Impact Events in Earth History: The Cretaceous-Paleogene Boundary Ejecta Layer and its Source Crater at Chicxulub

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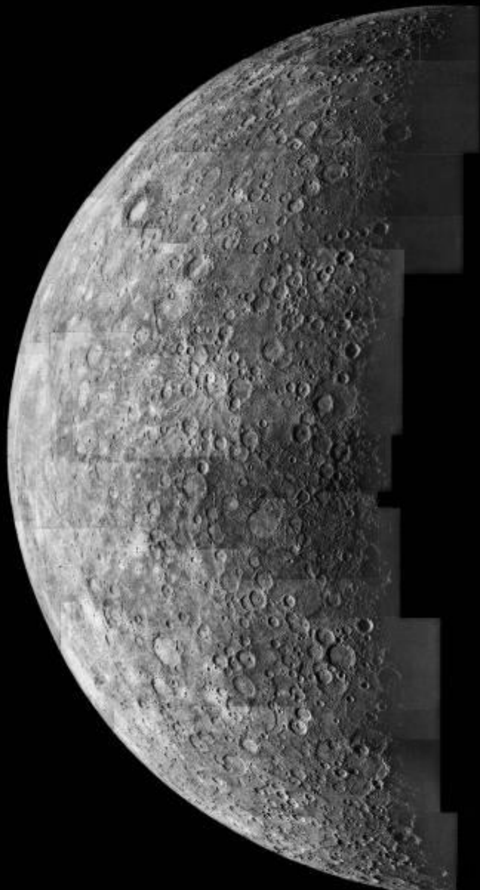
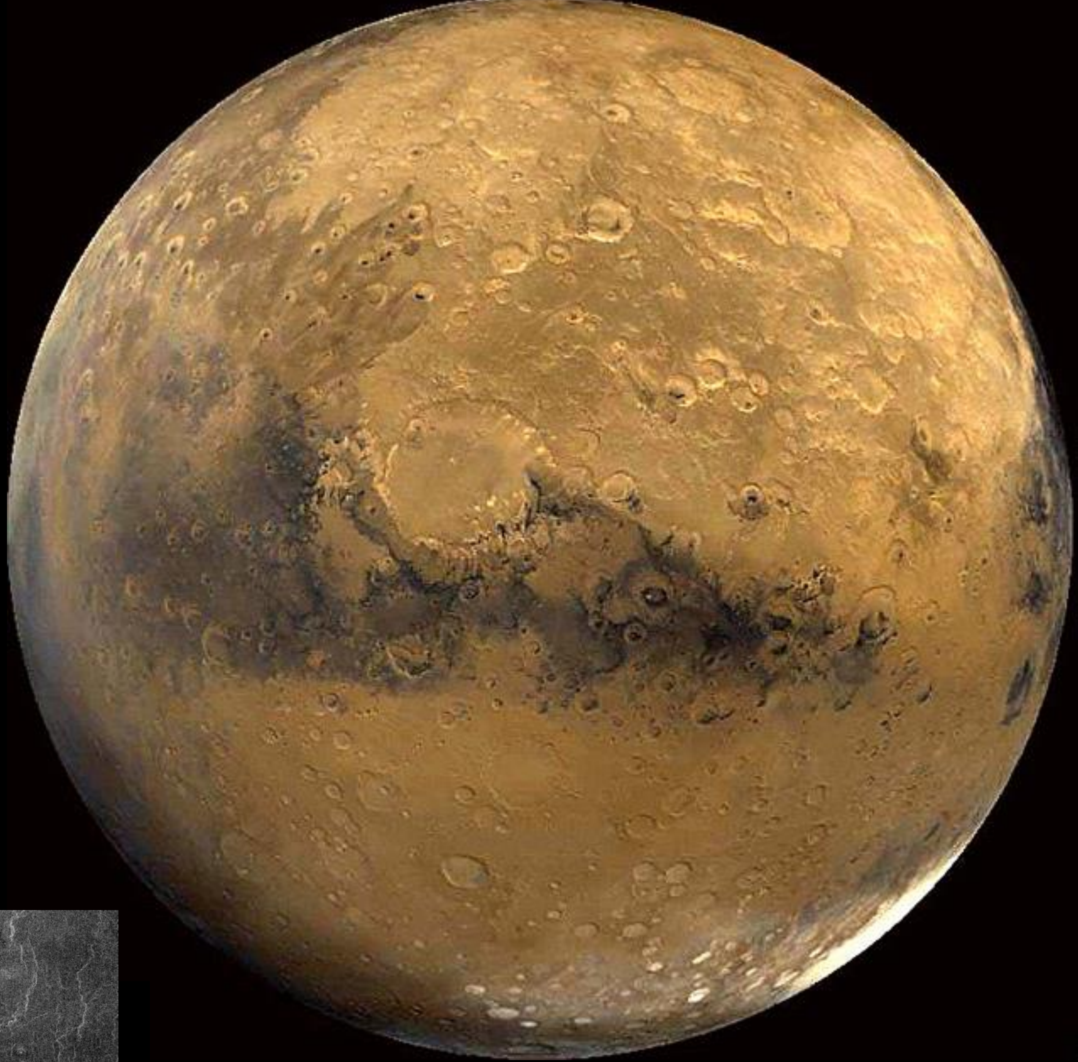
Earth is constantly accreting extraterrestrial material.

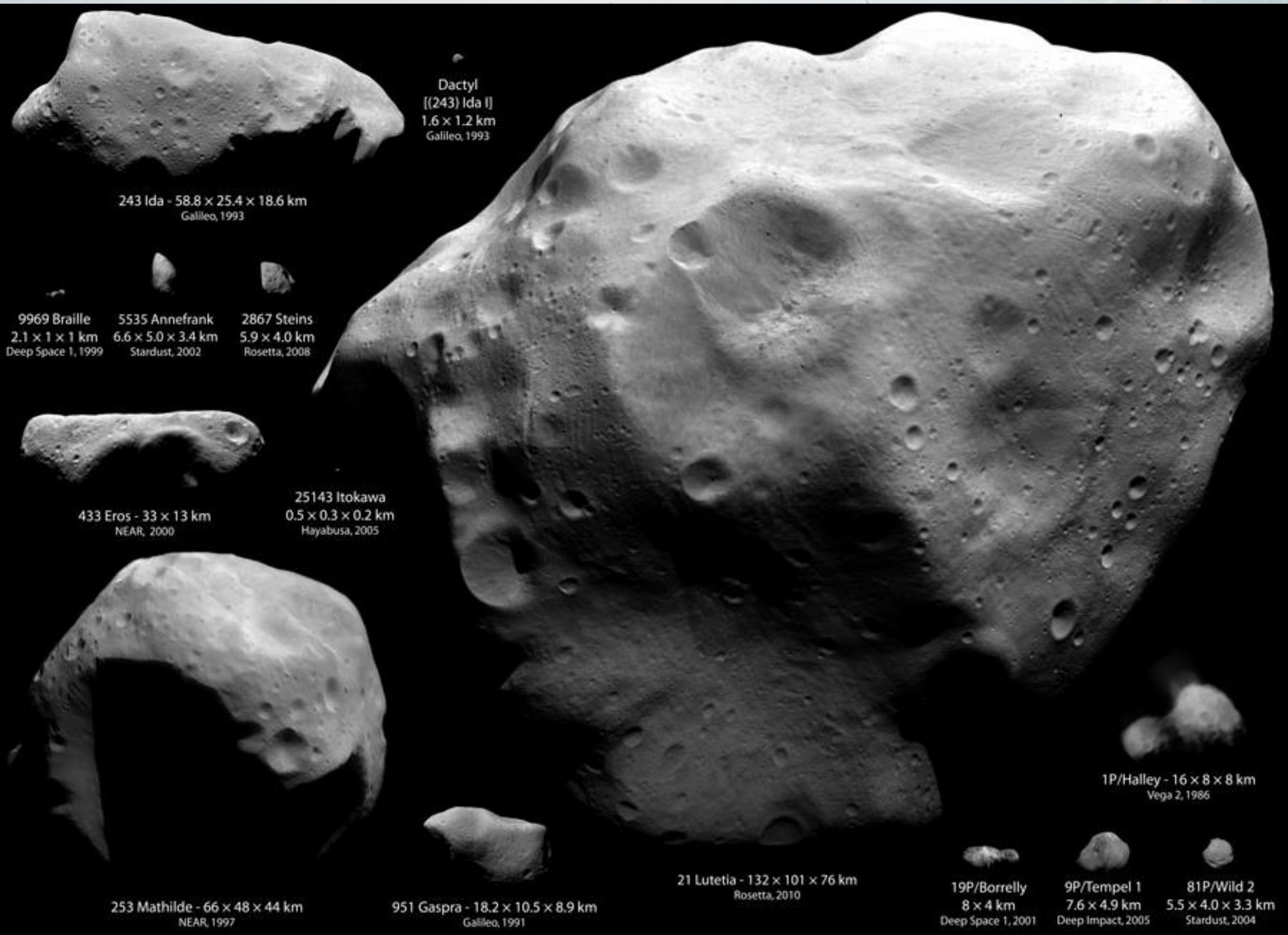
Total mass of extraterrestrial objects that strike the Earth is called meteorite flux.

This flux is at present around 10^7 to 10^9 kg/year.

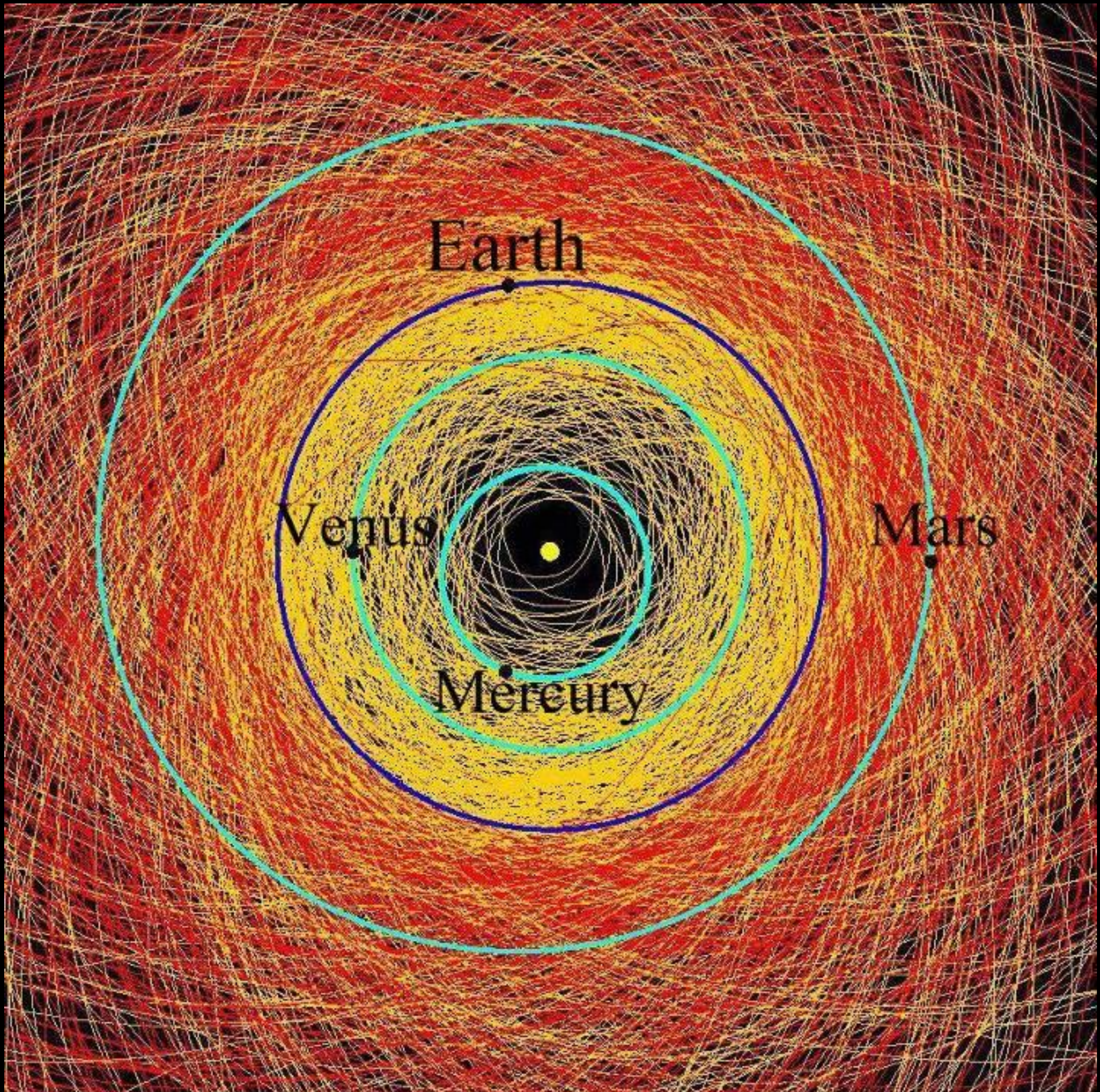
Much of this material comprises dust-sized objects called micrometeorites.

On occasion, there are catastrophic accretion events – cratering.

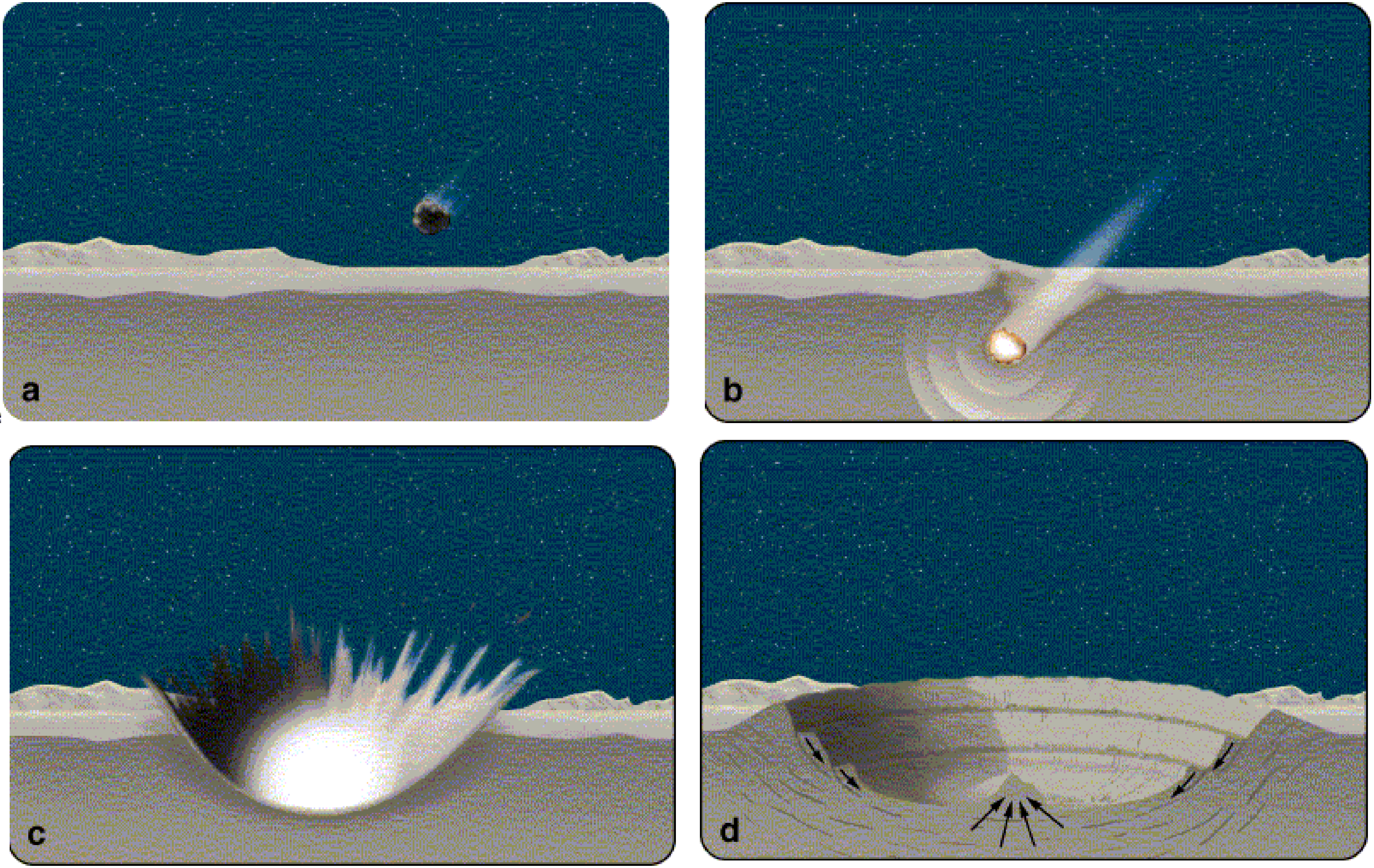



243 Ida - 58.8 × 25.4 × 18.6 km
Galileo, 1993
Dactyl
[(243) Ida I]
1.6 × 1.2 km
Galileo, 1993
9969 Braille
2.1 × 1 × 1 km
Deep Space 1, 1999
5535 Annefrank
6.6 × 5.0 × 3.4 km
Stardust, 2002
2867 Steins
5.9 × 4.0 km
Rosetta, 2008
433 Eros - 33 × 13 km
NEAR, 2000
25143 Itokawa
0.5 × 0.3 × 0.2 km
Hayabusa, 2005
253 Mathilde - 66 × 48 × 44 km
NEAR, 1997
951 Gaspra - 18.2 × 10.5 × 8.9 km
Galileo, 1991
21 Lutetia - 132 × 101 × 76 km
Rosetta, 2010
1P/Halley - 16 × 8 × 8 km
Vega 2, 1986
19P/Borrelly
8 × 4 km
Deep Space 1, 2001
9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004



Orbits of known asteroids >1 km in diameter (yellow are earth-orbit crossing)


a
b
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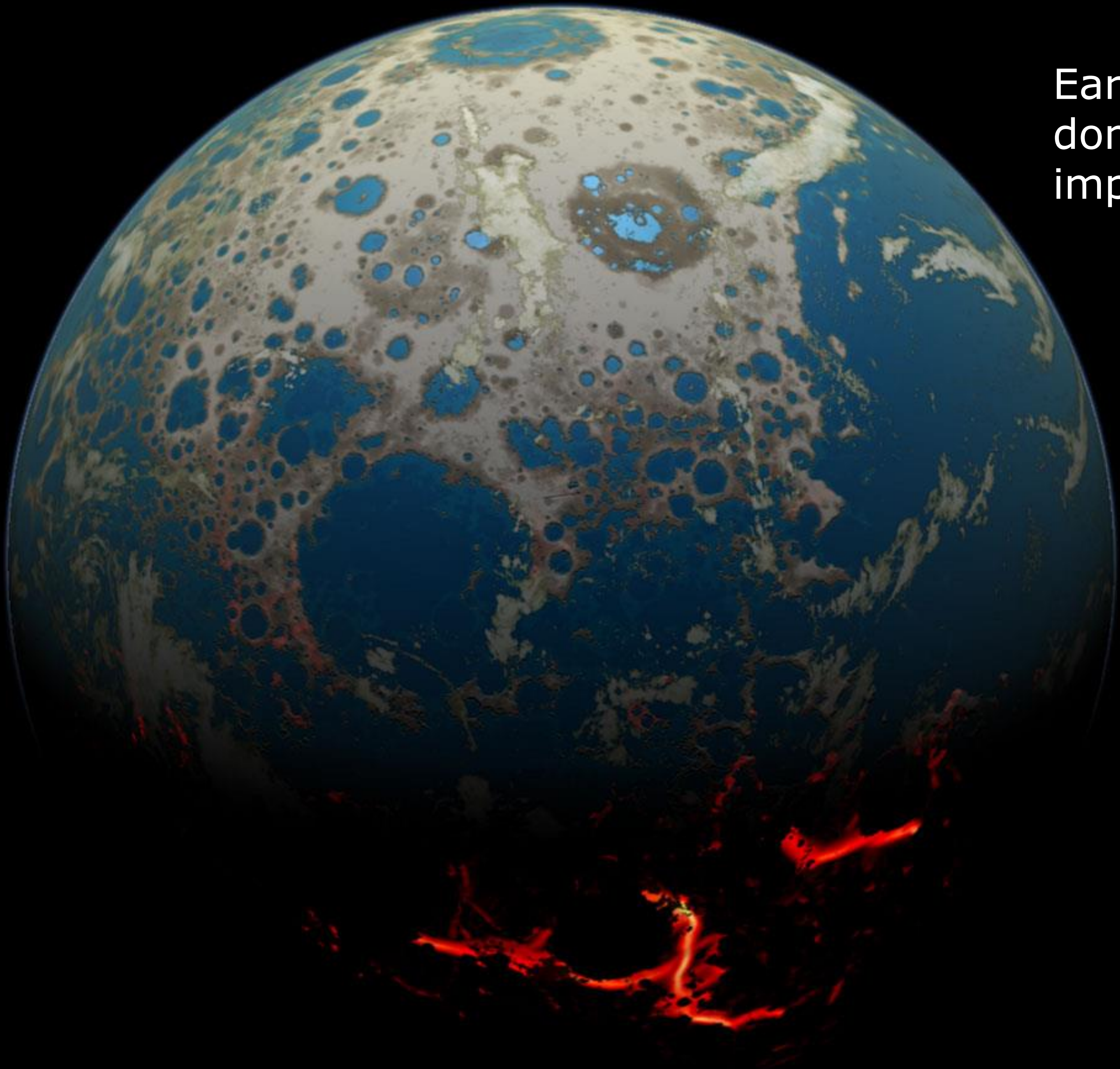
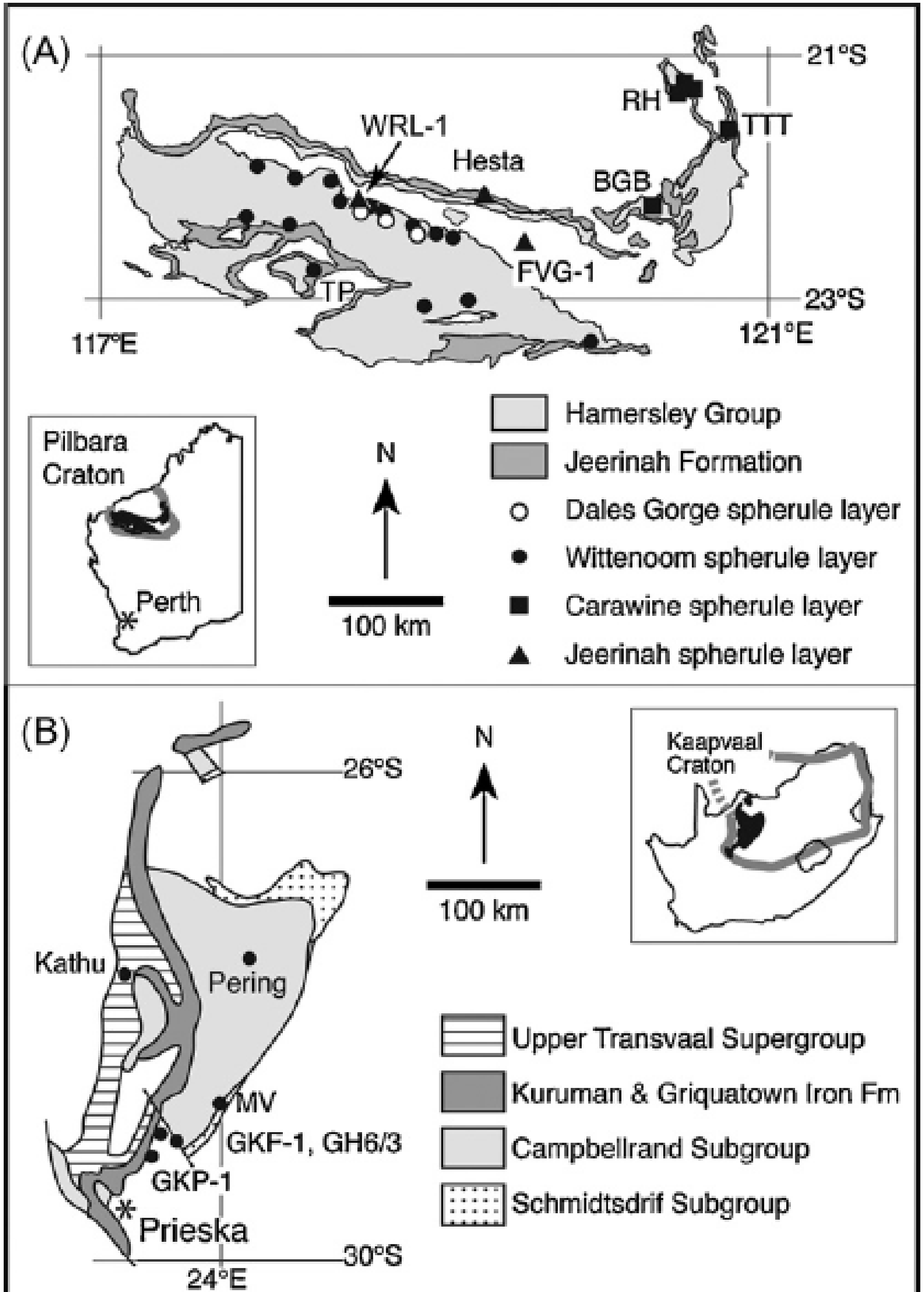
d

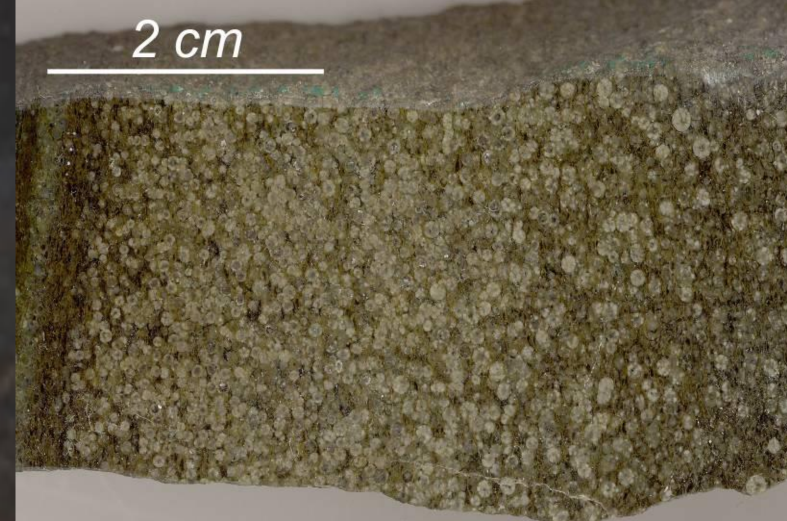


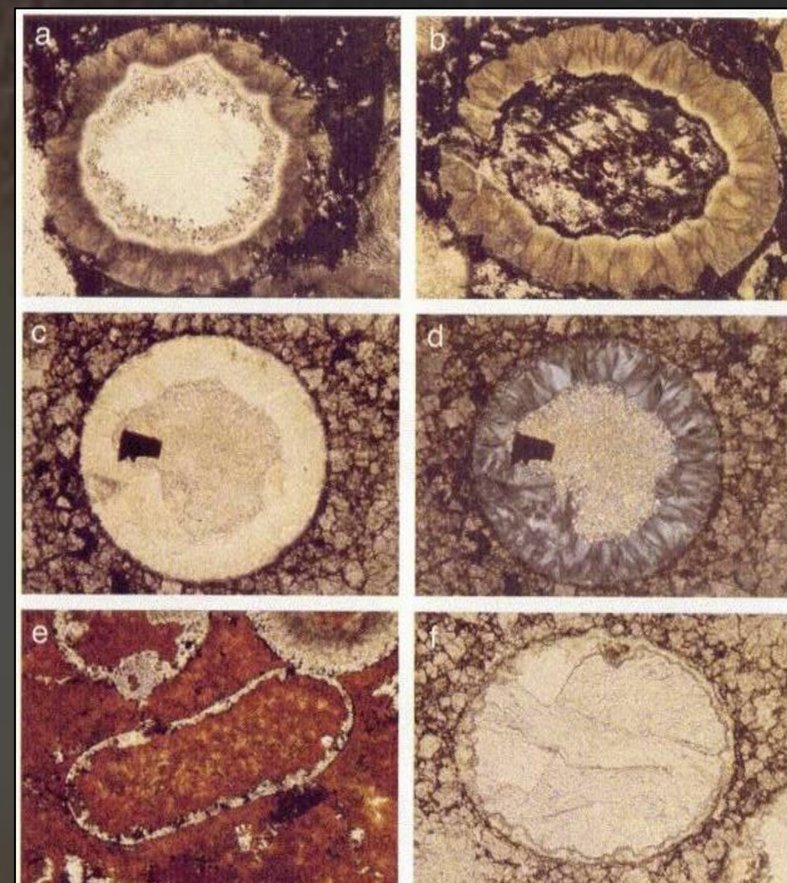
Early Earth dominated by impacts

Later (Early Archean) Impacts:

- Early record of impact on the Earth is limited and circumstantial
- First "real" rock record of impact events about 400 to 500 million years after end of the LHB
- Distal(?) ejecta layers - spherule layers in the ~3.4 Ga Barberton Greenstone Belt, South Africa
- Interpreted as the result of large asteroid or comet impacts onto the early Earth


(A)
21°S
23°S
117°E
121°E
RH
TTT
WRL-1
Hesta
BGB
FVG-1
TP
Pilbara
Craton
Perth
N
100 km
Hamersley Group
Jeerinah Formation
Dales Gorge spherule layer
Wittenoom spherule layer
Carawine spherule layer
Jeerinah spherule layer
(B)
26°S
30°S
24°E
N
100 km
Kaapvaal
Craton
Kathu
Pering
MV
GKF-1, GH6/3
GKP-1
Prieska
Upper Transvaal Supergroup
Kuruman & Griquatown Iron Fm
Campbellrand Subgroup
Schmidtsdrif Subgroup


2 cm


a
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e
f

Earliest Impact Craters Preserved on Earth

- **Vredefort structure** 2023±4 Ma (close to Johannesburg)

  The Vredefort Dome is an ~80 km wide relict of the central uplift of a complex crater (D=200-300 km); high-graded late Archean-Paleoproterozoic gneisses; variety of impact-related features (shatter cones, coesite, stishovite, PDFs, impact melt breccias)

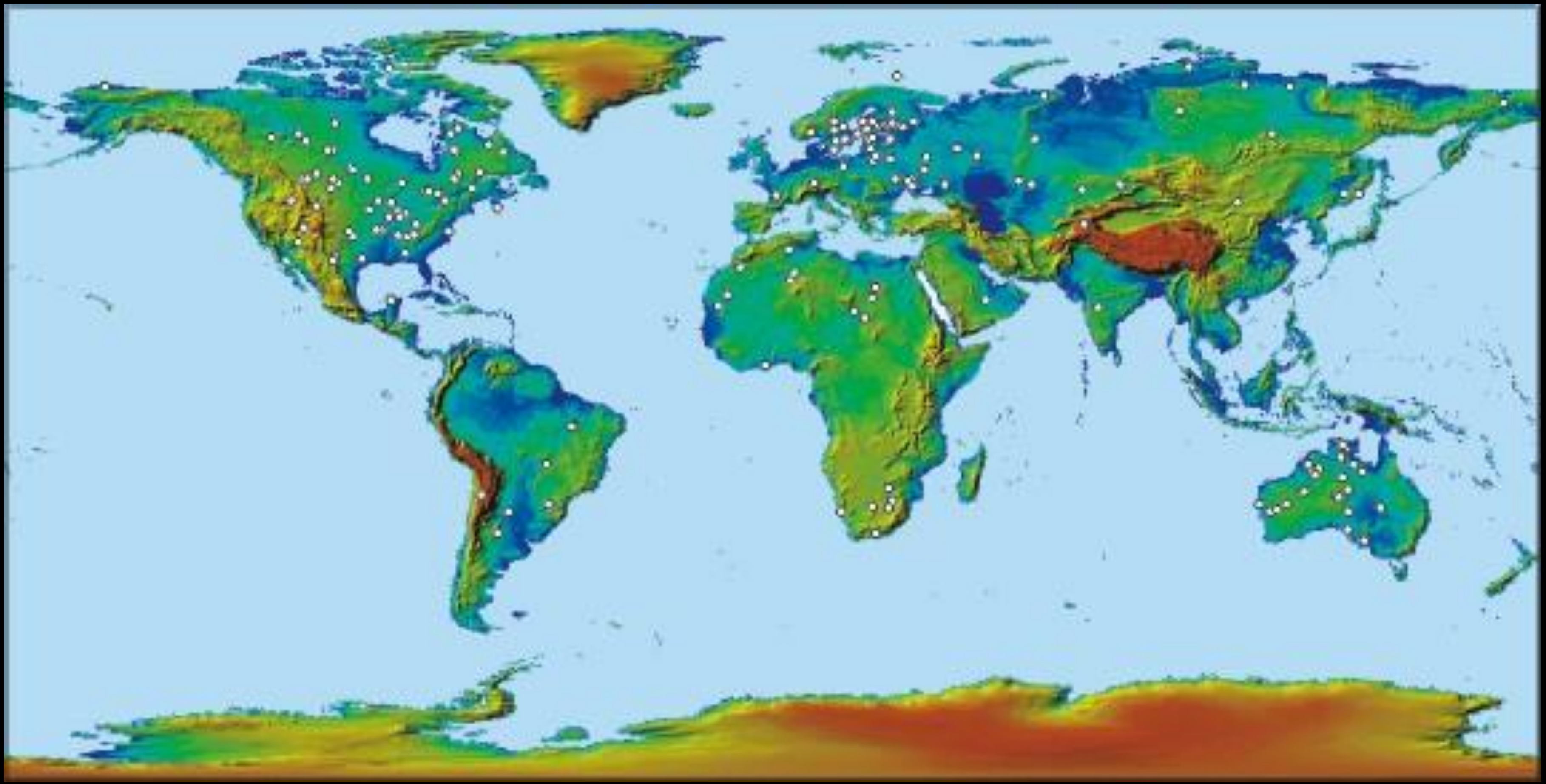
  Absence of a crater and fallback breccias suggest that intensive erosion has taken place (5-10m of post-impact deposits were removed); no ejecta have been found yet

- **Sudbury structure** 1850±3 Ma (close to Ontario)

  Only very recently (2005) impact ejecta layers 650-875 km from the impact site have been found

  A spherule layer in Greenland which has an age similar to of both of these craters (2.1 – 1.9 Ga) was found in 2001 and could represent distal ejecta from either of two impacts (new Cr isotope data indicate a meteoritic component & thus a link to Vredefort. Also at Karelia (Russia)

Impact Craters on Earth



- **Today:** The importance of impact cratering on terrestrial planets is obvious from the abundance of craters on their surfaces
- **In the 1970s:** Only about 50 impact craters recognized on Earth; studies of impact craters and shock metamorphism mostly restricted to few mineralogists, petrologists and cosmochemists who worked on lunar rocks; impact cratering not part of any geology curriculum

Torricella KT section, 1979

Luis and Walter Alvarez at Gubbio

6 June 1980, Volume 208, Number 4448 **SCIENCE**

Extraterrestrial Cause for the Cretaceous-Tertiary Extinction

Experimental results and theoretical interpretation

Luis W. Alvarez, Walter Alvarez, Frank Asaro, Helen V. Michel

In the 570-million-year period for which abundant fossil remains are available, there have been five great biological crises, during which many groups of organisms died out. The most recent of the great extinctions is used to define the boundary between the Cretaceous and Tertiary periods, about 65 million years

Summary. Platinum metals are depleted in the earth's crust relative to their cosmic abundance; concentrations of these elements in deep-sea sediments may thus indicate influxes of extraterrestrial material. Deep-sea limestones exposed in Italy, Denmark, and New Zealand show iridium increases of about 30, 160, and 20 times, respectively, above the background level at precisely the time of the Cretaceous-Tertiary extinctions, 65 million years ago. Reasons are given to indicate that this iridium is of extraterrestrial origin, but did not come from a nearby supernova. A hypothesis is suggested which accounts for the extinctions and the iridium observations. Impact of a large earth-crossing asteroid would inject about 60 times the object's mass into the atmosphere as pulverized rock; a fraction of this dust would stay in the stratosphere for several years and be distributed worldwide. The resulting darkness would suppress photosynthesis, and the expected biological consequences match quite closely the extinctions observed in the paleontological record. One prediction of this hypothesis has been verified: the chemical composition of the boundary clay, which is thought to come from the stratospheric dust, is markedly different from that of clay mixed with the Cretaceous and Tertiary limestones, which are chemically similar to each other. Four different independent estimates of the diameter of the asteroid give values that lie in the range 10 ± 4 kilometers.

microscopic floating animals and plants; both the calcareous planktonic foraminifera and the calcareous nannoplankton were nearly exterminated, with only a few species surviving the crisis. On the other hand, some groups were little affected, including the land plants, crocodiles, snakes, mammals, and many kinds

extinctions (*3*, *4*), and two recent meetings on the topic (*5*, *6*) produced no sign of a consensus. Suggested causes include gradual or rapid changes in oceanographic, atmospheric, or climatic conditions (*7*) due to a random (*8*) or a cyclical (*9*) coincidence of causative factors; a magnetic reversal (*10*); a nearby supernova (*11*); and the flooding of the ocean surface by fresh water from a postulated arctic lake (*12*).

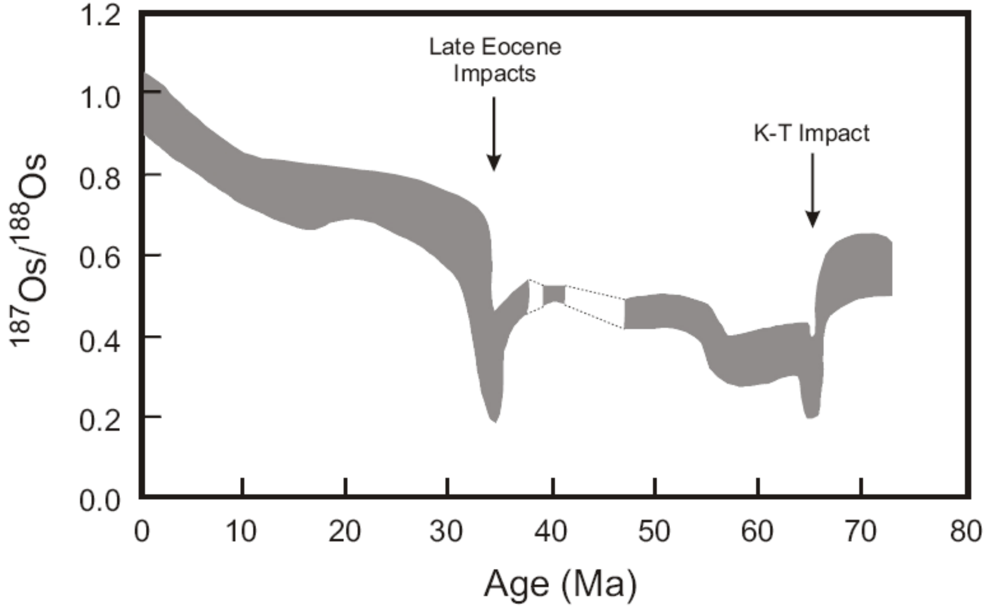
planktonic realm. None of the current hypotheses adequately accounts for this evidence, but we have developed a hypothesis that appears to offer a satisfactory explanation for nearly all the available paleontological and physical evidence.

There's nothing like discovering the smoking gun….

"So this is what killed the dinosaurs."

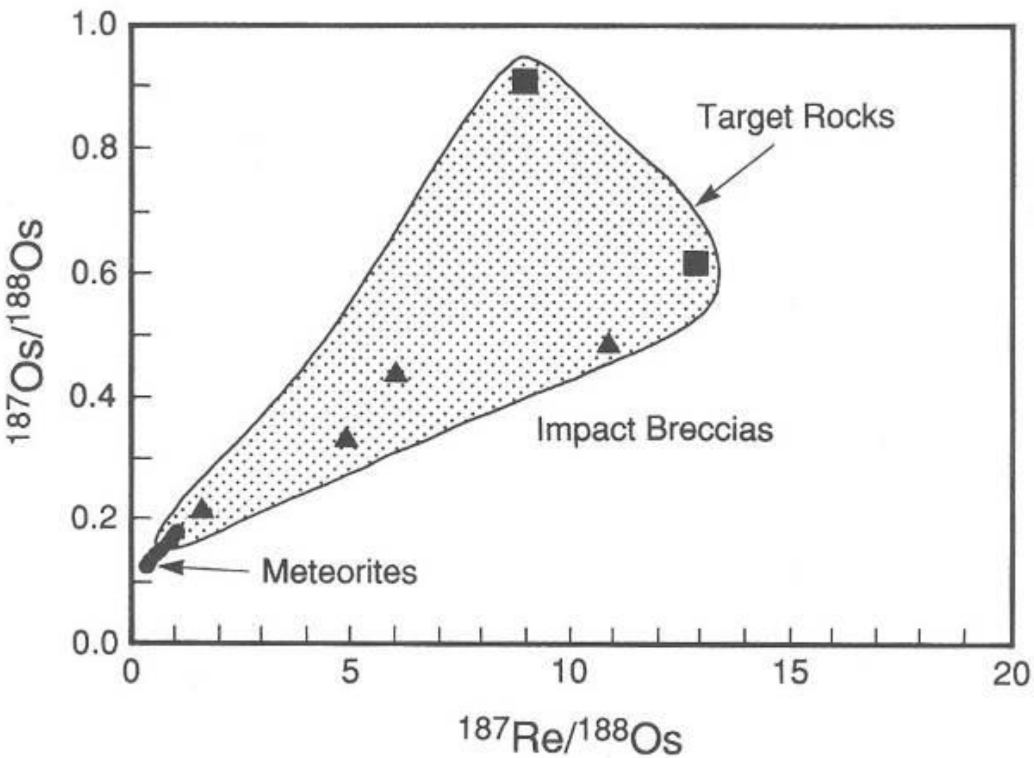
Impact evidence

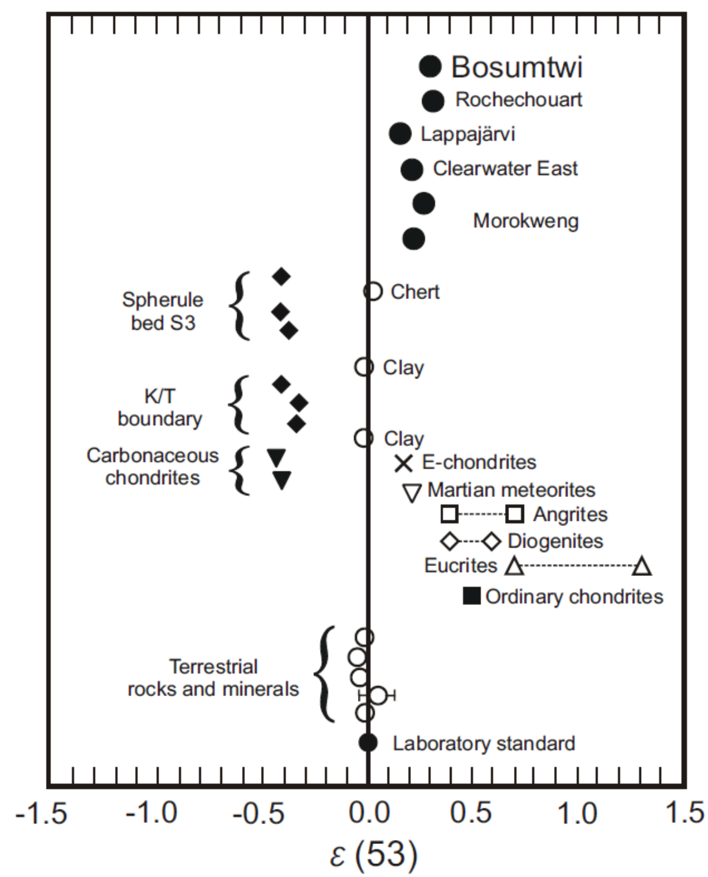
- interelement ratios of the PGEs in K-T boundary clay samples very similar to values observed in chondritic meteorites
- osmium- and Cr-isotopic studies of the K-T boundary provide further evidence of an extraterrestrial component
- later Os and Cr-isotope data indicated a carbonaceous chondritic composition of the impactor
- K-T boundary locations around the world show evidence for global wildfires in the form of a charcoal and soot layer that coincides with the Ir-rich layer

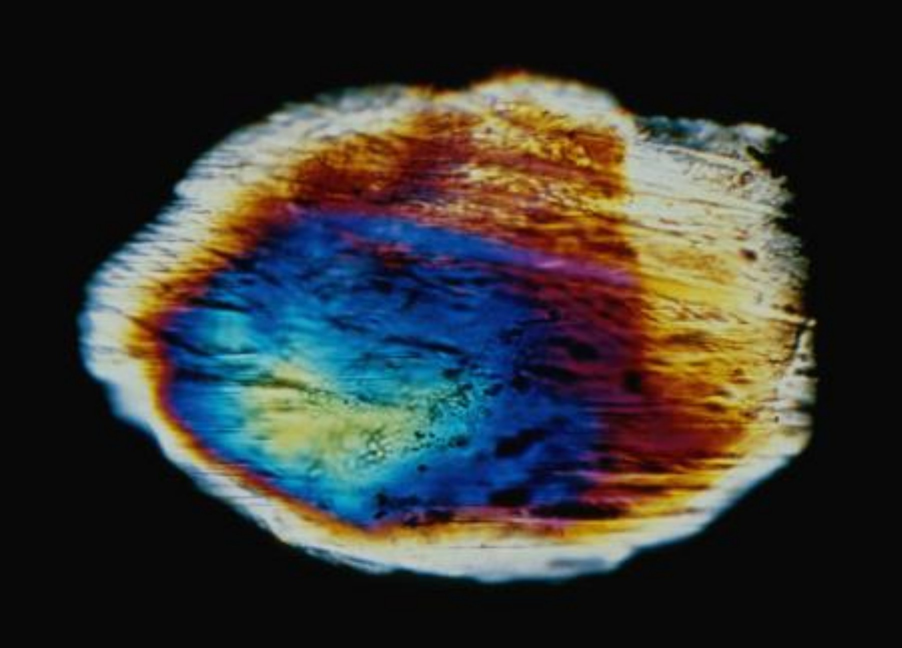


Distinct Os and Cr isotopic composition:

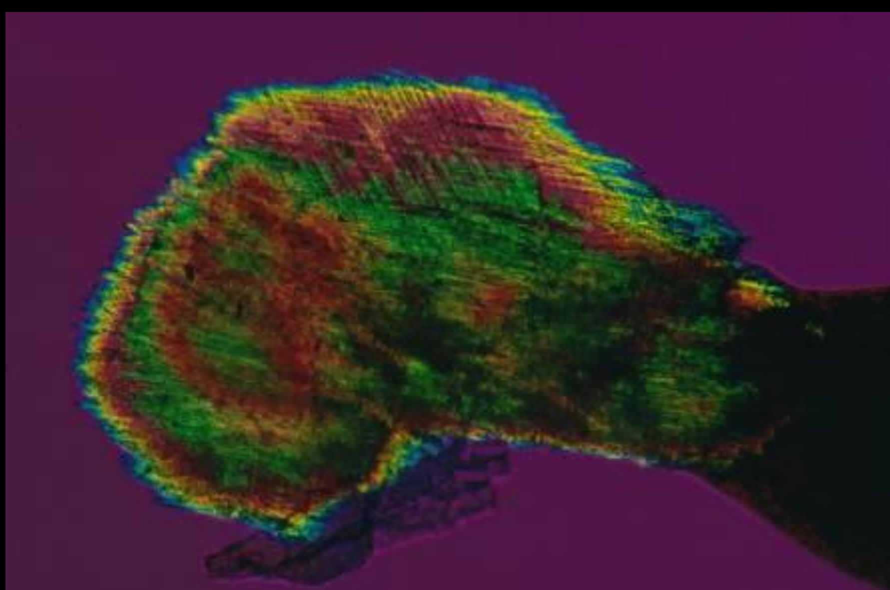
Evidence for extraterrestrial components

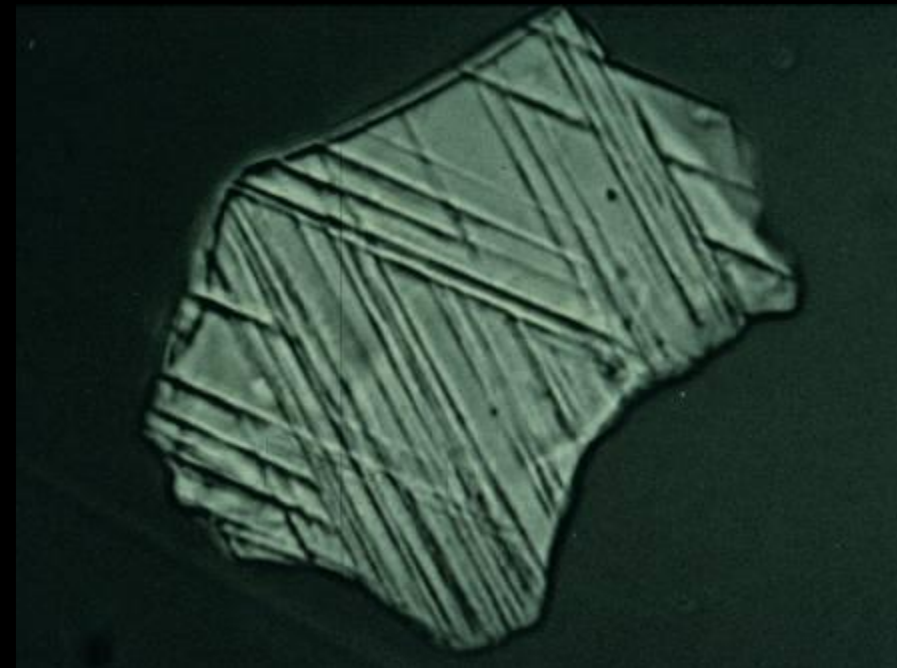




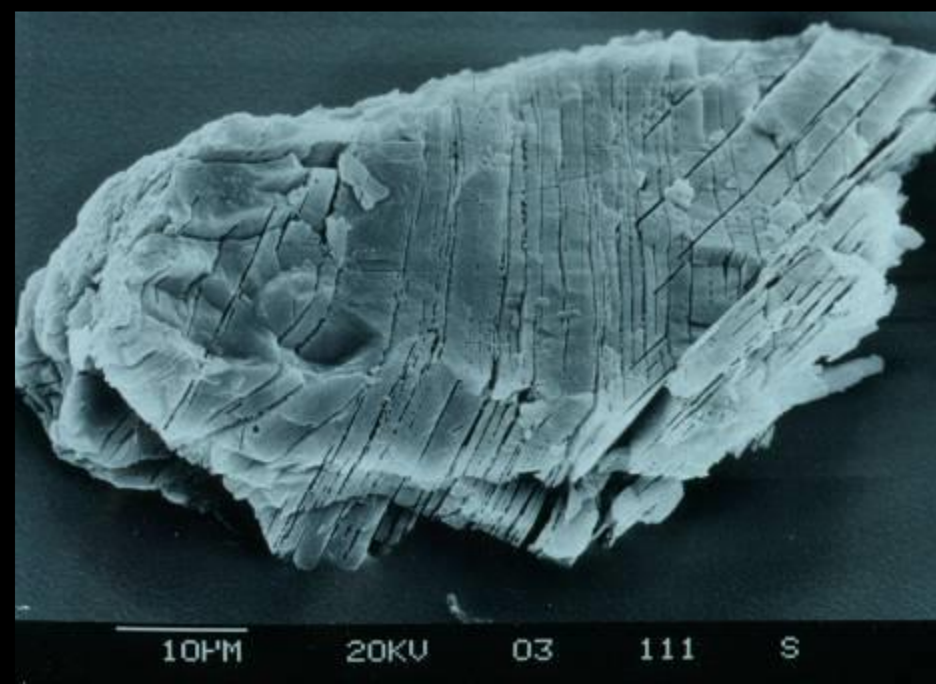


Shocked feldspar





Shocked quartz

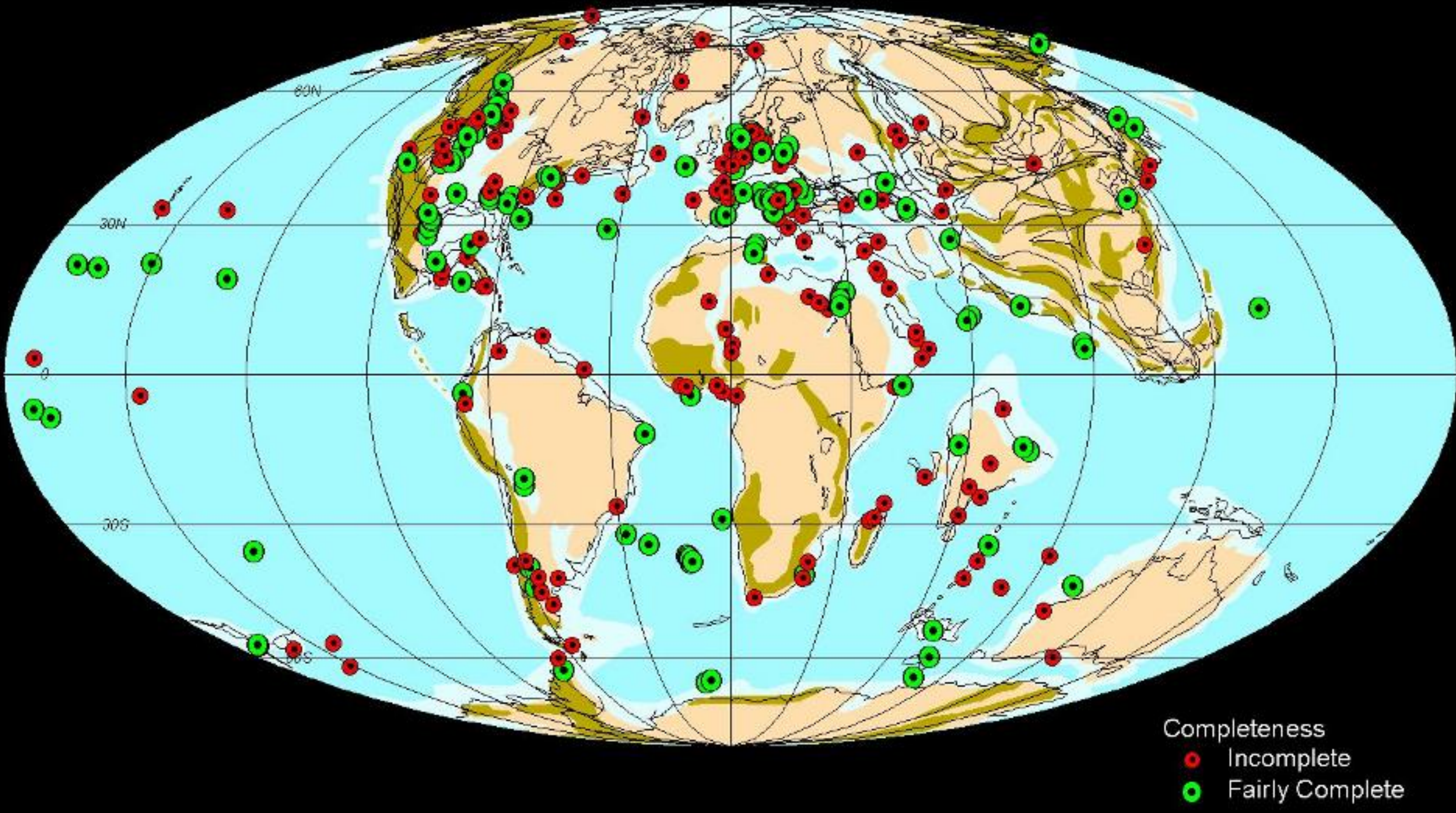


Impact evidence (continued):

- shocked minerals (including shocked quatz and shocked zircon)
- impact glass (some fresh, some devitrified)
- impact-derived diamonds
- spinel

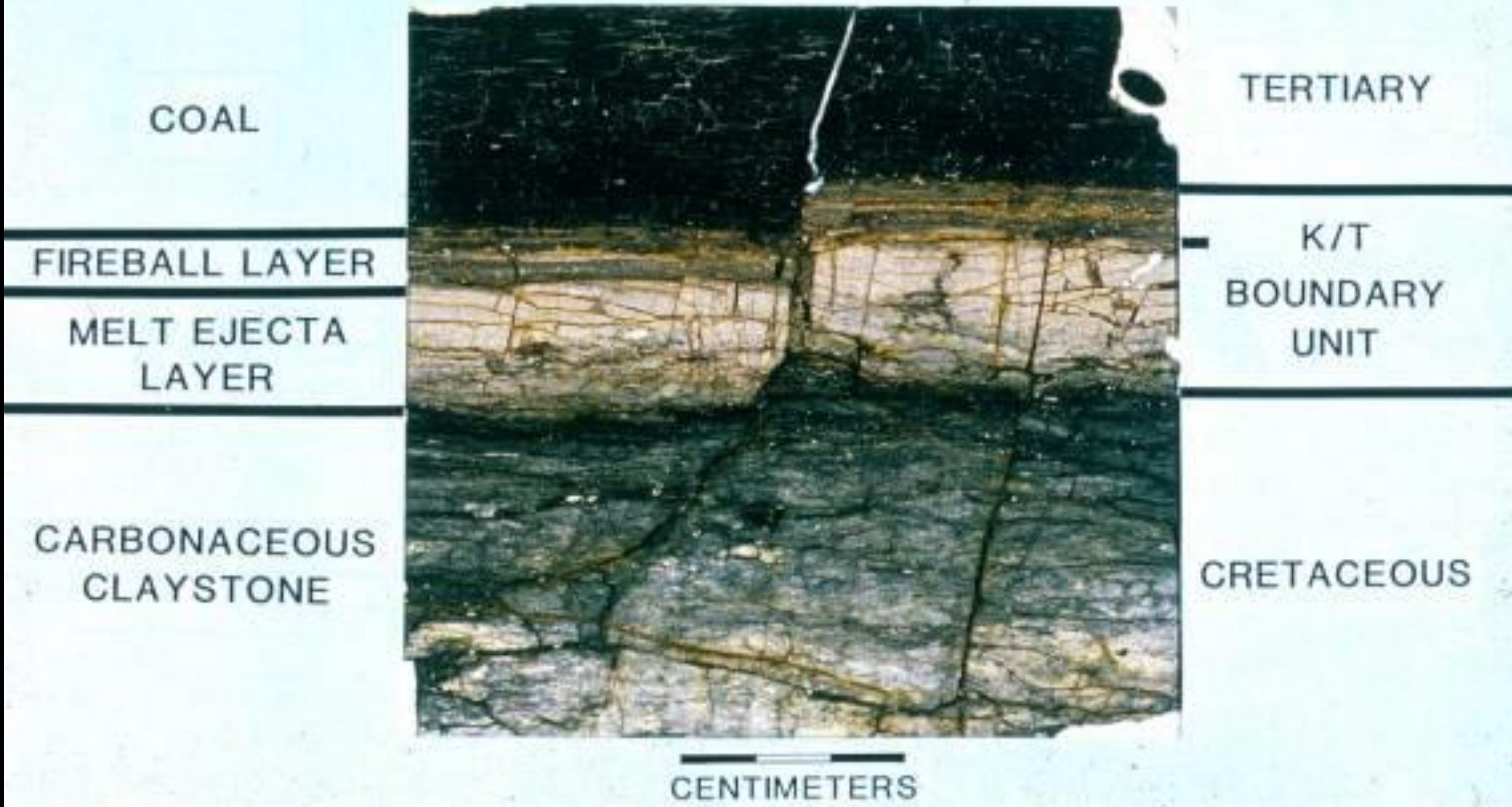
(spinel at the K-T boundary can be used as an event marker, as it shows an abundance peak similar to that observed for the PGEs)

KT Sections



BERWIND CANYON SITE

RATON BASIN, COLORADO



At terrestrial sections (e.g., Western Interior of North America) the K-T boundary consists of two layers:

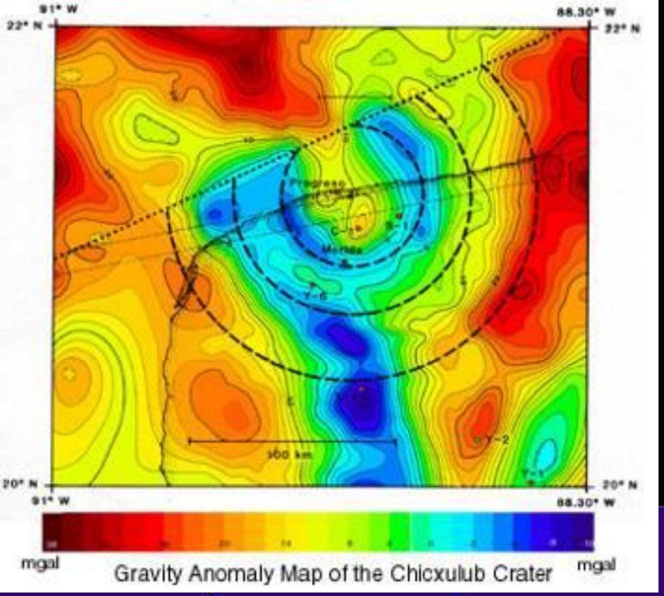
- lower kaolinitic (melt ejecta) layer (altered distal impact ejecta deposit)
- upper smectitic (fireball) layer (with shocked minerals, high-nickel magnesioferrite crystals, and high amount of iridium) --- originated from a cloud of vaporized bolide and entrained target material
- at some sites, the lower and upper boundary layers were deposited in a coal swamp, interbedded with or overlain by coal or impure coal

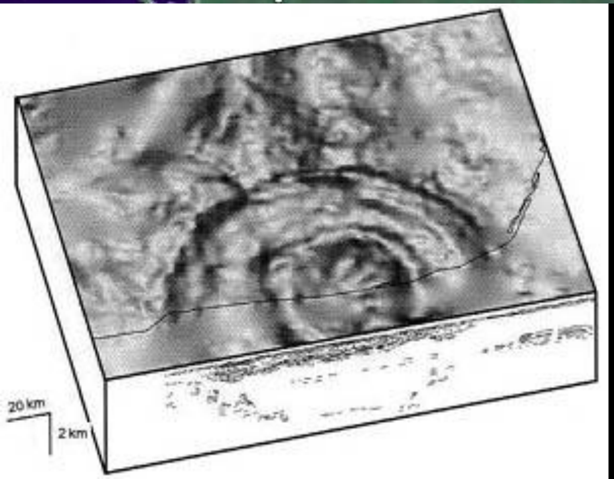
AGENT OF ENVIRONMENTAL CHANGE	TIME SCALE
Fireball irradiance	Minutes
Thermal pulse from ejecta (fires)	Hour+
Winds (500 km/hr), giant waves	Hours
Dust veil (cold, darkness)	Months
Acid rain (nitric and sulphuric)	Year
Stratospheric aerosols (cold)	Decades
Ozone depletion (UV exposure)	Decades
H_2O greenhouse effect	Decades
Poisons and mutagens	Years-millenia
CO_2 greenhouse effect	Millenia
Impact-triggered volcanism	Millenia?
Disrupted climate	Million years

Chicxulub Impact Structure, Mexico

ca. 200 km diameter, 65 Ma

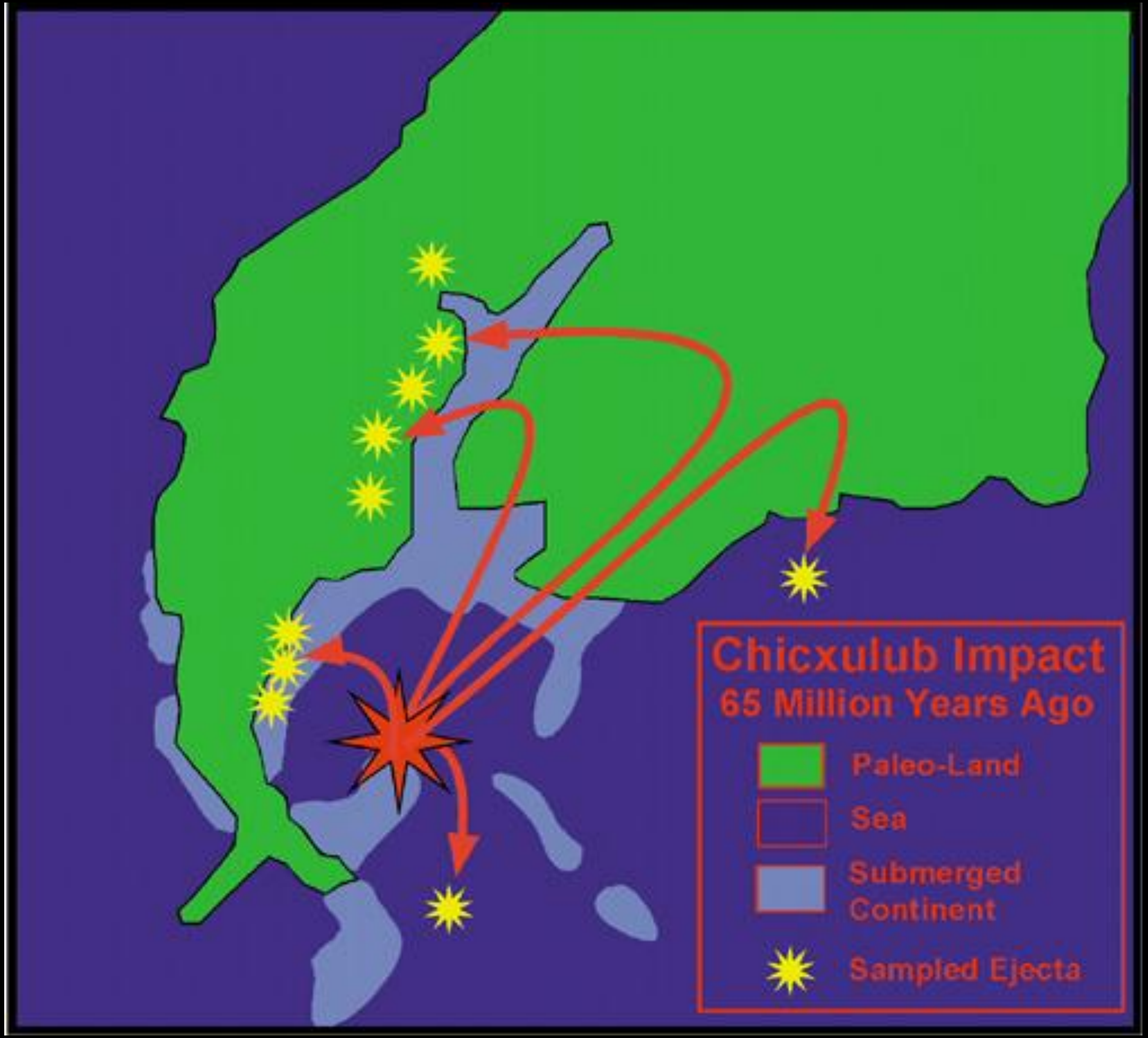
is the K-T boundary impact crater:



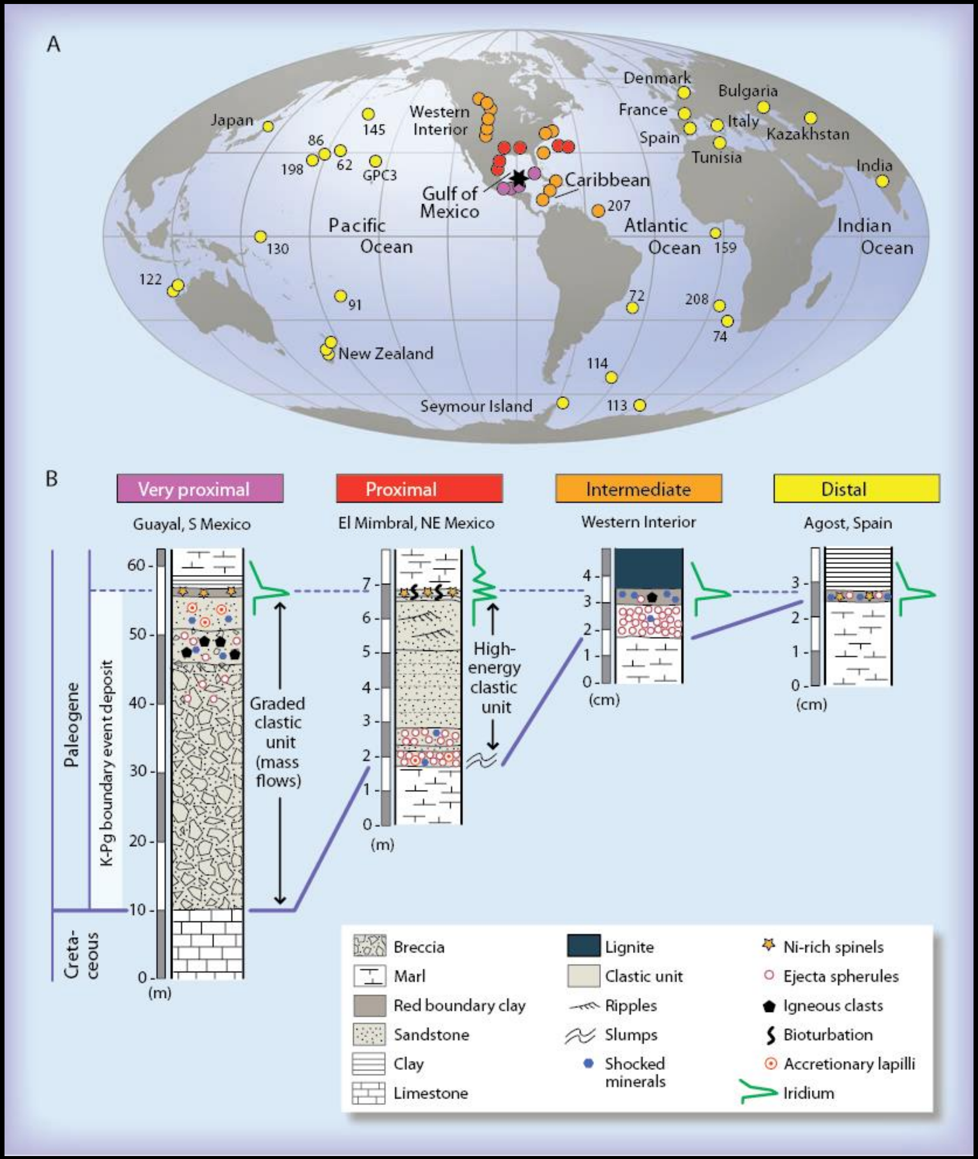


- Distribution of ejecta led to Chicxulub location
- Geochemistry (isotopic composition) of ejecta identical to melt rock composition; ejecta mineralogy fits with source region
- Zircon isotopics in ejecta and in melt rocks the same

- Largest crater during past several 100 Ma (similar crater statistics on Venus); two craters implausible; need two ejecta layers
- High-resolution and quantitative planktic foraminiferal biostratigraphy of ejecta


Chicxulub Impact
65 Million Years Ago
Paleo-Land
Sea
Submerged Continent
Sampled Ejecta

Evidence Correlating Chicxulub with K/Pg Boundary



Schulte et al., Science, 2010

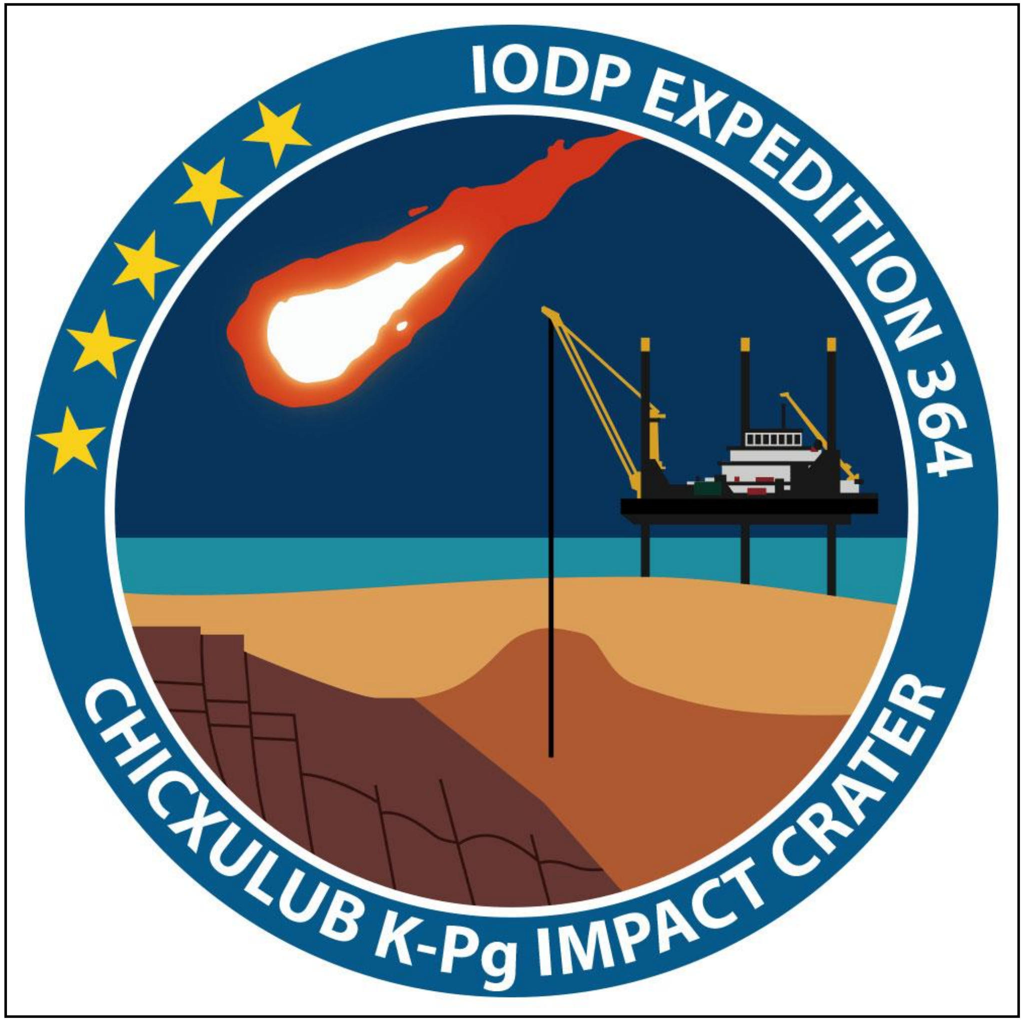
- K/Pg boundary sites show a distinct ejecta distribution pattern related to distance from the Chicxulub crater.
- 1 to >80-m-thick ejecta-rich deposits are present in the surrounding Central American region.
- In the NW Gulf of Mexico region the boundary is indicative of tsunamis and gravity flows.
- 1000-5000 km distances the layer is 2 to 10-cm-thick with spherules and shocked minerals.
- Distal sections 2 to 5-mm-thick clay rich in impact ejecta material and iridium.

IODP EXPEDITION 364
Chicxulub K-Pg Impact Crater - 2016

INTERNATIONAL OCEAN DISCOVERY PROGRAM

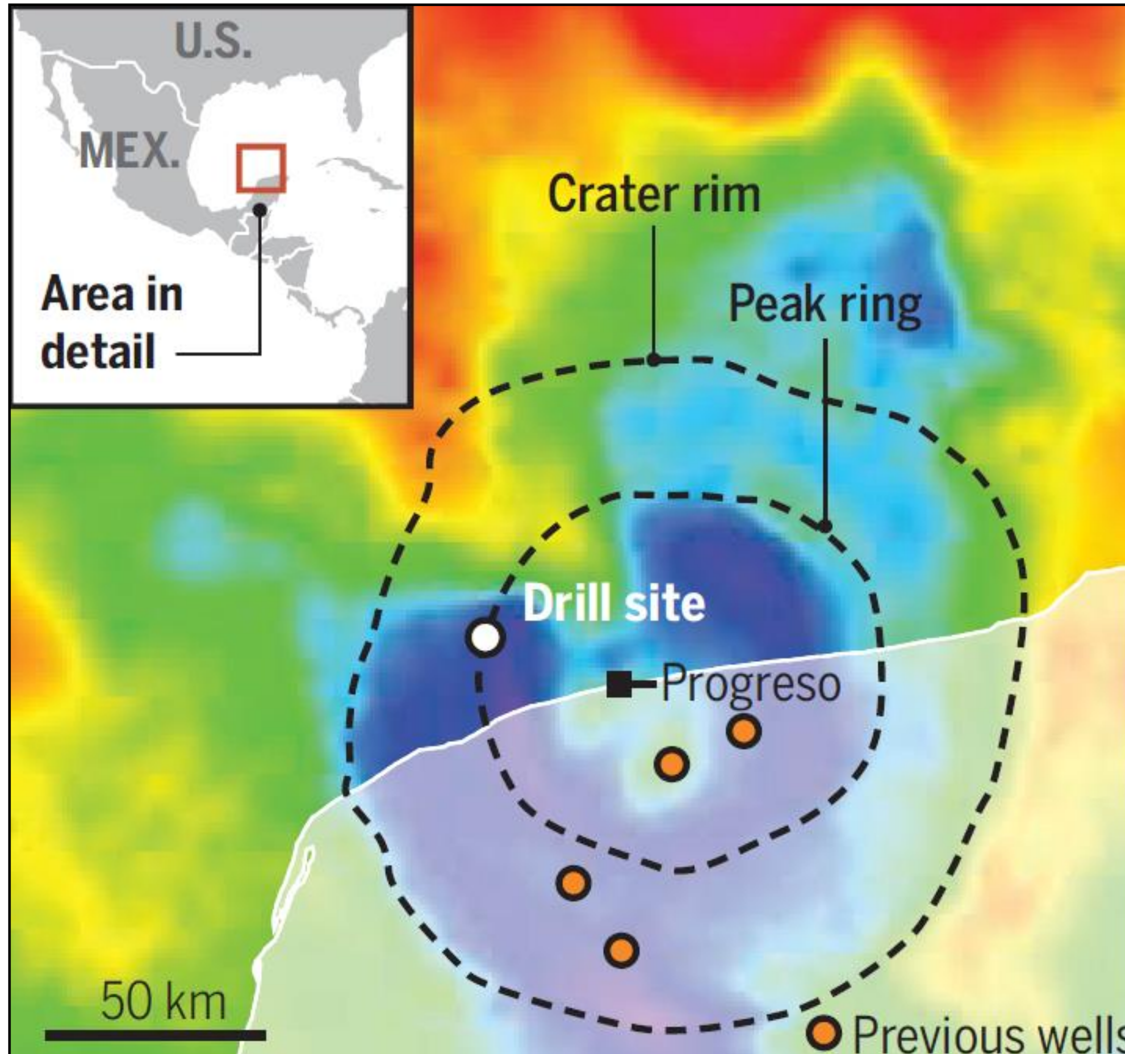
EUROPEAN CONSORTIUM FOR OCEAN RESEARCH DRILLING

icdp



IODP EXPEDITION 364
Chicxulub K-Pg Impact Crater

Drill site is located at ~30 km off the coast of the Yucatan peninsula (Mexico).



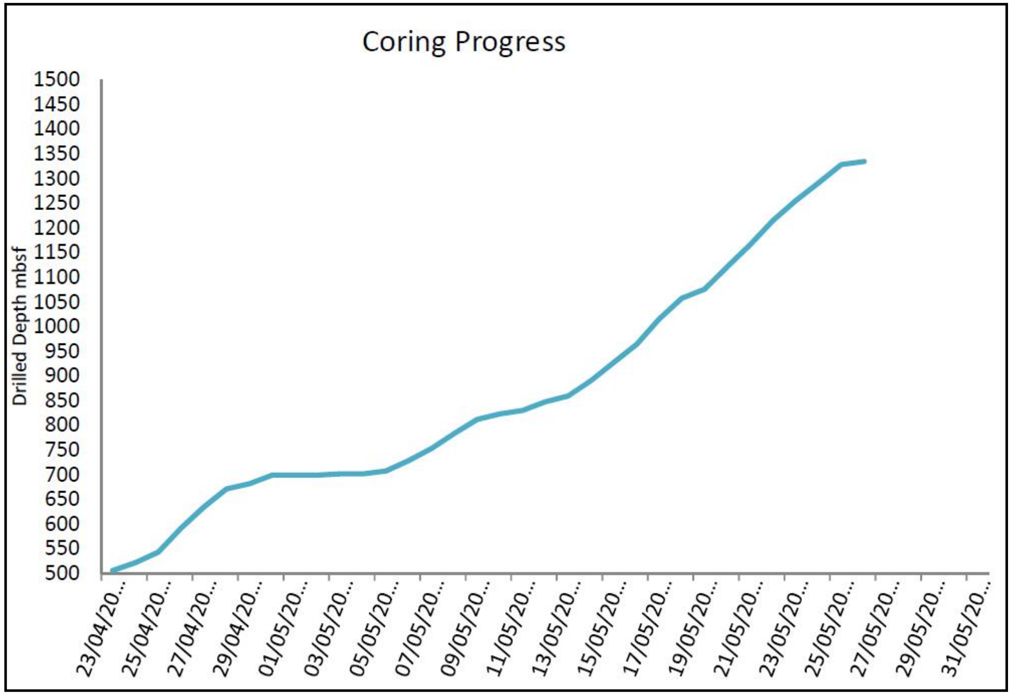
(Hand, Science, 2016)

IODP EXPEDITION 364
Chicxulub K-Pg Impact Crater

Coring completed!

Coring was completed on May 26th to a depth of 1334.69 meters below sea floor.

Downhole logging at the borehole (with tools used to collect data on resistivity, gamma ray, sonic velocity, magnetic susceptibility and temperature, as well as acoustic and optical images, VSP logging, etc.) was achieved on May 28th.

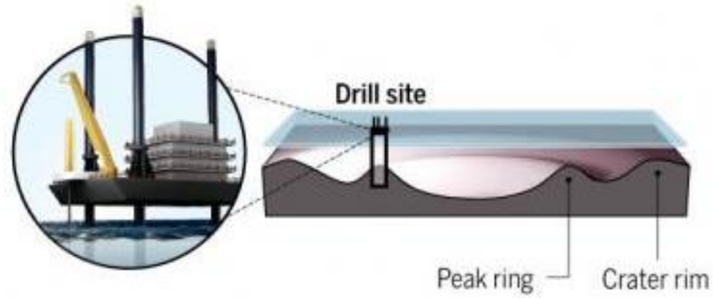


IODP EXPEDITION 364
Chicxulub K-Pg Impact Crater

IODP EXPEDITION 364
Chicxulub K-Pg Impact Crater

Going deep

Using a three-legged lift boat to create a stable drilling platform, scientists will drill 1500 meters deep, and back in time. Some layers took millions of years to form, whereas others were laid down in minutes.



1 Switching of the bits (500 m)

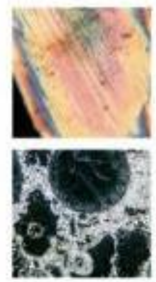
At first, no cores will be taken in layers of limestone. After casing the hole with steel, scientists will switch from a tungsten-carbide roller cutter to a diamond-tipped system that can retrieve 3-meter-long cores.

2 Paleocene–Eocene Thermal Maximum (550 m)

A time 55 million years ago when Earth was 5°C warmer. The warmth may have triggered algal blooms that died and fell to the sea floor. These might show up in the rock record as black shales amid the limestone.

3 Life returns (550–650 m)

The scientists will look for life coming back after the impact, as the shelled animals that make up limestone return and evolve into new species. Moving downhole and back in time to the impact, the size and number of species of forams and coccolithophores is expected to shrink.



4 Impact layer (650–800 m)

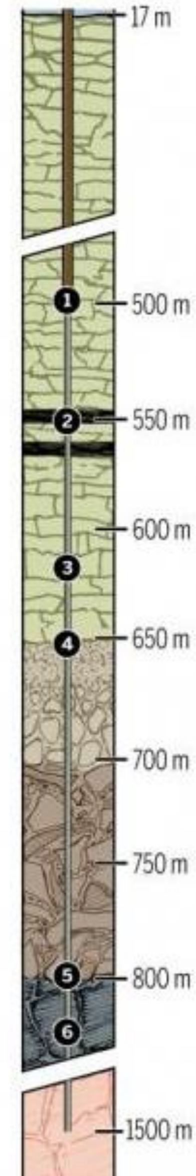
Rocks at the base may contain chunks of rock and impact melt. The ocean rushing in to fill the crater hole could have deposited overlying sediment, perhaps containing glassy impact spherules. Settling on top could be fine ash containing crystals of shocked quartz.

5 Peak ring (800–1500 m)

If formation models are correct, peak ring rocks—probably volcanic granites—could be sitting "out of order." Deeper granites, with darker minerals, could rest on top of granites with lighter minerals.

6 Microbial life (800–1500 m)

The peak ring is expected to be fractured and filled with mineral veins that were once part of a vast hydrothermal system. Scientists will look for DNA evidence that chemosynthetic microbes live in the cracks.



The offshore phase of Expedition 364 Chicxulub K-Pg Impact Crater is complete!

Summary of IODP Expedition 364 Offshore phase:

- Number of holes: 1
- Number of expedition days: 55
- Total depth drilled: 1334.69 m
- Open hole drilled: 0 – 505.7 m
- Length cored: 828.99 m
- Length recovered: 839.55 m
- Recovery: 100%!
- Number of core bits used: 8
- Number of cores: 303
- Number of sections: 830
- Number of samples: 1075
- Total length of open hole downhole logs: 5.8 km

- Number of visitors and media: 46

A success (so far)!

IODP EXPEDITION 364
Chicxulub K-Pg Impact Crater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Artist's reconstruction of Chicxulub crater soon after impact, 66 million years ago. DETLEV VAN RAVENSWAAY/SCIENCE SOURCE

Scientists gear up to drill into 'ground zero' of the impact that killed the dinosaurs

By Eric Hand | Mar. 3, 2016 , 2:00 PM


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Scientists have been analyzing rock cores retrieved from the Chicxulub crater in a drilling expedition that began in April. JLofi / ECORD_IODP

Scientists hit pay dirt in drilling of dinosaur-killing impact crater

By Eric Hand | May. 3, 2016 , 3:00 AM


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Project to drill into 'dinosaur crater' gets under way

By Jonathan Amos
BBC Science Correspondent

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Science & Environment

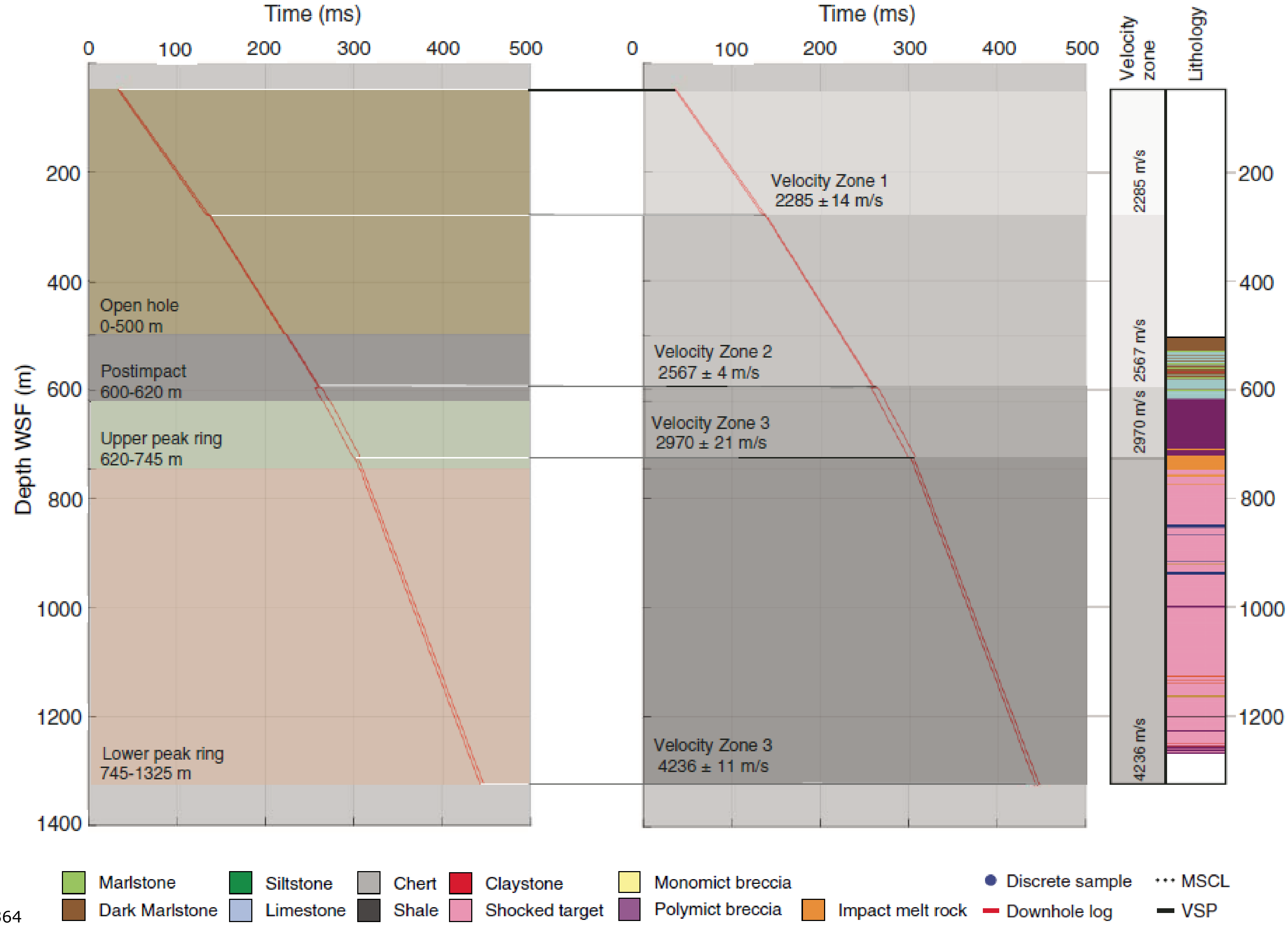
Chicxulub 'dinosaur' crater drill project declared a success

By Jonathan Amos
BBC Science Correspondent

25 May 2016 | Science & Environment

MAX ALEXANDER/B612/ASTEROID DAY

Impact breccia: Rock recovered from the peak ring of the Chicxulub Crater


Time (ms)
0
100
200
300
400
500
Depth WSF (m)
200
400
600
800
1000
1200
1400
Open hole
0-500 m
Postimpact
600-620 m
Upper peak ring
620-745 m
Lower peak ring
745-1325 m
Velocity Zone 1
2285 ± 14 m/s
Velocity Zone 2
2567 ± 4 m/s
Velocity Zone 3
2970 ± 21 m/s
Velocity Zone 3
4236 ± 11 m/s
Velocity zone
Lithology
2285 m/s
2567 m/s
2970 m/s
4236 m/s
Marlstone
Dark Marlstone
Siltstone
Limestone
Chert
Shale
Claystone
Shocked target
Monomict breccia
Polymict breccia
Impact melt rock
Discrete sample
Downhole log
MSCL
VSP

Soot effects after the impact (Bardeen et al., PNAS, 2017)**:**

- after the impact: ca. 1 Mio tons soot in the atmosphere
- little or no sunlight reaches the surface for over a year
- photosynthesis is impossible and continents and oceans
- cool by as much as 28 °C and 11 °C, respectively.
- absorption of light by the soot heats the upper atmosphere by hundreds of degrees
- these high temperatures, together with a massive injection
- of water, which is a source of odd-hydrogen radicals, destroy the stratospheric ozone layer
- thus Earth’s surface receives high doses of UV radiation for about a year once the soot clears, five years after the impact
- temperatures remain above freezing in the oceans, coastal areas, and parts of the Tropics
- photosynthesis is severely inhibited for the first 1 y to 2 y
- Freezing temperatures persist at middle latitudes for 3 y to 4 y
- Refugia from these effects would have been very limited

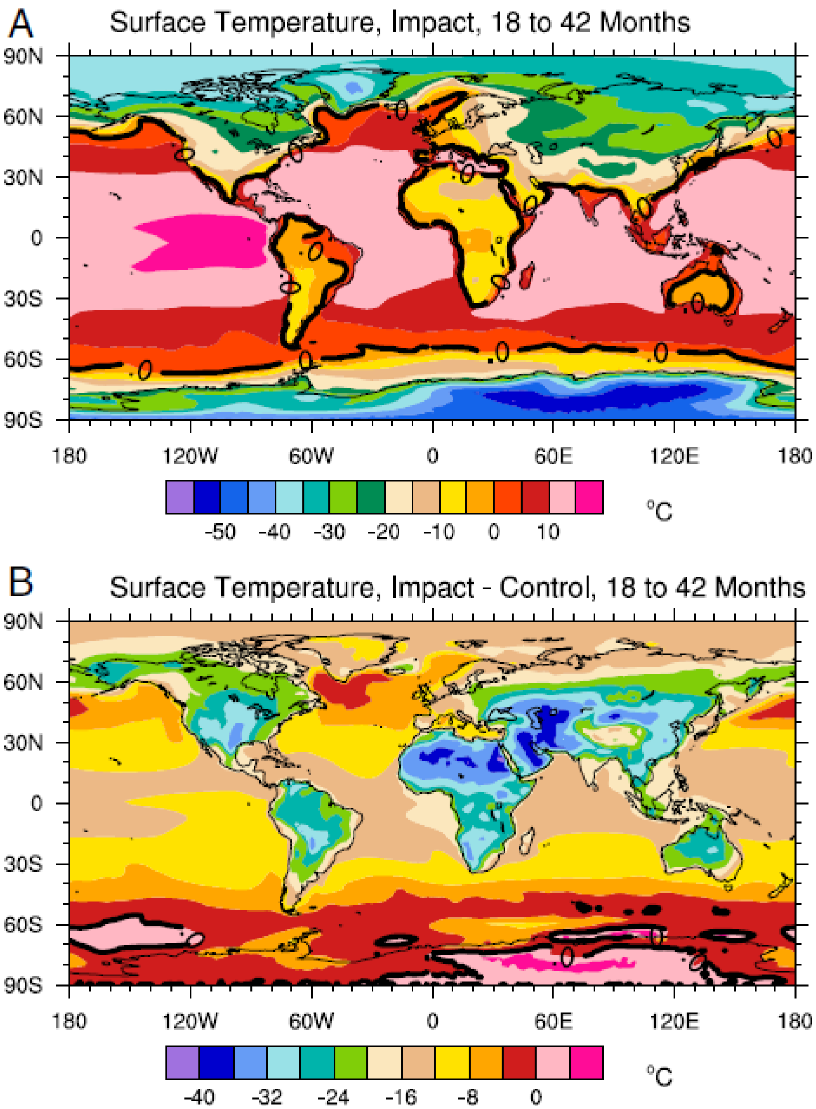


Fig. 5. (*A*) The average surface temperature from 18 mo to 42 mo after the impact from the simulation with 15,000 Tg of soot and impact generated water vapor, and (*B*) the temperature change with respect to the control simulation. The thick black line is the 0 °C contour.

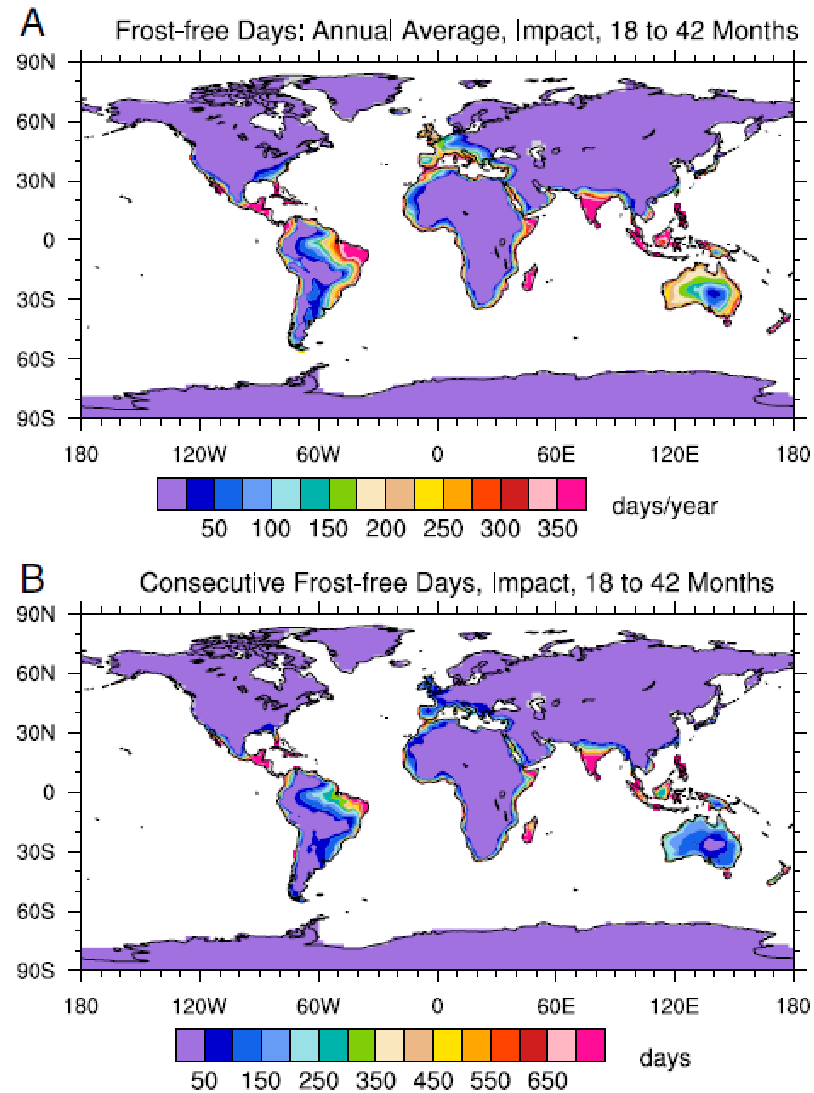


Fig. 6. Frost-free days during the period from 18 mo to 42 mo after the impact from the simulation with 15,000 Tg of soot and impact generated water vapor. Frost-free days are days where the minimum temperature is larger than 0 °C. (*A*) The average number of frost-free days per year. (*B*) The longest period of consecutive frost-free days in the two years.

Soot effects after the impact (Bardeen et al., PNAS, 2017)

Summary

- The debate that followed the suggestion by Alvarez et al. (1980) finally led over the 1990s and the 2000s to a more general realization that impact cratering is an important process on the Earth as well, and not only on other planetary bodies.
- For the last few decades, planetary scientists, astronomers, and meteoriticists, who work with the products of impact cratering, have grown to accept impact cratering as a normal geological phenomenon, whereas “another group, the paleontologists, is confounded by what appears to be an ad hoc theory about a non-existent phenomenon” (Raup, in Glen, 1994, p. 147).
- The evidence for a large-scale impact event exactly coinciding with the K-Pg boundary/mass extinction is overwhelming
- Effects of the impact event were „rather nasty“ for quite some time....

Thank you for your attention!