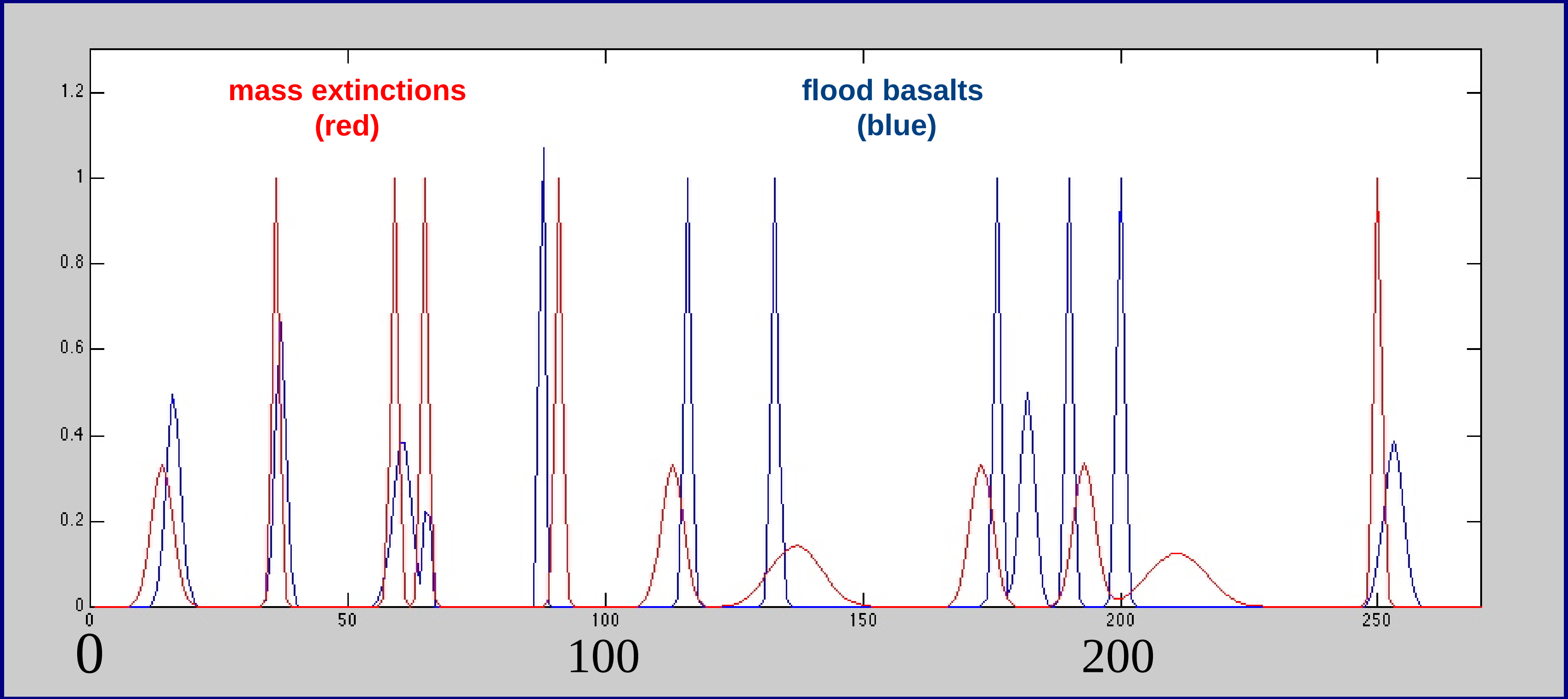

Ocean
Oceanic crust
Moho
Continental crust
0
25
50
100
150
200
Kilometers
Vertical scale is 10x the horizontal scale
Crust
Oceanic crust
Mantle
Crust
Asthenosphere
Lithosphere
Mesosphere
Liquid outer core
Solid inner core
5140 km
6371 km
2883 km
350 km
100 km
Continental crust thickness greatly exaggerated
Temperature and pressure increase with depth
Mesosphere: hot but stronger due to high pressure
350 km
100 km
0
Surface
Asthenosphere: hot, weak, plastic
Lithosphere: cool, rigid, brittle

Extinctions (and other things) for the last 250 million years



Extinctions: Sepkoski, Muller   Craters: Koeberl   Iridium: Asaro, Orth, others   Volcanism: Wignall, Haggerty

Flood basalts & mass extinctions



age (millions of years)

Extinctions placed at boundaries

Basalt flows > 200,000 km^3

M. Rampino, V. Cortillot, B. Haggerty, others
thanks to W. Alvarez and D. Shimabukuro

Eocene-Oligocene
Iridium 35 Myr ago
Eocene-Oligocene

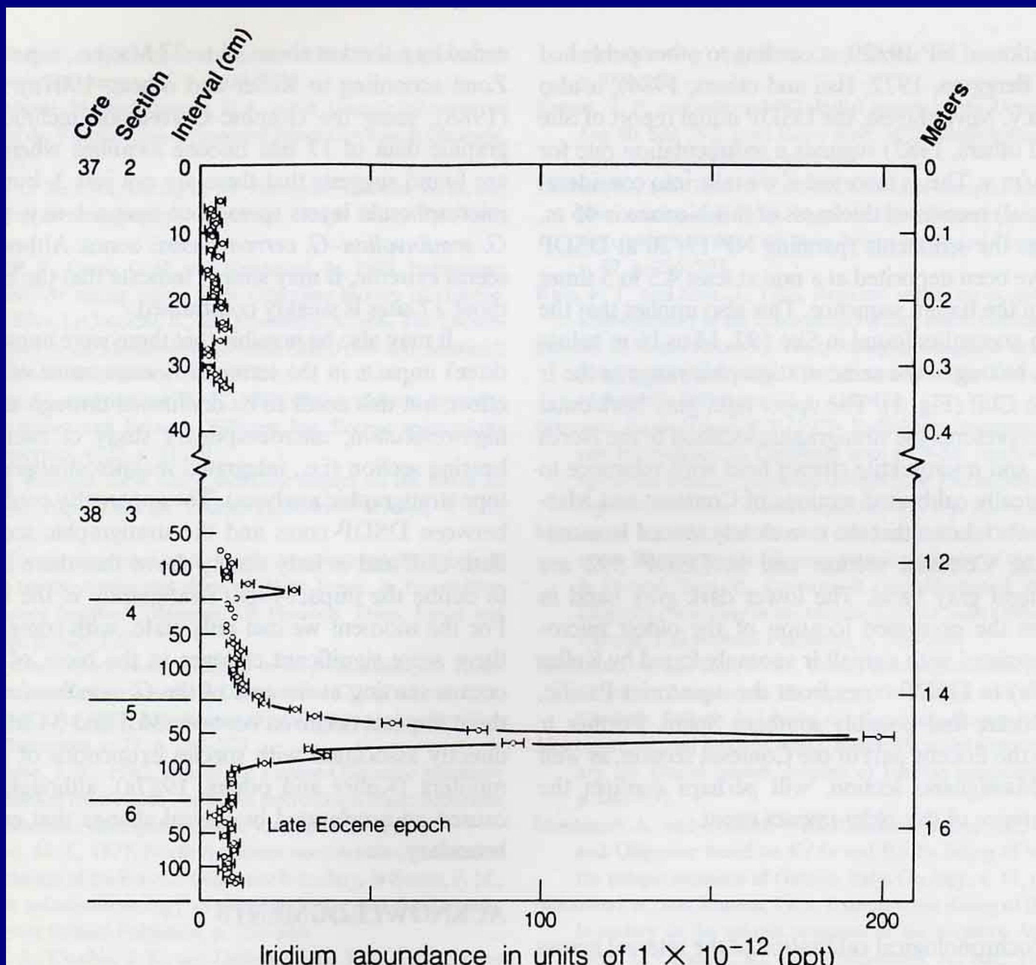
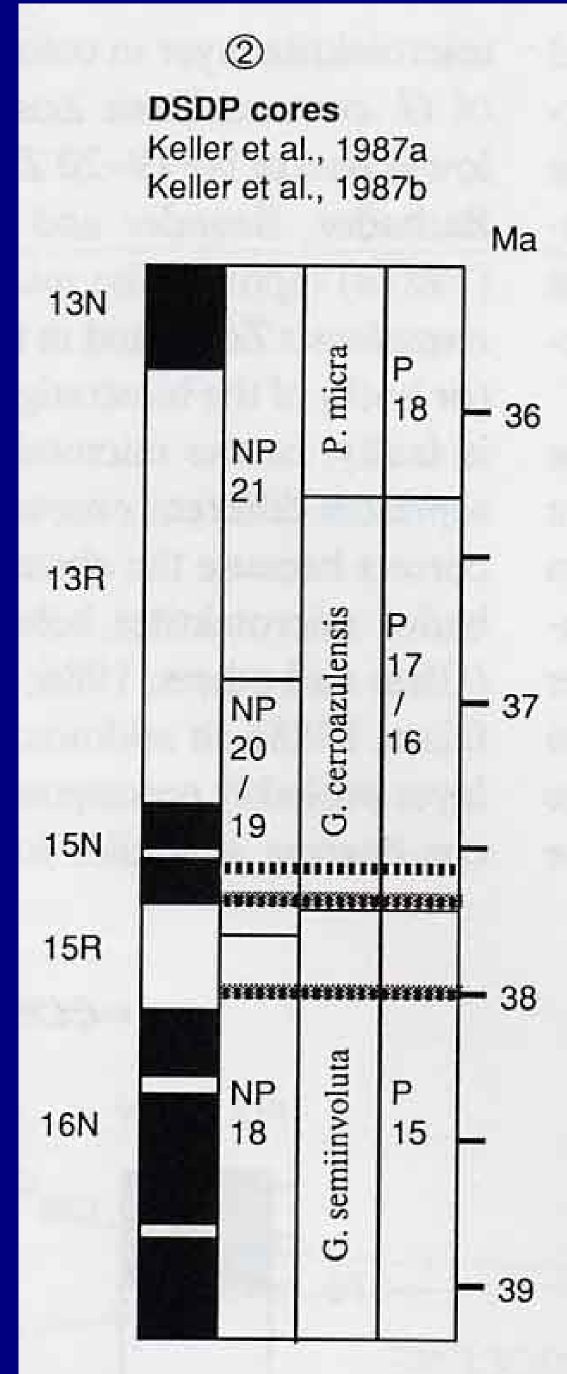


Figure 5. Occurrence of two small Ir anomalies in the upper part of NP 19/20 nannofossil range zone (upper Eocene) from DSDP Site 592 (Tasman Sea), core 38 (courtesy of Frank Asaro).



Iridium 35 Myr ago
Eocene-Oligocene

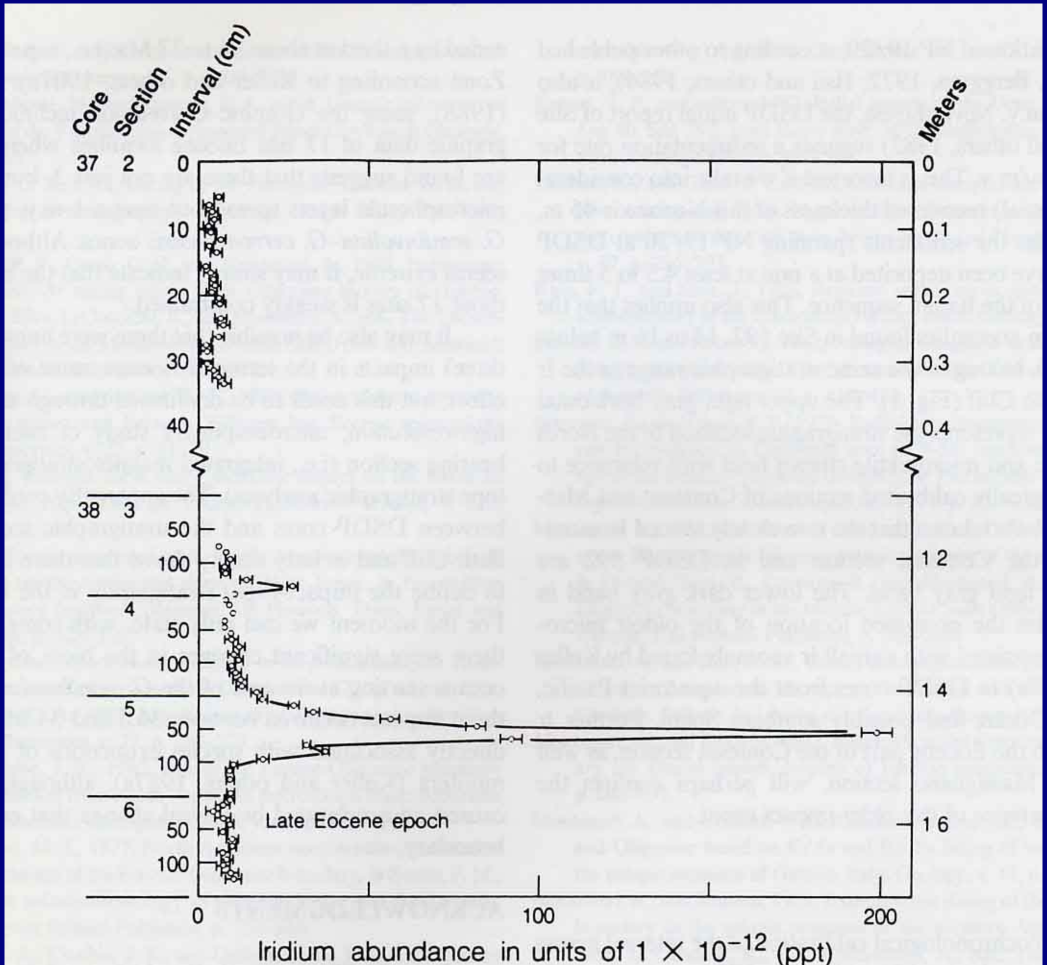
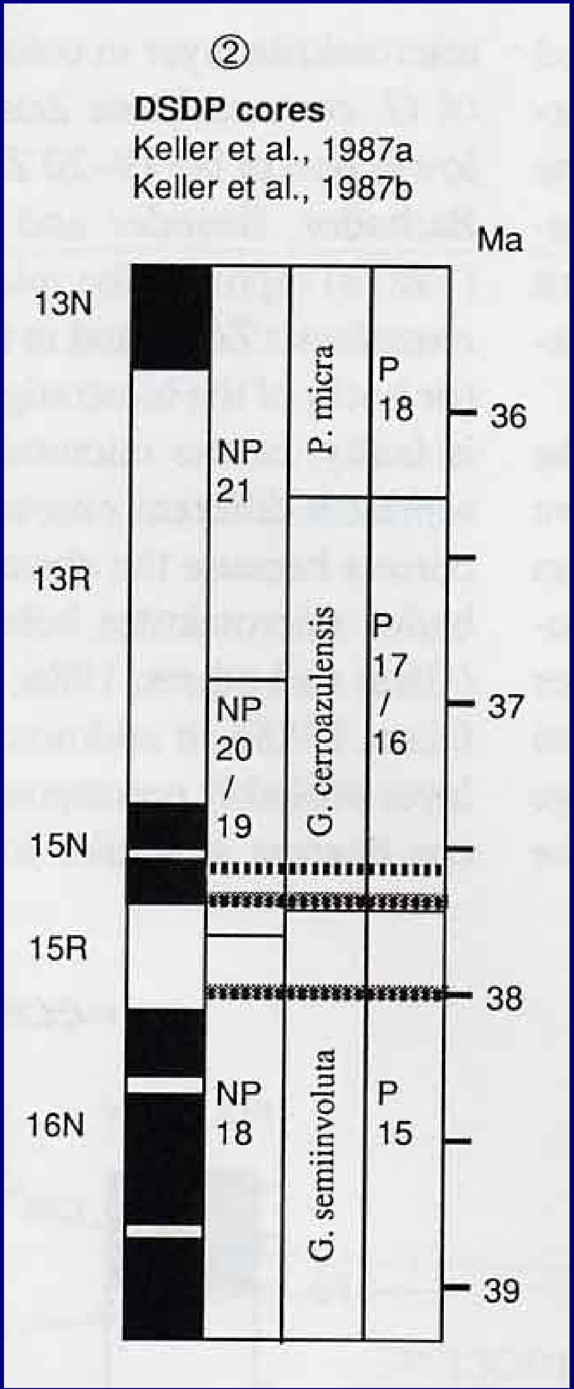
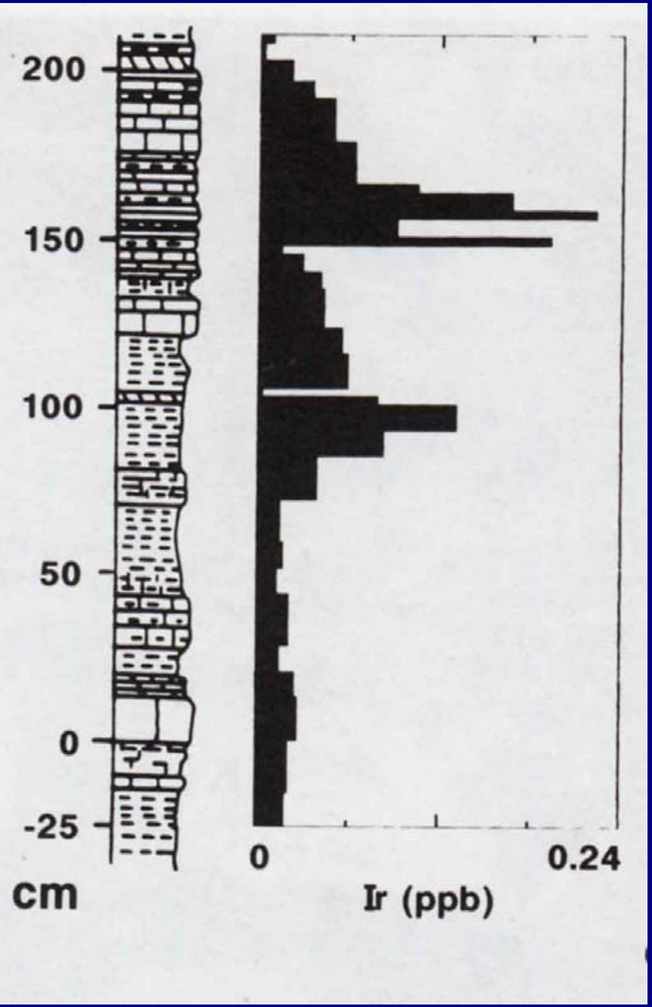


Figure 5. Occurrence of two small Ir anomalies in the upper part of NP 19/20 nannofossil range zone (upper Eocene) from DSDP Site 592 (Tasman Sea), core 38 (courtesy of Frank Asaro).

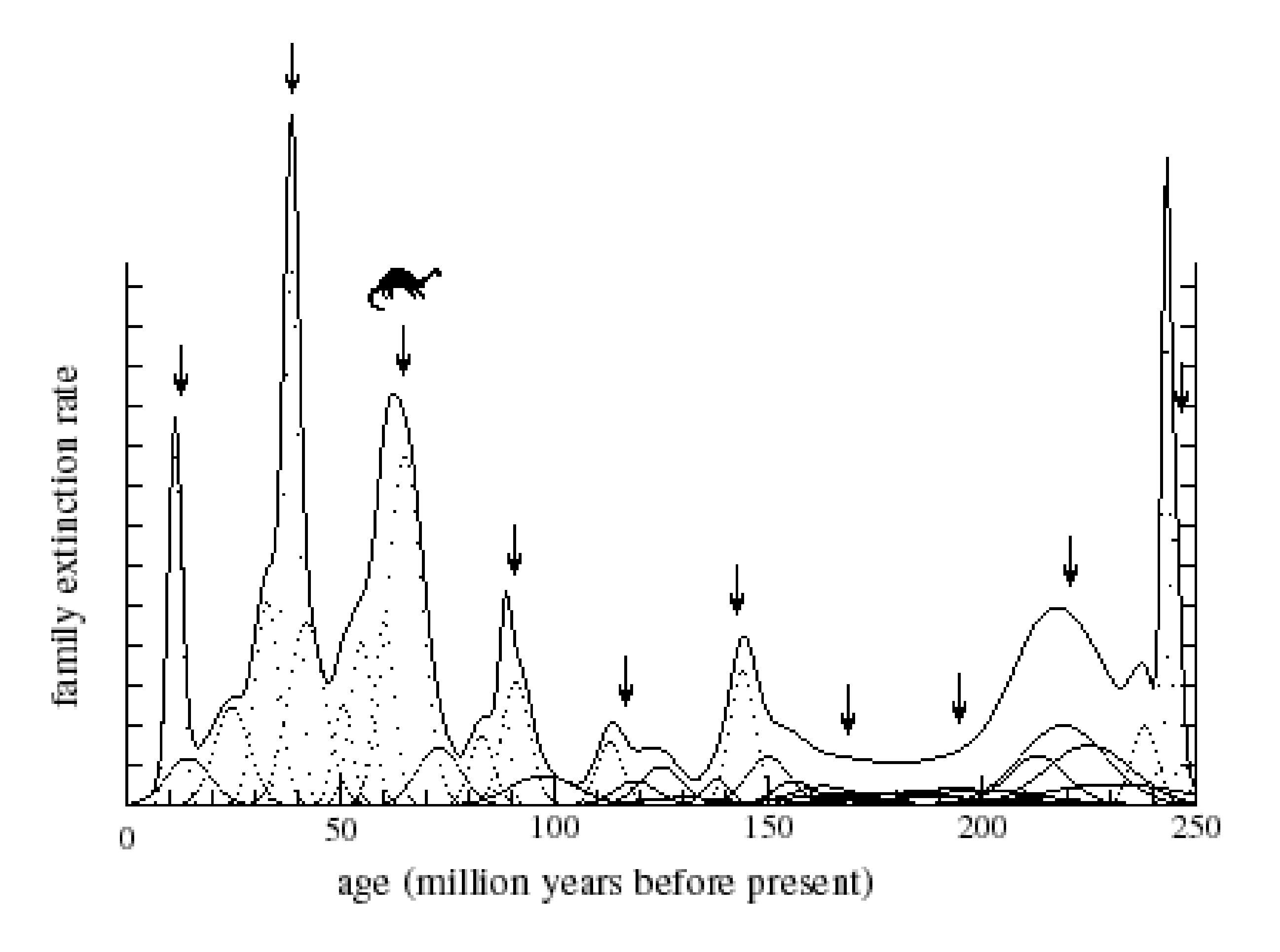


Iridium layer(s) 81 Million years ago

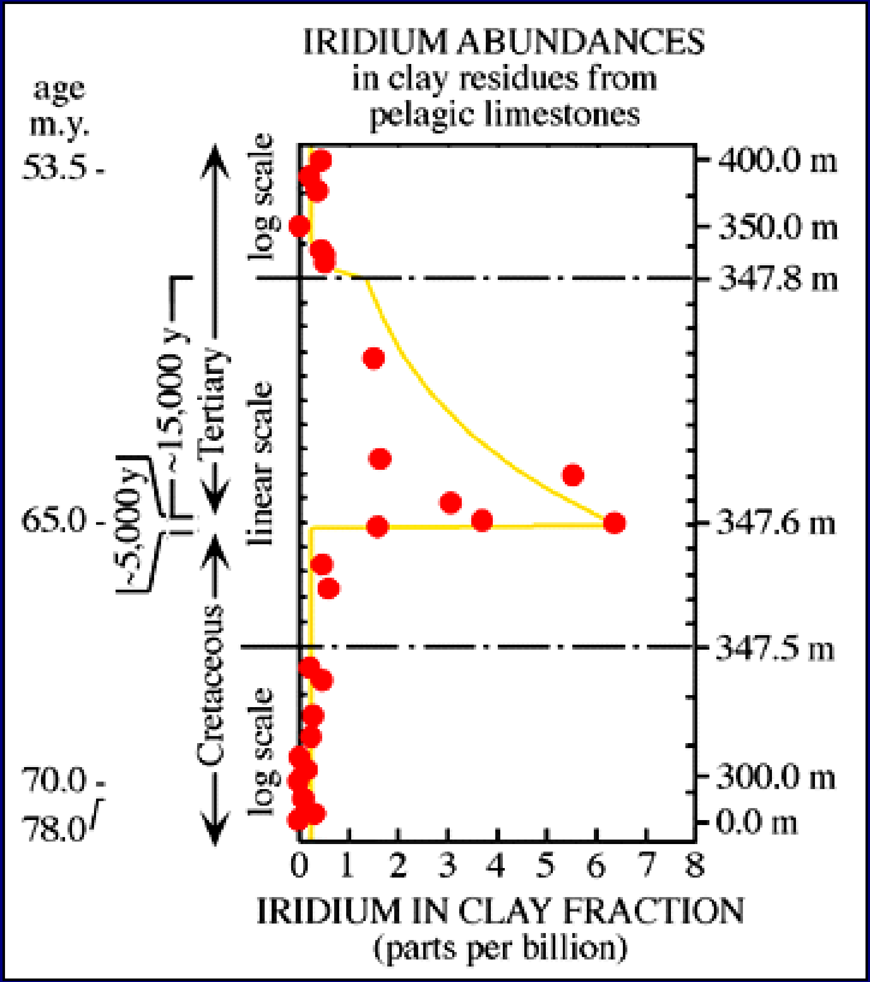


from Carl Orth et al.
Special Paper 247 p.55

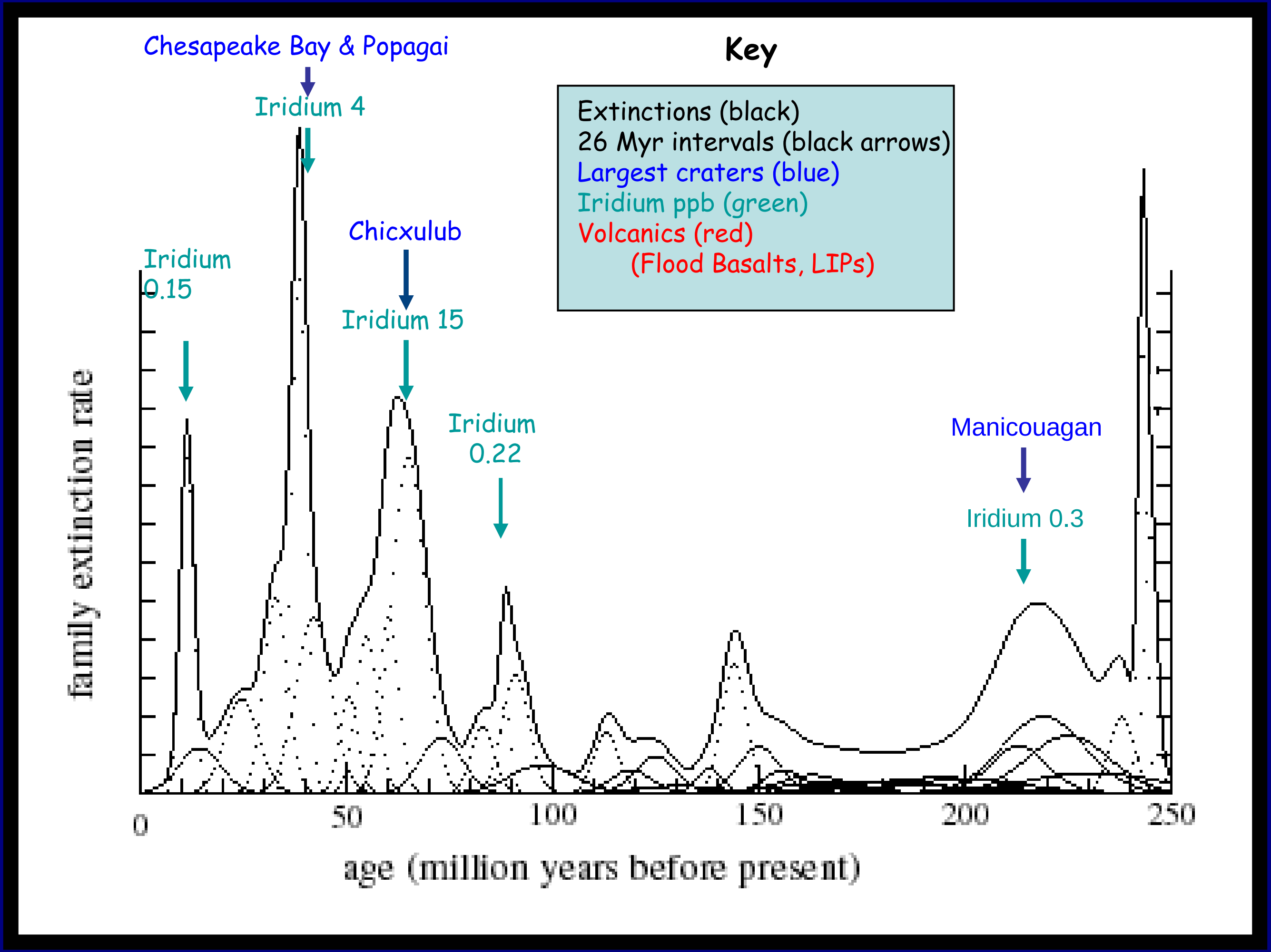
Extinctions for the last 250 million years



from D. Raup and J. Sepkoski, 1984

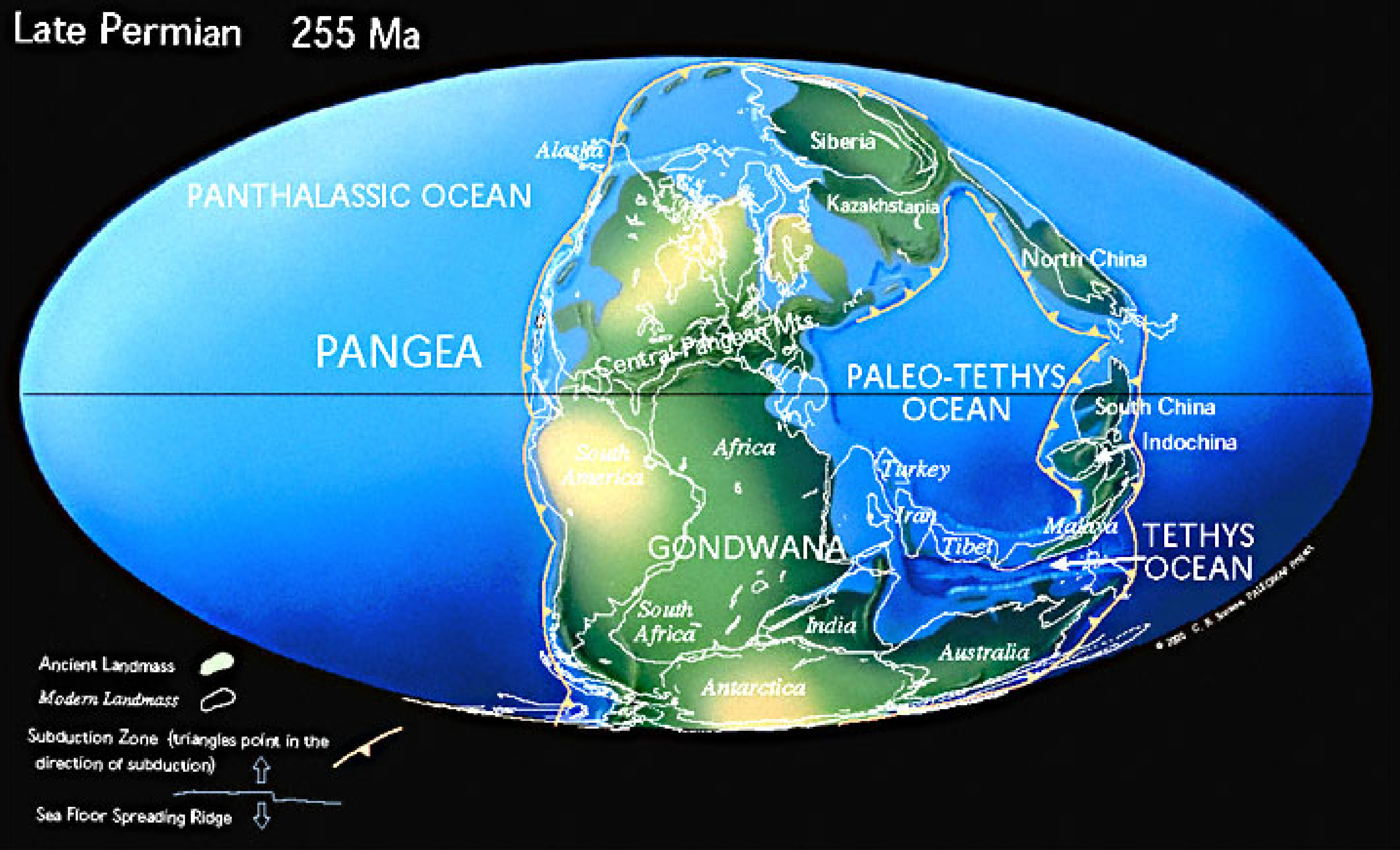

IRIDIUM ABUNDANCES
in clay residues from
pelagic limestones
age
m.y.
53.5 -
65.0 -
70.0 -
78.0
~5,000y
~15,000 y
Tertiary
Cretaceous
log scale
linear scale
log scale
400.0 m
350.0 m
347.8 m
347.6 m
347.5 m
300.0 m
0.0 m
0 1 2 3 4 5 6 7 8
IRIDIUM IN CLAY FRACTION
(parts per billion)

The largest impact craters



Extinctions: Sepkoski, Muller Craters: Koeberl Iridium: Asaro, Orth, others Volcanism: Ernst & Buchan

Barringer meteor crater in Arizona



courtesy of Christopher Scotese


WHAT ON EARTH
HAPPENED LAST NIGHT?

Columbia River Flood Basalts

associated with the extinctions 15 million years ago?