The Bombardment History of the Early Earth

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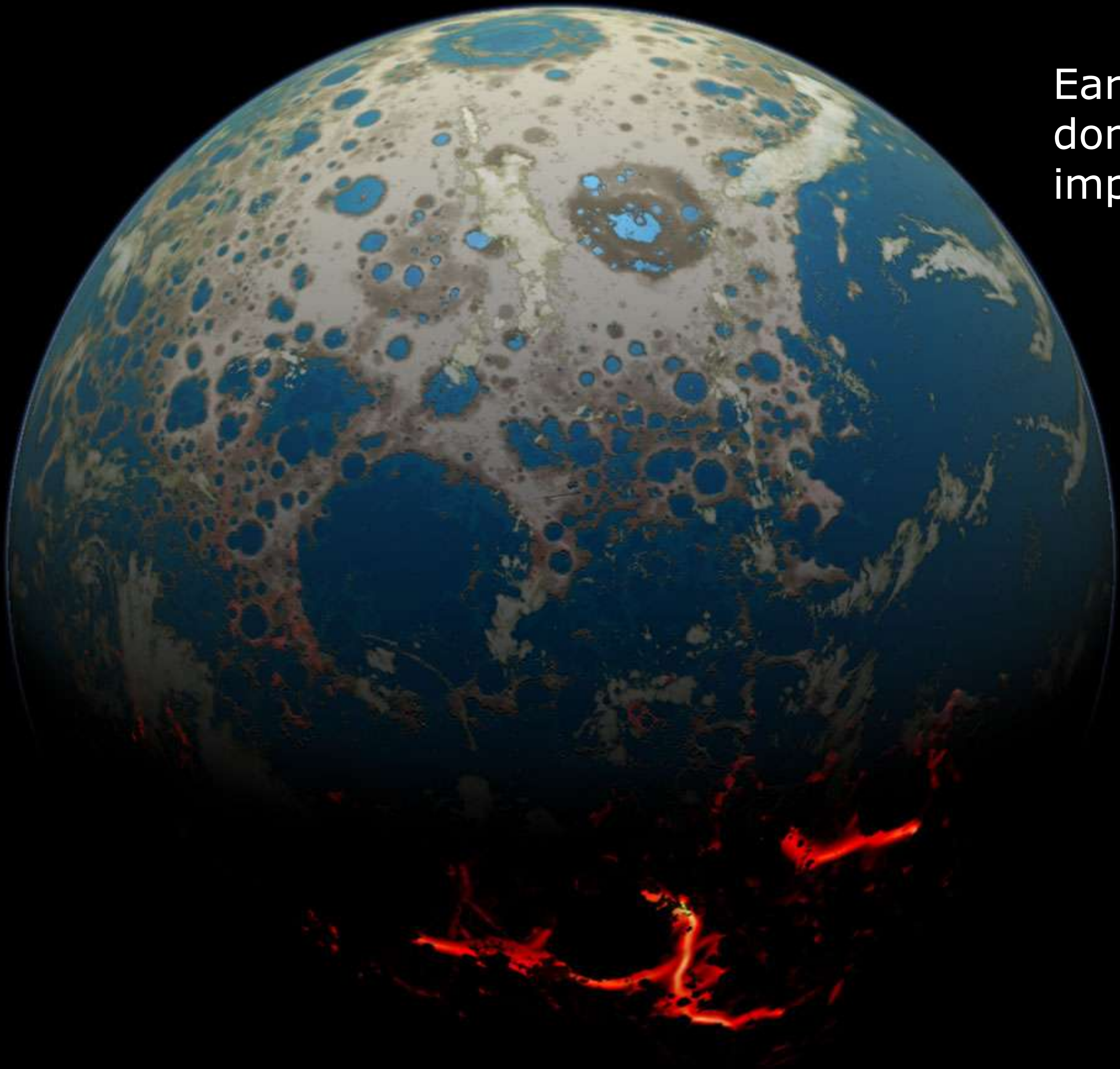
- Impact processes have been important in the solar system from the very beginning
- Accretion of the Earth through collision, followed by a violent early history - only circumstantial evidence
- Moon was subjected to intense post-accretionary bombardment between about 4.5 and 3.9 Ga
- Evidence for a short and intense late heavy bombardment period, around 3.9   0.1 Ga
- If late heavy bombardment the Moon, Earth must have been subjected to more intense bombardment
- Devastating consequences for the Earth

- No unequivocal evidence of a late heavy bombardment on the early Earth
- Indirect geochemical evidence for a single large impact event at about 4.5-4.45 Ga
- Related to the formation of the moon
- Long gap in the rock record
- First solid evidence for impact processes:
    - various spherule layers in South Africa and Australia
    - ages between about 3.4 and 2.5 Ga
    - these represent several large-scale impact events
- Oldest preserved impact crater on Earth is 2 Ga old

- Consequences of large impact event for proto-Earth severe
- Almost complete re-melting of the Earth
- Loss of any primary atmosphere,
- Admixture of material from the impactor
- Core of Mars-sized impactor likely to have merged with core of proto-Earth almost instantaneously

Many open questions regarding the Hadean and Early Archean Earth

- Composition of the atmosphere?
- Composition of the crust?
- When did plate tectonics start?
- Composition and formation of oceans? (source of water?)



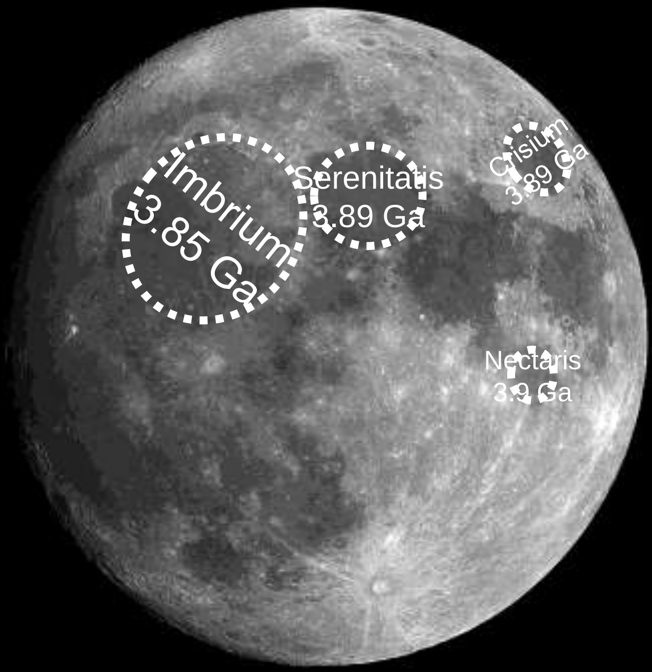
Early Earth
dominated by
impacts

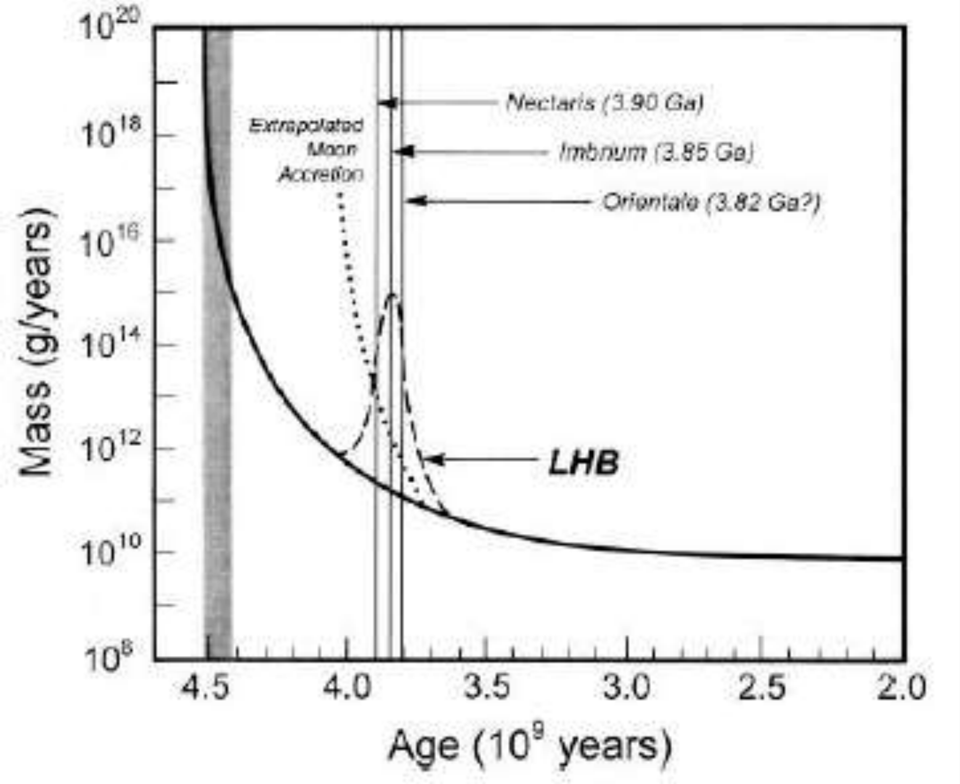
A Late Heavy Bombardment at 3.9 Ga?

- Data from Apollo rocks indicate that the Moon was subjected to intense post-accretionary bombardment between about 4.45 and 3.9 billion years ago
- Some lunar data indicate that a short and intense late heavy bombardment (LHB) period occurred around 3.9 0.1 Ga ago
- Not universally accepted

Impacts on the early Earth

- ~ 3.9 Ga: elevated meteorite flux ("LHB")
  - formation of impact basins on the Moon
  - possible destruction of Hadean crust on Earth





- Lunar highland crust formed soon after formation of the Moon
- Geochronological studies of brecciated highlands samples show impact-related thermal events concentrated at ~3.8 to 3.9 Ga.
- Ages represent either tail end of heavy but declining bombardment, or sharp and cataclysmic increase in bombardment for that short period
- Back-extrapolating masses of basin-forming projectiles accreting onto Moon at 3.8-4 Ga
- current mass of the Moon is exceeded already at about 4.1 Ga instead of 4.45 Ga
- Argues for a spike in the impact flux centered at about 3.9 Ga

Earth’s oldest crust?

- Very few rocks on Earth with ages of 3.9 Ga found
- Some rare older detrital zircon grains up to ca. 4.4 Ga
- oxygen isotopic composition in zircons indicates the presence of liquid water at about 4.2 Ga
- evidence from Nd-142 isotopic studies that Earth's upper mantle had already undergone differentiation at the time of formation of oldest rocks on Earth's surface
- Hadean Earth had thick basaltic crust, covered by an ocean, with little dry land and minor amounts of felsic rocks (granitoids)

Evidence of LHB on the Earth?

- Zircons are only record that persisted from Hadean times, other sedimentological record lost
- Search for shock effects in Hadean zircons
- Early Hadean crust may have been destroyed at around the same time that the LHB reshaped the surface of the Moon
- Zircons in Isua metasediments do not show any shock effects (Koeberl et al., 2000)

Wielicki et al., EPSL (2012):

Ti-in-zircon thermometry indicates an average of 773 °C for impact-produced zircon, ~100 °C higher than the average for Hadean zircon crystals.

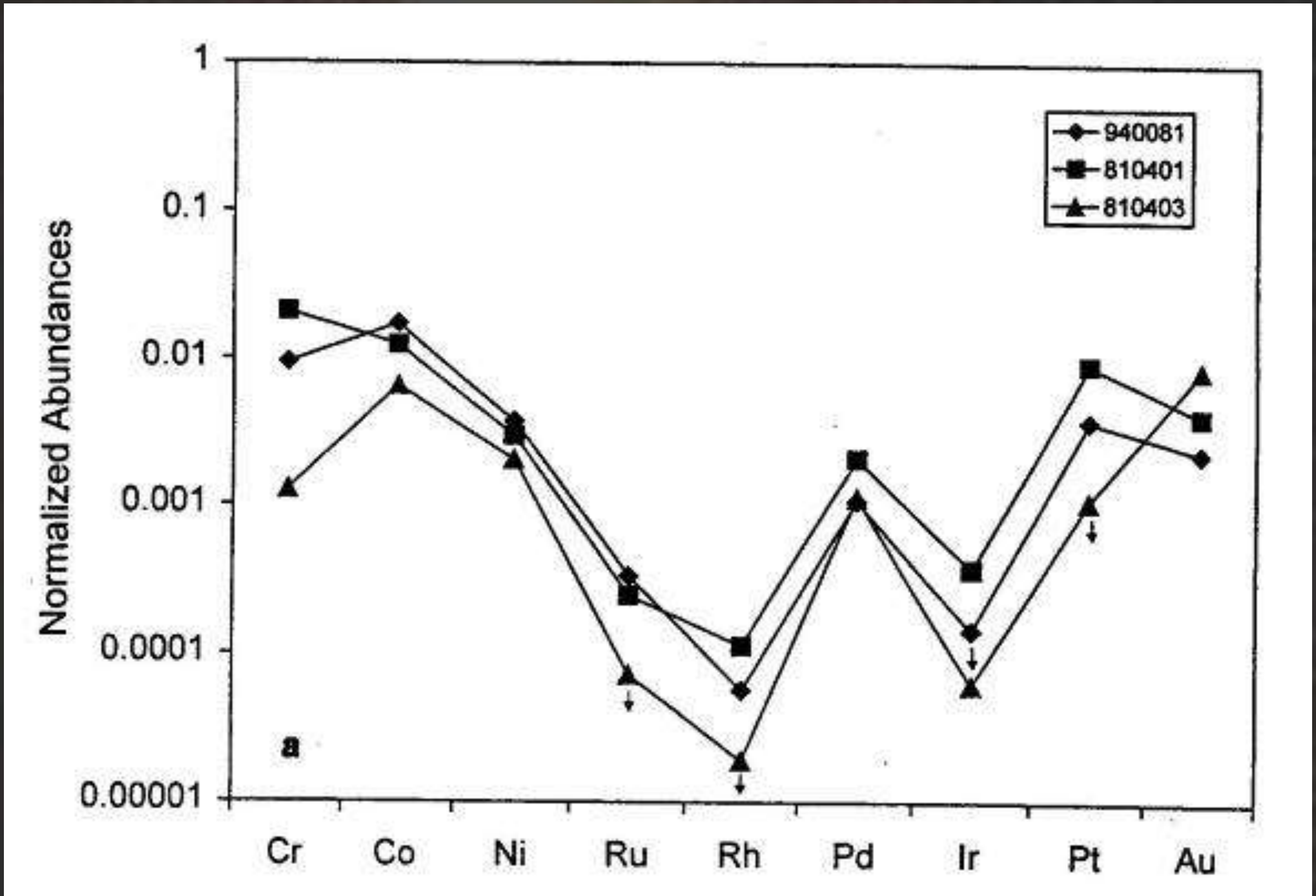
The agreement between whole-rock based zircon saturation temperatures for impactites and Ti-in-zircon thermometry implies that Ti-in-zircon thermometry record actual crystallization temperatures for impact melts.

Zircon saturation modeling of Archean crustal rock compositions undergoing thermal excursions associated with the Late Heavy Bombardment predicts equally high zircon crystallization temperatures.

The lack of such thermal signatures in the Hadean zircon record implies that impacts were not a dominant mechanism of producing the preserved Hadean detrital zircon record.

Evidence of LHB on the Earth?

- Attempt to find a possible extraterrestrial component, similar to what is observed in some ejecta layers (PGE abundances)



Koeberl et al. (2000)

But the results are the same:

Even though the Ir abundances reach a few hundred ppt, the chondrite-normalized PGE abundance data do not show any clear evidence for a meteoritic component

- Tungsten (W) isotopic studies by Schoenberg et al. (2002) supposedly indicate extraterrestrial component in ca. 3.85 Ga metasedimentary rocks from Greenland
- Difficult to understand why a similar signal would not show up in the PGE abundances - W is not common in meteorites

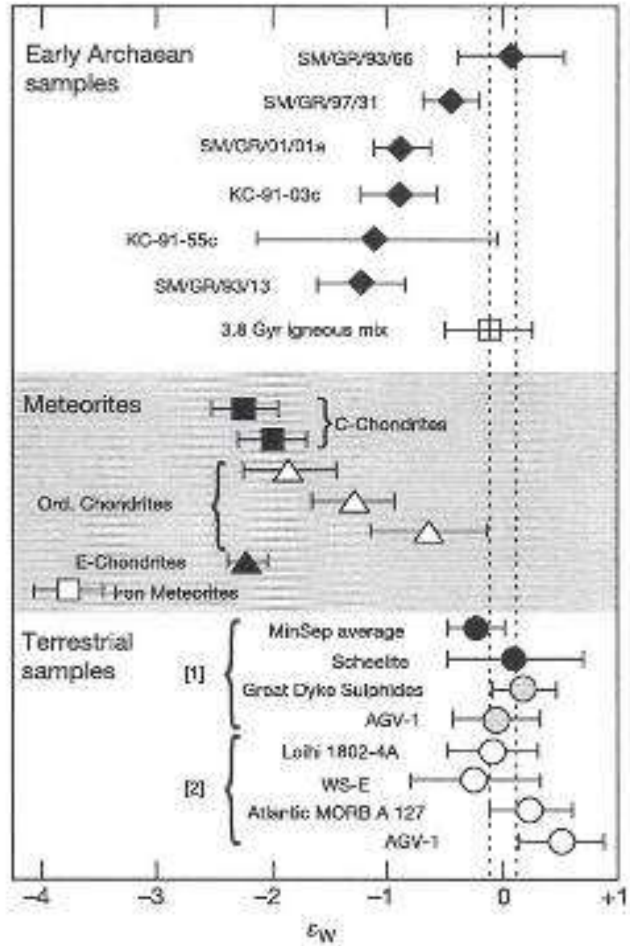
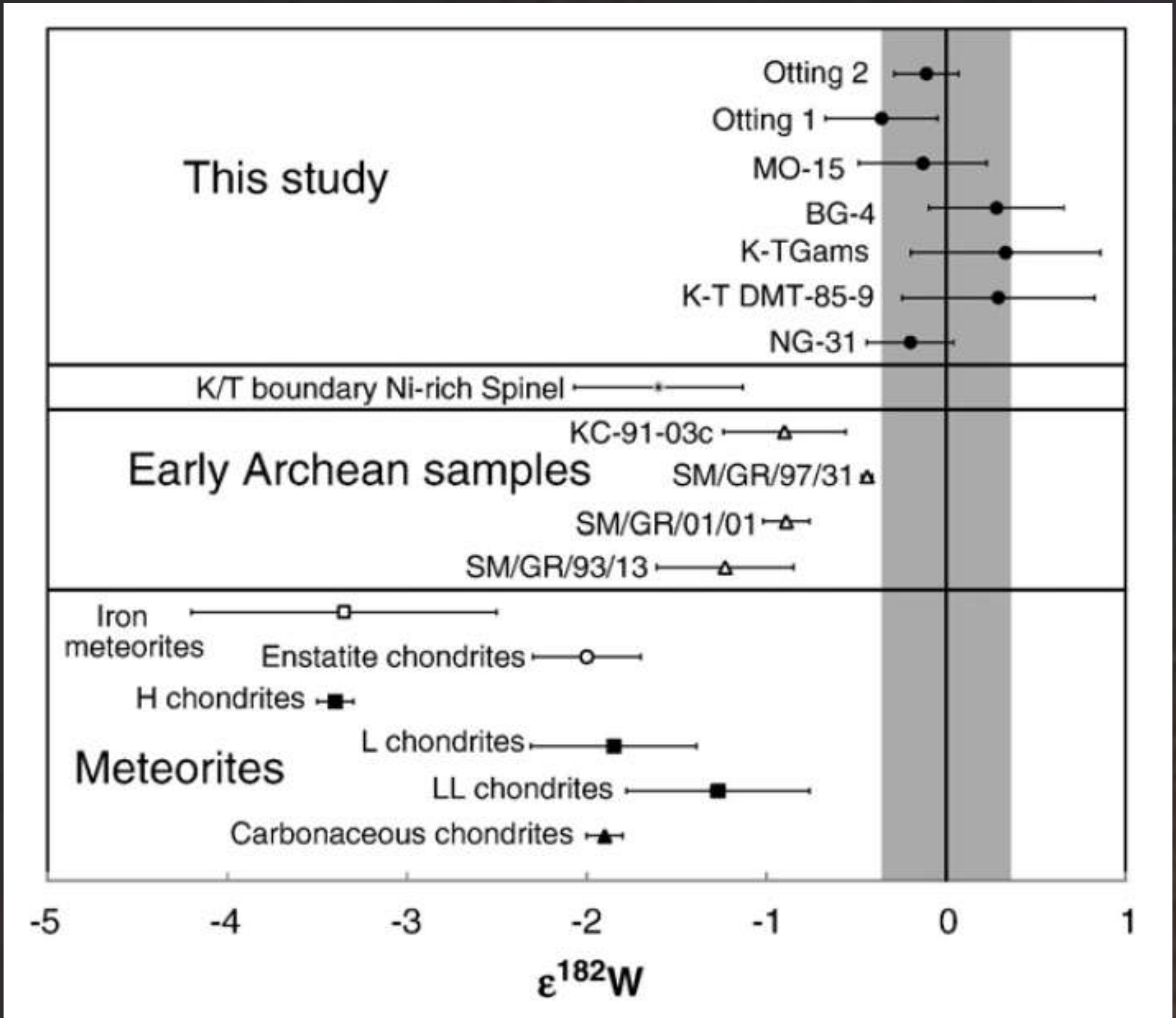


Figure 1 Values of ε_W for terrestrial rocks, meteorites and early Archaean samples relative to the composition of a tungsten standard, ACQUIRE-W. Dashed lines show 2 s.d. of mean uncertainty envelope of the standard ($n = 46$). Grey circles, terrestrial samples measured previously[7]; filled circles, present results (Table 1). Results highlighted with [1] were analysed at the University of Queensland. Open circles, previously published[8,21] terrestrial samples. Results highlighted with [2] were analysed at the University of Michigan. Open square, average of published iron meteorites[9]; filled triangle, average of bulk rock enstatite chondrites[10]; open triangles, bulk rock ordinary chondrites[12]; filled squares, new data for Allende carbonaceous chondrite[7,12]. Crossed square, average early Archaean crust (text and Table 1); filled diamonds, early Archaean metasediments (text and Table 1). External error (22 p.p.m.) was assigned to samples with smaller internal errors.



Moynier, Koeberl, Quitté, Telouk – EPSL (2010)

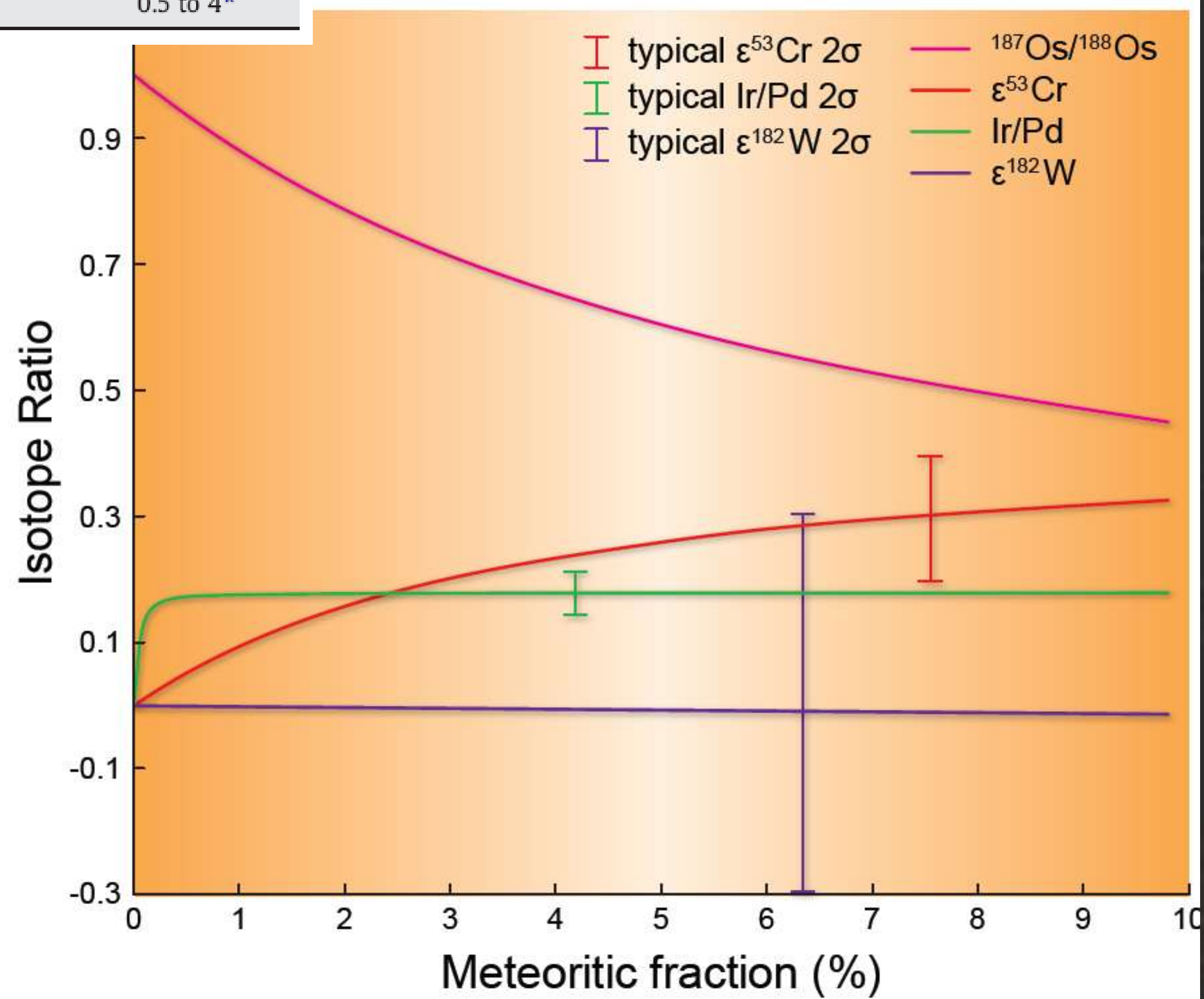
Analysis of known impact deposits clearly shows the absence of any W isotopic anomalies – casting severe doubt on measurements and/or interpretation of earlier Isua data

Table 1
W isotopic compositions and concentrations in the Earth crust, chondrites, and iron meteorites.

Sample name	$\varepsilon^{182}W$	[W] (ppm)
Average terrestrial crust	0	1.29[a]
Carbonaceous chondrites	-1.90 ± 0.10[b]	0.089[c]
LL chondrites	-1.27 ± 0.51[d]	0.128[d]
L chondrites	-1.85 ± 0.46[d]	0.110[e]
H chondrites	-3.4 ± 0.10[f]	0.160[e]
Enstatite chondrites	-2.3 to -1.7[g]	0.115 to 0.140[g]
Iron meteorites	-4.2 to -2.5[h,i,j]	0.5 to 4[k]

Moynier, Koeberl, Quitté, Telouk – EPSL (2010)

Even when percent-level abundances of extraterrestrial material is present, W isotopes show no measurable effect



additional problem:

Quote from Willbold et al., Nature (2011):

to meteoritic additions[22]. Our work also includes one of the samples (SM/GR/97/31) analysed by ref. 20 but we find that it has a positive $\varepsilon^{182}W = 0.14 \pm 0.05$ (2 s.e.; Table 1). Therefore, we share the puzzlement of others[15,22] over the reported negative $\varepsilon^{182}W$ values for Isua metasediments[19] and we suggest they are likely to be analytical artefacts.

Impacts and early life…

- It is quite possible that life started as soon as environment became safe enough, which means as soon as there were liquid water on the surface (4.4 or 4.2 Ga)

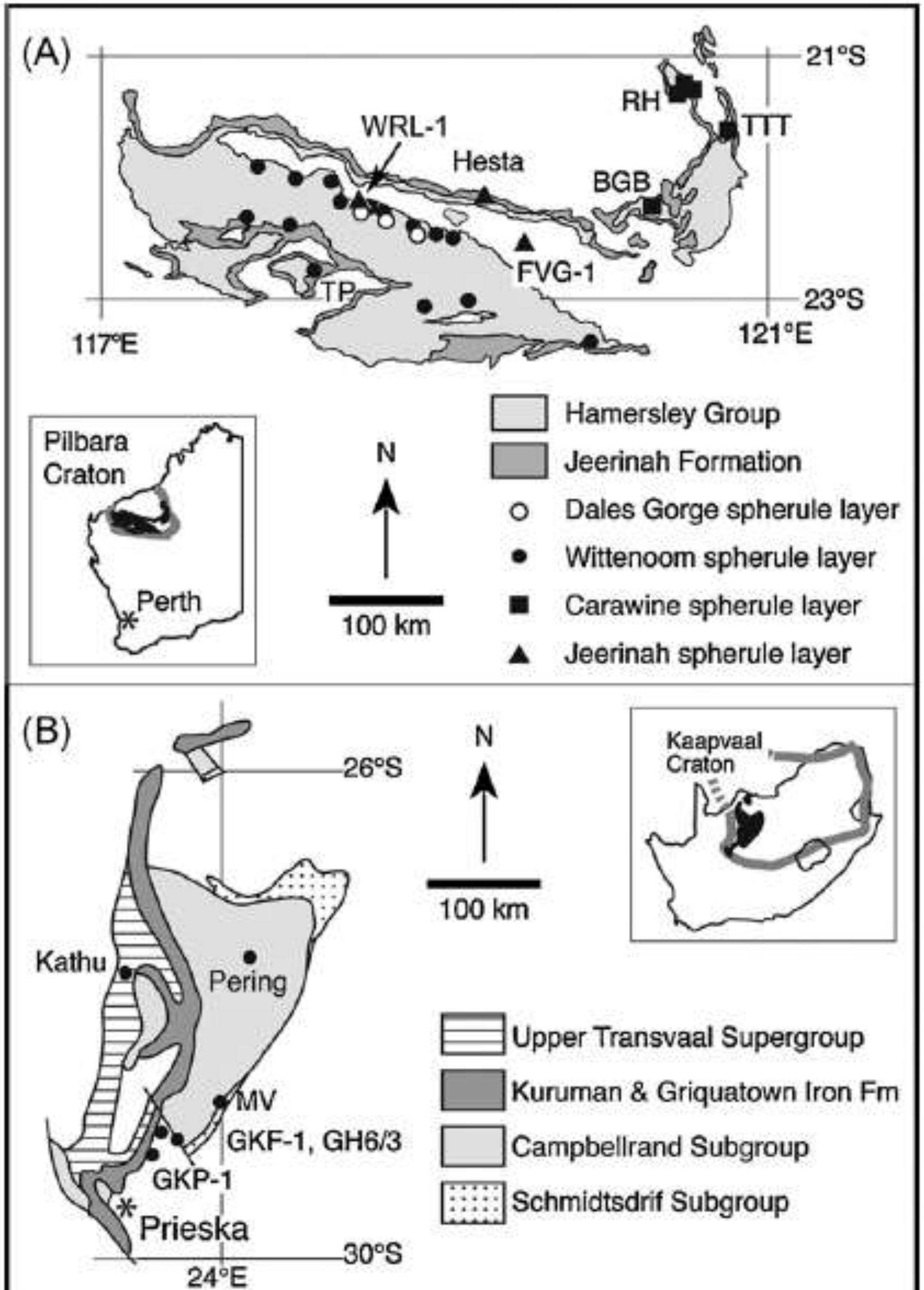
- Recent studies show that it is not necessary to “wait” for life to originate after the LHB because of the “sterilization” that such an event could have caused

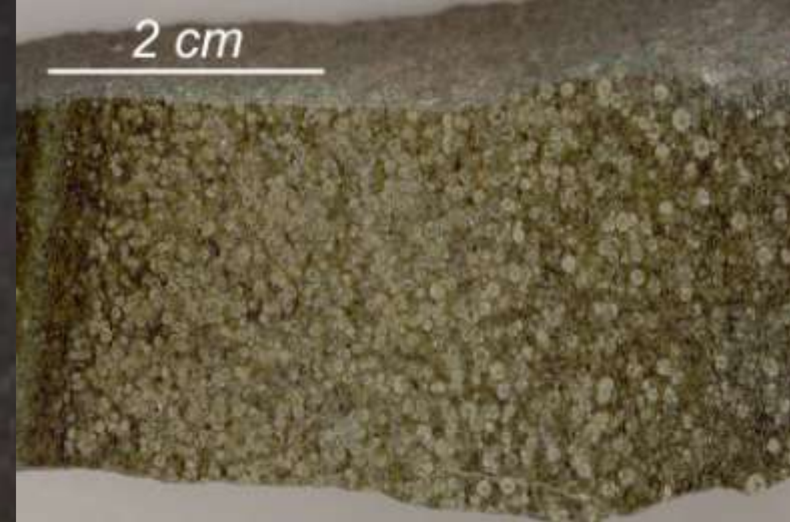
- Imbrium-sized impactor could have had only 1% of the energy required to evaporate Earth’s ocean and it could have boiled off up to 40m of sea surface water (destroying life in only that part of water column)

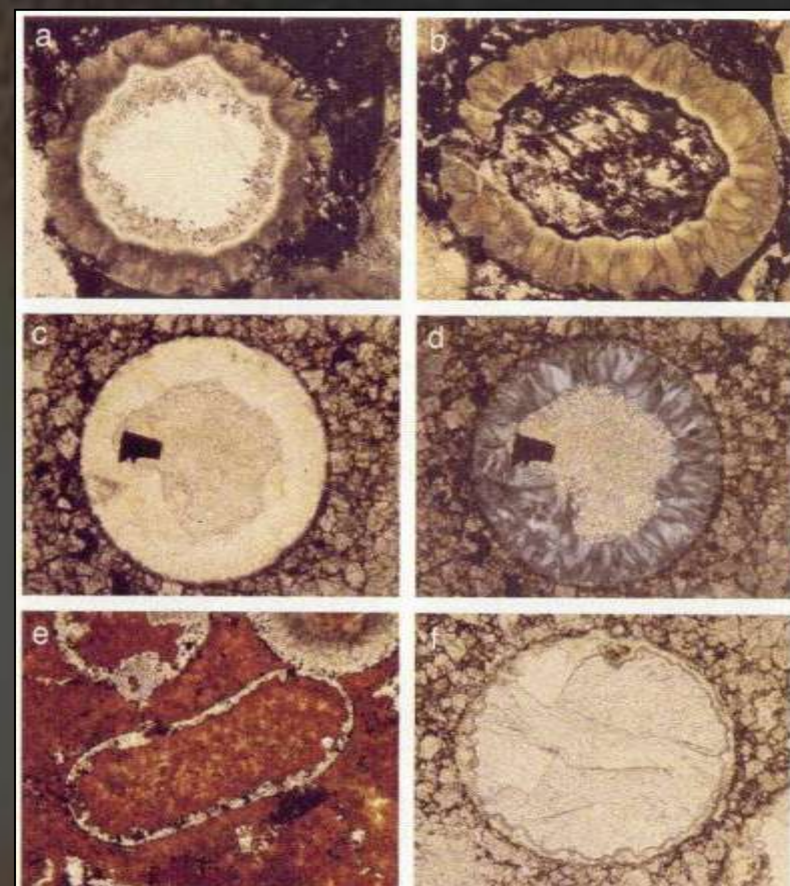
Later (Early Archean) Impacts:

- 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

Barberton Greenstone Belt, South Africa


(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
b
c
d
e
f

Earliest Impact Craters Preserved on Earth

The oldest we have…

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

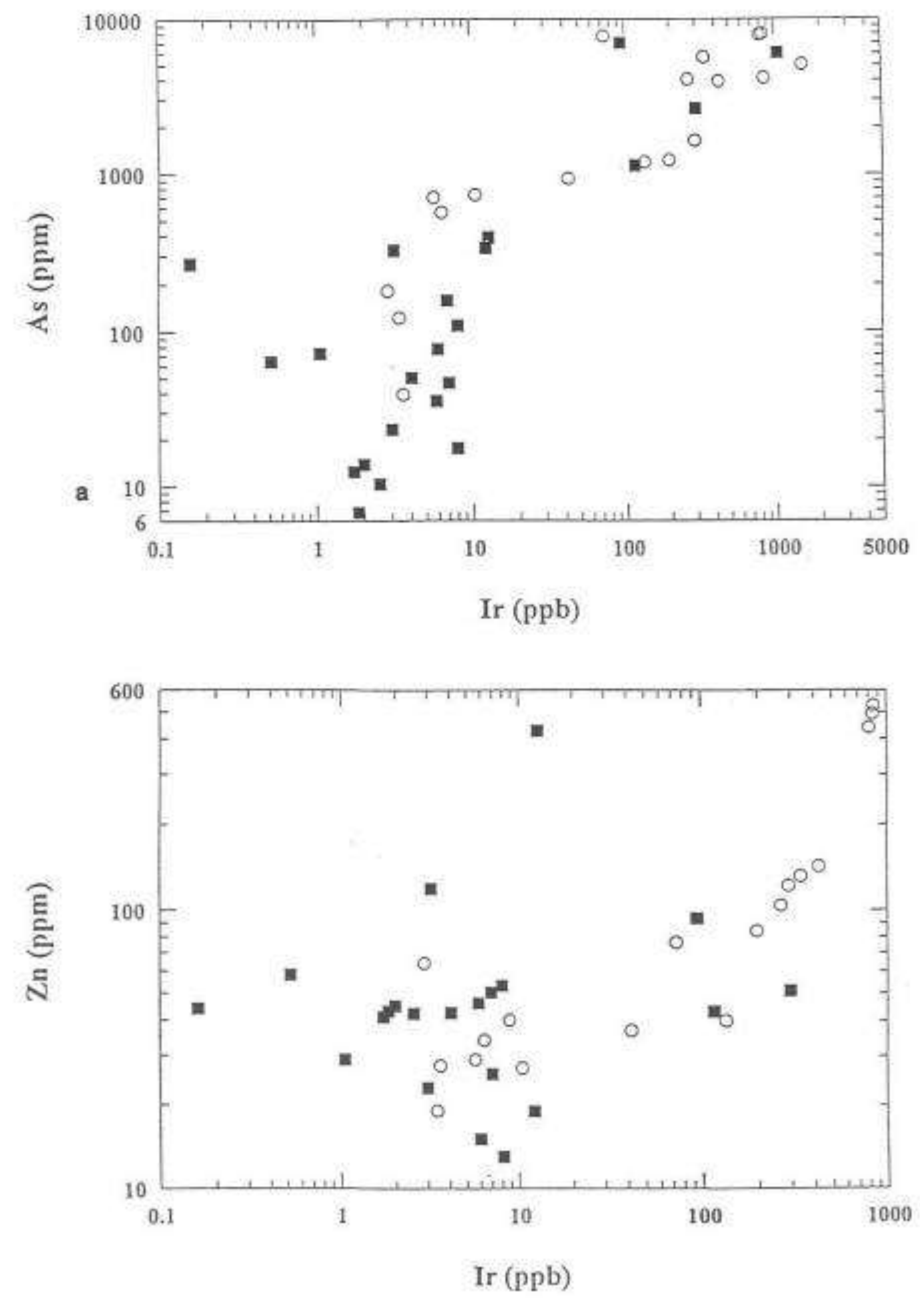
  The Vredefort Dome is an ~80 km wide relict of the central uplift of a complex crater (D=200-300 km); high-graded late Archean-Paleoproterozoic gneisses; variety of impact-related features (shatter cones, coesite, stishovite, PDFs, impact melt breccias)

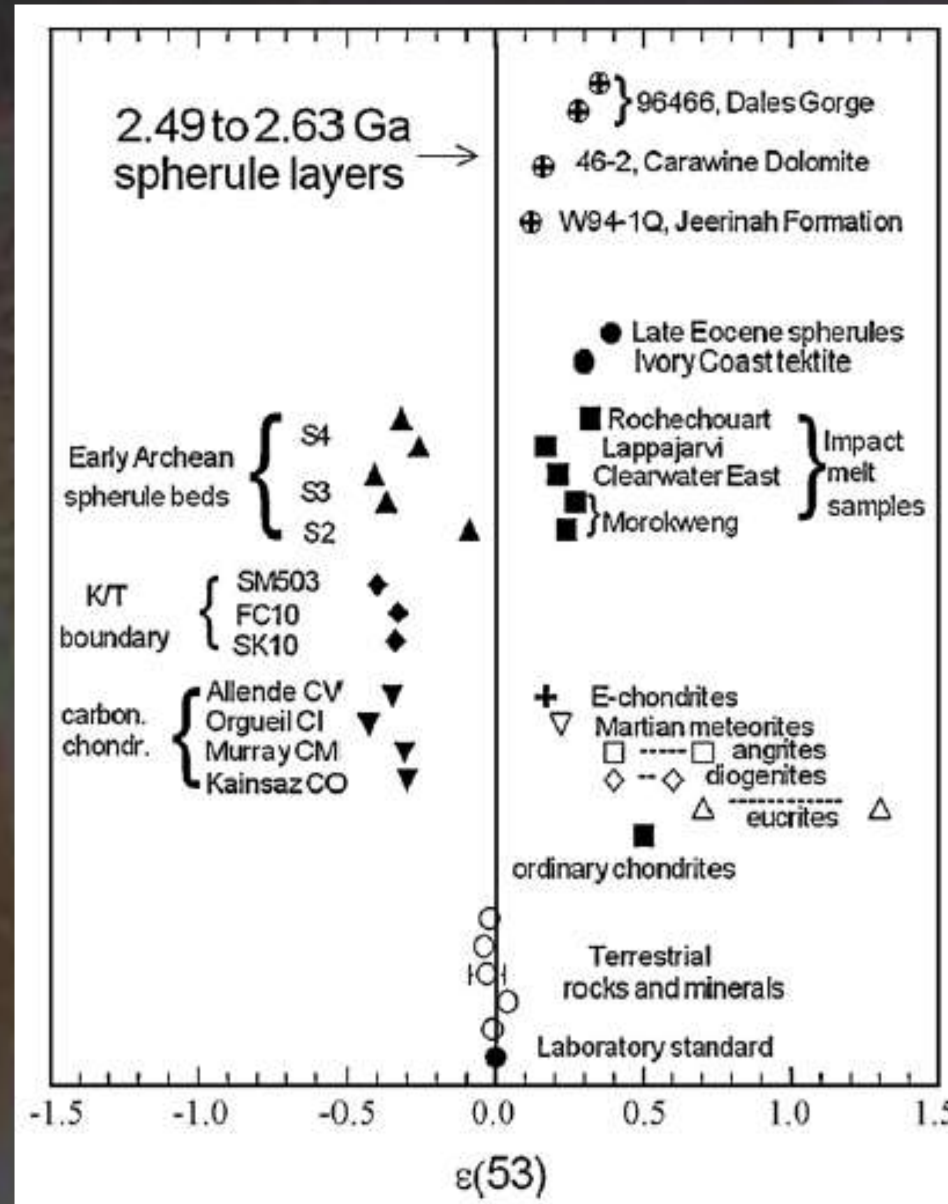
  Absence of a crater and fallback breccias suggest that intensive erosion has taken place (5-10m of post-impact deposits were removed); no ejecta have been found yet

- **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)





Ir contents up to 5x chondritic - but Cr isotopes indicate meteoritic component

- No definitive criteria for the identification of Archean impact deposits
- No source crater found for any of the South African or Australian spherule layers
- Scarcity of the early Archean geological record makes it is likely that it will never be found
- Unclear why impact events in Archean predominantly produce large volumes of spherules – are absent from post-Archean impact deposits (for which source craters are known)

Summary

- Oldest impact crater on Earth is 2.02 Ga Vredefort
- For “next” billion years impact record on Earth is quite sparse (both for craters and ejecta layers)
- Impact record on Earth is limited:

    nothing for the first billion years,

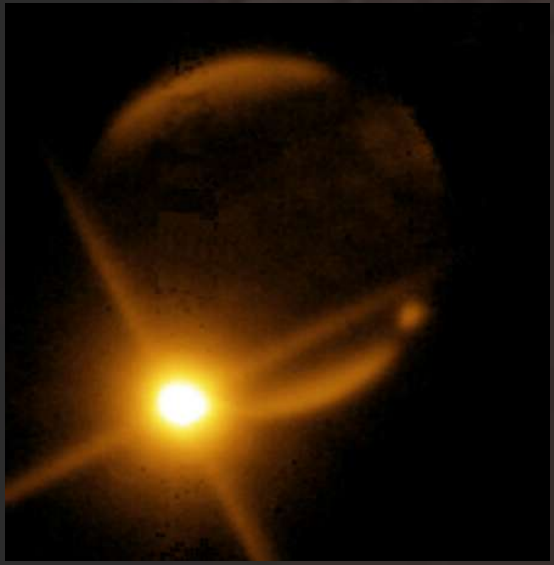
    some spherule layers 3.4 - 2.5 Ga

    impact craters <2 Ga

- But study of spherule layers aids in discussion of importance of impact events for very early Earth
- The “early” impact record on Earth, which spans more than half of the age of our planet, is still a wide-open field of research

Implications for Exoplanets

- Impacts on exoplanets must have been of similar importance as in the early solar system
- Difficult to detect – however, Flagg et al. (2016; Icarus) note that impacts similar to those of Comet Shoemaker-Levy 9 might be detectable on exoplanets in the near-infrared in the methane band near 2.3 μm
- Observing cometary impacts in young systems, and finding out how often they occur, could have implications for our own Solar System.




Thank you!