The Last Paper of Warren B. Hamilton

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Over the last year of his life, Warren focused on writing a synthesis paper he viewed as the culmination of his career.

He knew this was a race against time.

Time won that race, but just barely. When Warren passed away in October 2018, he left behind a 39,000-word manuscript, which he considered to be 95% complete.

Still, much was undone. The draft lacked an abstract or conclusion. Several sections consisted of just headings, or a few lines of notes. It had not been edited or reviewed.

Gillian Foulger took on the heroic task of bringing this work to publication. Keith Howard, Donna Jurdy, Anne Hofmeister, Robert Criss, Barbara John and Toby Rivers gave valuable assistance. Comments by James Natland and an anonymous reviewer helped to improve the final draft.

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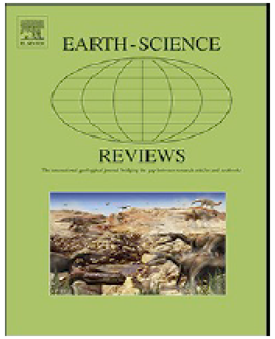

Toward a myth-free geodynamic history of Earth and its neighbors

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“I recognize that my comments are outspoken.
At the same time I have no illusion of personal infallibility.”

- Earth's **Archean** was the era of *internally mobile crust*. TTG crust formed by hydrous melting of mafic protocrust leaving dense, depleted, garnet-rich residue that delaminated and sank, beginning re-enrichment of the mantle. Archean granite and greenstone crust has no modern analogue.
- **Proterozoic** dynamics, driven by vertical variations in density, reflect the *deposition and collapse of basins*. Paleomagnetic data cast doubt on the existence of a strong dipole magnetic field at that time. Only in the late Proterozoic did a weak asthenosphere develop over which lithospheric plates could slide.
- The **Phanerozoic** has been the *era of plate tectonics*. Lithosphere motions documented by paleomagnetism suggest Earth's dipole magnetic field may have developed at ~600 Ma. The Cambrian explosion in which most modern phyla evolved may have required its shielding against radiation.

- In modern Earth, hinges migrate oceanward as subducting slabs sink to 660 km beneath overriding plates. Plate boundaries change radically, *incompatible with plume-driven tectonics*.

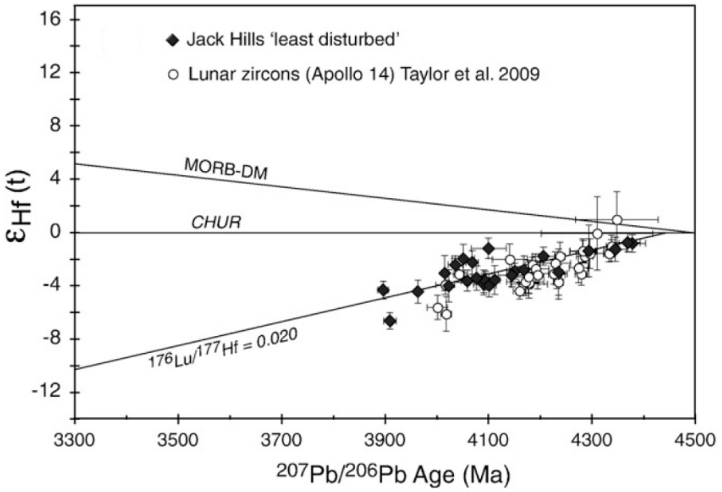
- Earth, Mars, Venus & Moon fractionated by 4.5–4.4 Ga. Bombardment saturated surfaces with craters & pools of impact-melted mafic protocrust that fractionated into layered igneous complexes.

- Mars, Venus & Moon retain ancient, impacted surfaces. They lack asthenospheres or liquid cores, and cannot sustain plate tectonics.

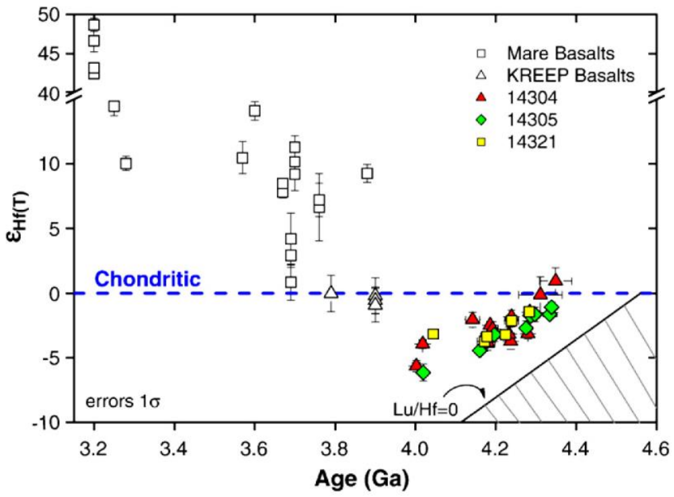
- *Variants of plume theory have been inappropriately exported to these planets.*

- Volatiles reached inner planets with icy bombardments starting ~4.0–3.9 Ga. Ocean remnants survived for 2–3 b.y. on Venus, and ~1 b.y. on Mars.

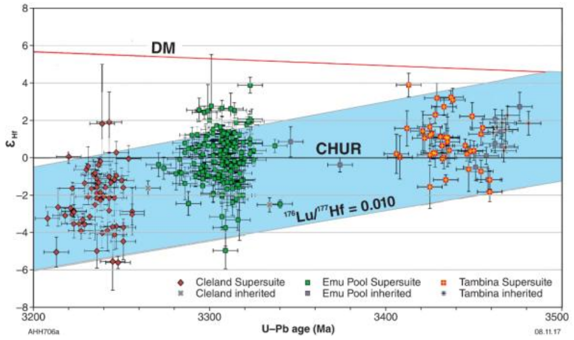
- Only Earth was internally hot & active enough to circulate volatiles downward enabling hydrous melting, slow re-enrichment of the upper mantle and, **at ~600 Ma, plate tectonics and rapid biological evolution.**

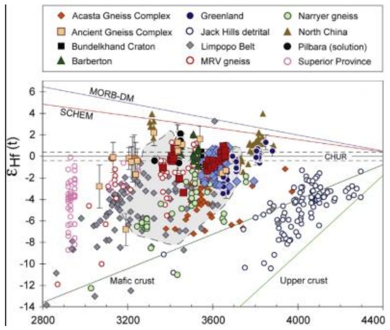


These conclusions synthesize evidence from hundreds of studies, also *new analysis of lutetium/hafnium systematics.*



Earth, the Moon and Mars show Hf-isotopic evidence for similar histories of anhydrous very early fractionation.





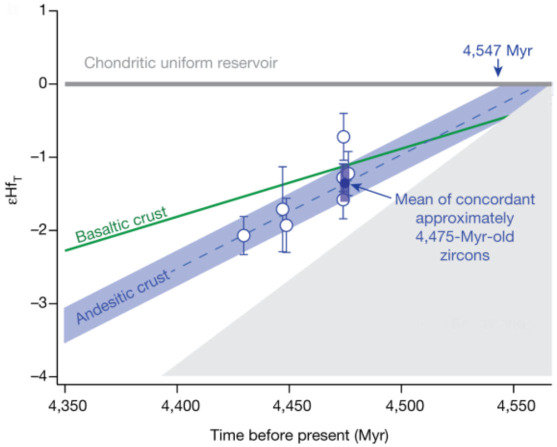


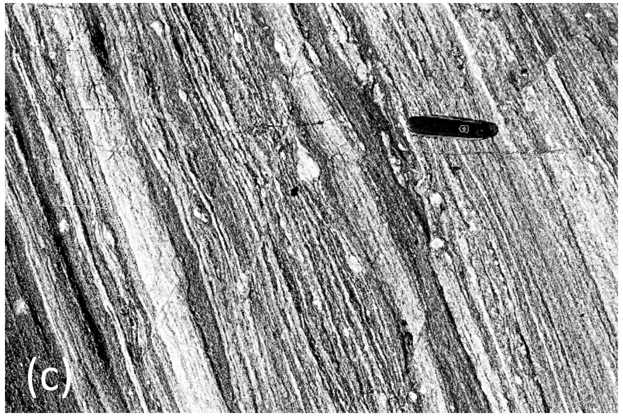
Fig. 2. Earth, the Moon and Mars show Hf-isotopic evidence for similar histories of anhydrous very early fractionation. Earth and the Moon show in Hf data a later bombardment by volatile-rich material. Ages young to the left in these diagrams. The down-to-the left slopes of εHf(t) of data points > ~3.9 b.y. in panels (a), (b), (c) and (e) show those points to represent samples partly melted from mafic and thus crustal rocks and not from hypothetical ultramafic mantle rocks. The high εHf (t) < ~3.9 b.y on Fig. 3b, c, and d represent a large influx of bolides with high ^{176}Lu, Hf and water. (a) Hf isotope-time systematics of the best-constrained Hadean zircons (age > 3.9 b.y.) of Earth. Horizontal scale is ^{207}Pb/^{206}Pb age of zircon in m.y. (b) Global compilation of Earth's Archean and Hadean zircons. Much of the wide scatter of points of Archean and Hadean age includes many poorly constrained post-3.9 b.y. determinations but red squares and blue diamonds are high-quality data from Pilbara Archean craton of Western Australia. Diagonal line to lower left corner of (b) is that of the linear array in (a). (c) Lunar zircons from impacts on the Moon. I interpret (b) and (c) to show that both Earth and the Moon received a barrage of hydrous and high-Lu C-chondrite and icy bolides starting about 3.95 ± 0.05 b.y. ago. (d) Hf isotope-time systematics of Archean TTG and granite zircons from the Mt. Edgar dome, NE Pilbara craton, Western Australia. These granitoids cannot have come from slowly depleting fertile mantle, as conventional interpretation claims, because sub-Archean-crust mantle was already depleted dunite. (e) Hf isotopetime systematics of zircons from a Martian impact-breccia meteorite. These zircons record ages of impact(?) melts of Martian mafic crust that had formed by about 4.50 b.y. ago. (Sources: (a) from Kemp et al., 2010, (b) from Kemp et al., 2015, (c) from Taylor et al., 2009, (d) from Gardiner et al., 2018 and (e) from Bouvier et al., 2018).

They also draw heavily on Warren's own fieldwork around the world.

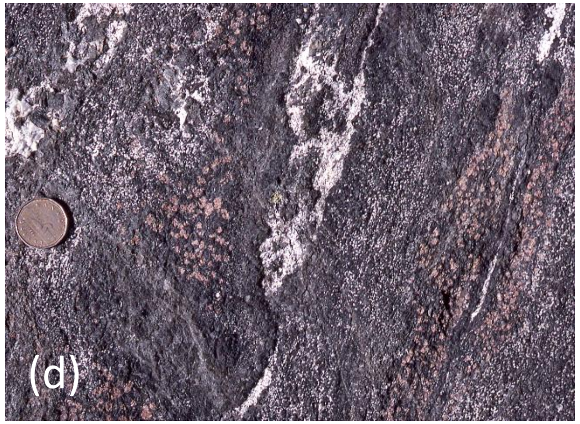
(a)

Much Archean TTG-dominated lower crust shows high mobility continuing for ~1 b.y.

(b)



(c)



(d)

Fig. 4. Much Archean TTG-dominated lower crust shows high mobility continuing for 1 b.y. or so, with both synmagmatic and synmetamorphic flattening and complex intershearing of diverse types. (a) Extreme ductile mixing of lower-crust Archean TTG and other rock types, SW Greenland. Systematic dating and mapping have not been done in such Greenland tracts. Scattered zircon ages are mostly 3.8–3.0 b.y., and younger ones, to 2.7 b.y., are subordinate. Dismembered amphibolitized dikes (black) are 3.5–3.2 b.y. old where dated elsewhere in the region. Photograph by Victor McGregor, location about 10 km southeast of Nuuk. (b) polycyclic migmatite of tonalite, hornblendite, pegmatite and fragments of dark dikes, (c) migmatite mylonitized at high temperature of midcrustal Acasta gneiss, basement to Neoarchean greenstone sections. These and nearby outcrops have yielded zircons, including xenocrysts, with U-Pb ages scattered from 4.2 to 2.9 Ga (e.g., Bowring et al., 1990; Iizuka et al., 2007) and record>1 b.y. of crustal mobility. From Acasta Lake, west-central Slave craton, northwest Canada. (d) xenoliths of garnet-clinopyroxene granulite (possible protocrust densified by extraction of TTG melts?) and hornblendic garnet-free reaction rocks in basal TTG crust, at the eastern base of Proterozoic Kapuskasing uplift, Superior craton, Canada. Photos (b)–(d) by the author.

Observations from space probes inform the planetary conclusions.

Mars global dichotomy — analogue for early Earth?

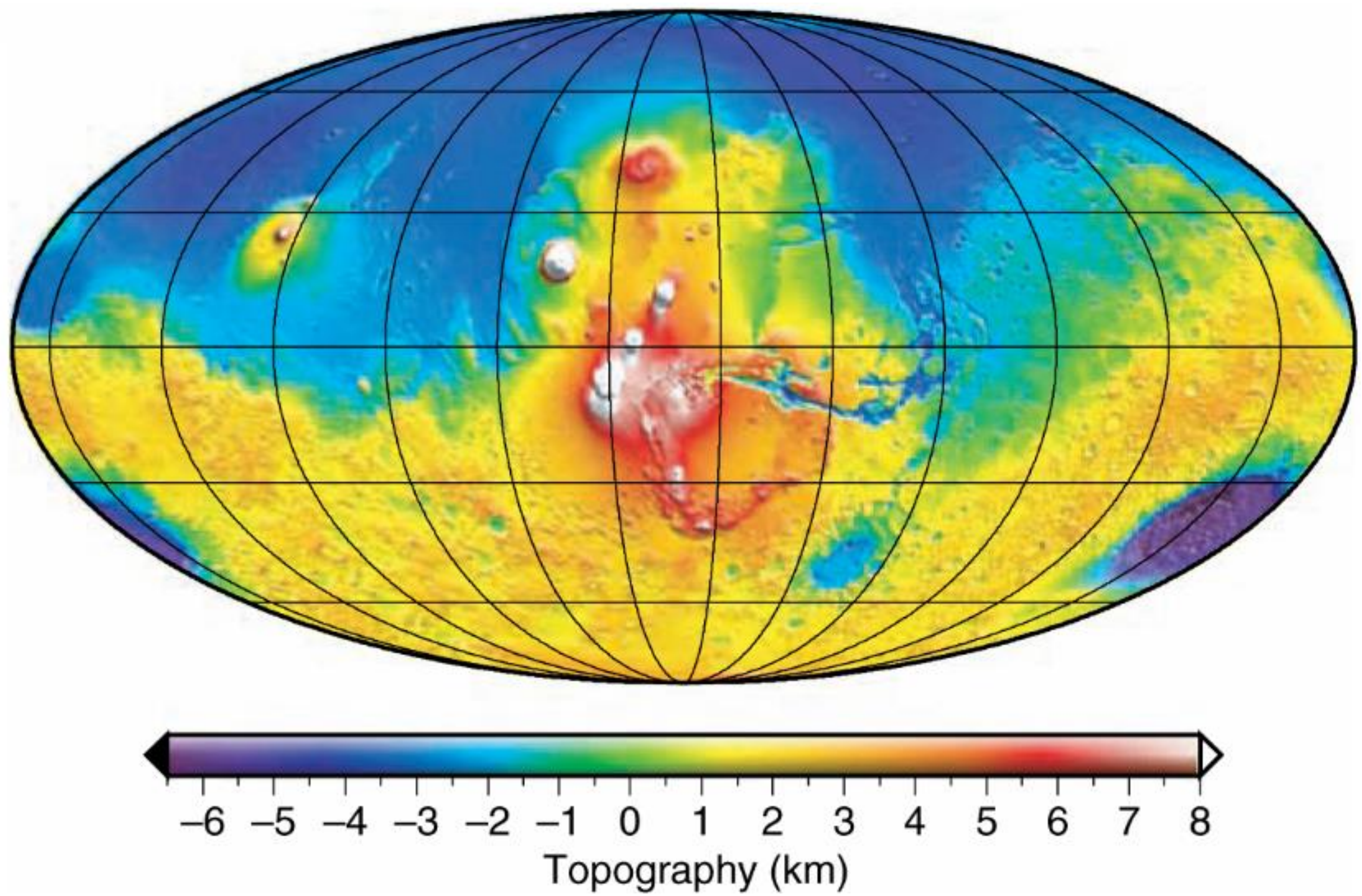


Fig. 7. Topographic map of Mars. The lower altitude of the northern half of the planet compared with the southern half may be the product of a massive impact during accretion. Earth perhaps developed a similar bimodal topography from loss of the material that makes up the Moon, by impact or spinoff, during accretion. Map by Wieczorek, 2007.

First-order field observations do not support plume theories, instead suggesting that plate motions are driven primarily from the top down, as lithosphere cools & sinks.

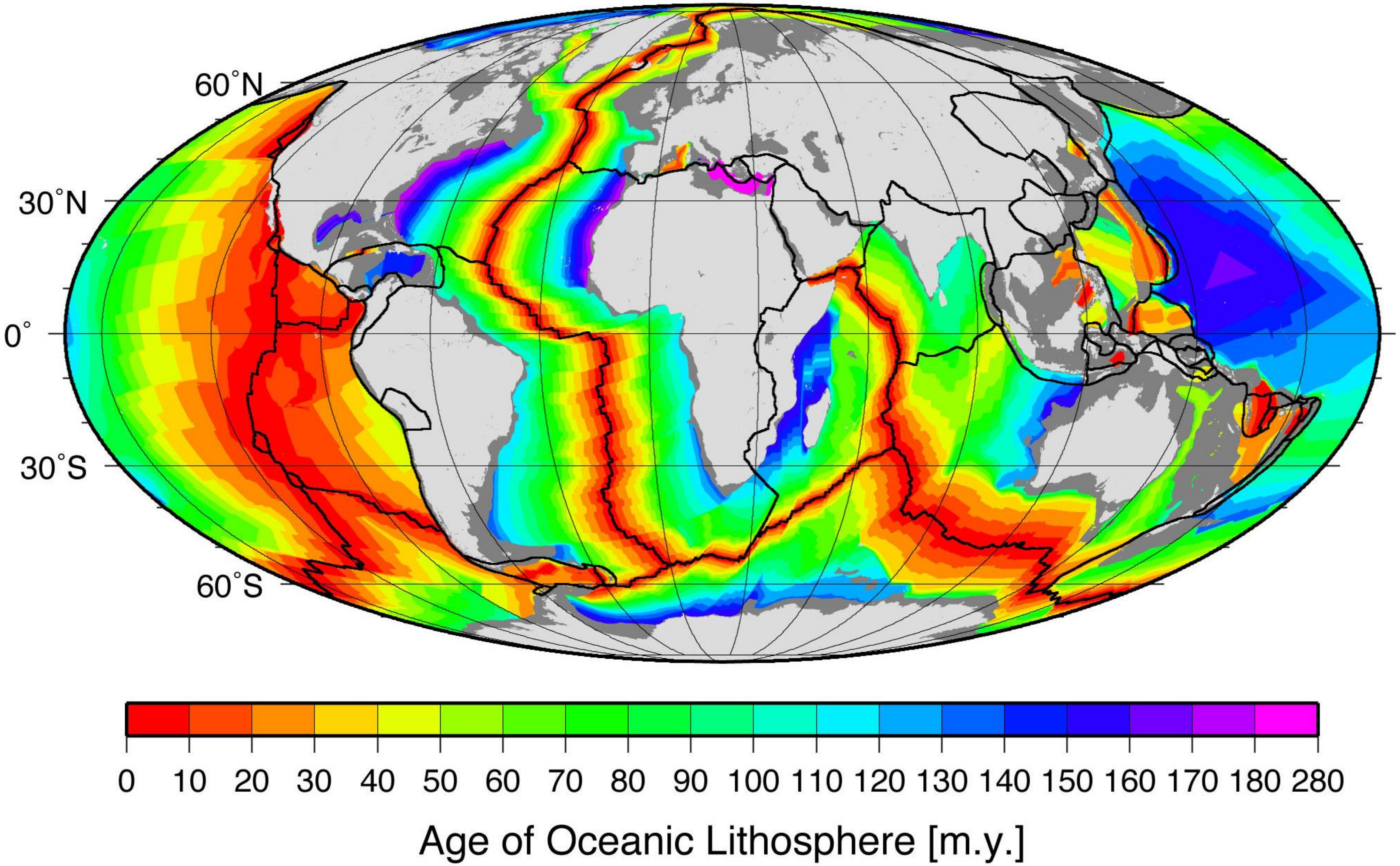
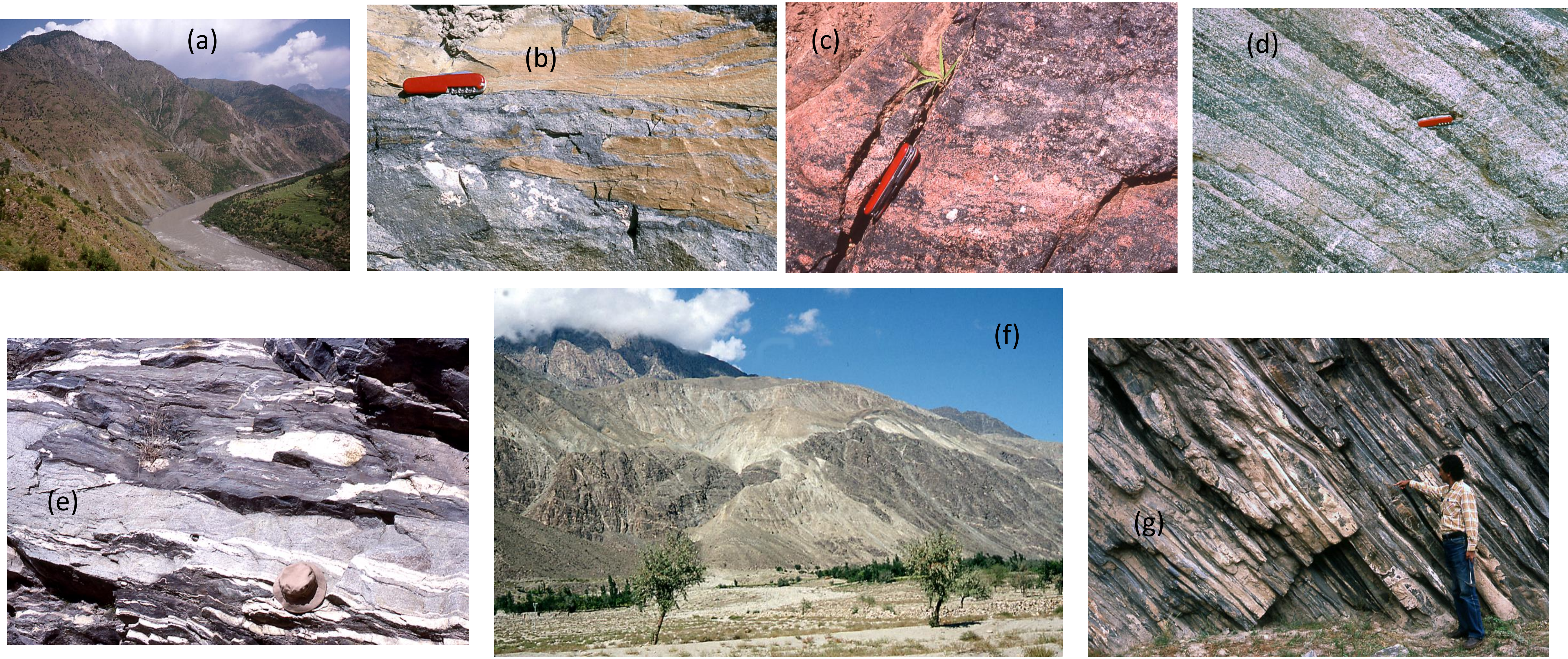


Fig. 17. Age of oceanic lithosphere with generalized plate boundaries. Conventional geodynamics is incompatible with several first order features of plate tectonics. Where collisions of continents or arcs with each other are not involved (as they are from Gibraltar through the Middle East and Southeast Asia to Melanesia) subduction trenches mark the sinking of oceanic lithosphere and advance of overriding plates. Subduction trenches are not fixed, downgoing plates do not slide down inclines and overriding plates do not crumple against fixed hinges as in popular cartoons. The nonsubducting Atlantic is slowly growing at about the same areal rate as the fast-spreading Pacific is shrinking as a result of peripheral subduction around its rim. The Antarctic plate is surrounded by spreading centers and grows as they migrate away from it. The African plate is growing as a result of spreading centers on three sides. Major plate boundaries greatly change shapes and lengths while migrating huge distances, a fact that may be overlooked in over-simplistic presentations of plate tectonics. Map by National Geophysical Data Center, NOAA, from 2007, with data by R.D. Muller, M. Sdrolias, G. Gaina, and W.R. Roest.

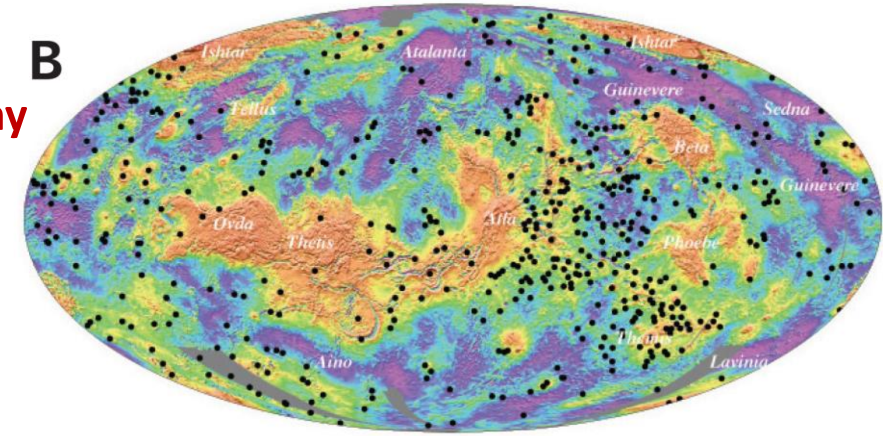


Phanerozoic crustal sections in Pakistan — much different from Archean

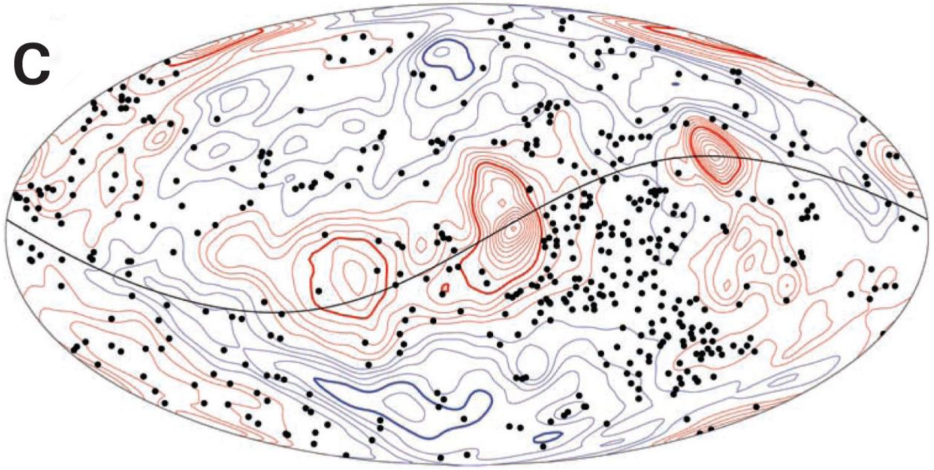
Fig. 20. Rock types illustrating petrologic development of the Kohistan Cretaceous island arc, north Pakistan. (a): The Moho. Dunite-rich mantle on left, garnet-rich basal crust on right. (b): Mantle rock, brown-weathering dunite and gray clinopyroxenite, part of arc-magmatic construct, not old mantle? (c): Garnetite of basal crust. (d): Flow-layered norite, main rock of thick mafic underplate; mantle melt, the main heat engine for partial melting of lower crust. (e): Granite factory—ancient arc rock above norite, now restitic hornblende-rich rock and partial-melt sodic granite formed from it. (f): small granitoid plutons aggregated above granite factory. (g): Highest rock preserved in section, flattened pillow basalt. Photographs by author.

The 1970s conjectures of terrestrial plumes were exported to Mars and Venus. However, those planets are fundamentally different from Earth. They lack plate tectonics, so new rationales were developed — often contrary to geologic evidence.

Venus **topography**



Venus **geoid**



Earth **geoid uncorrelated with topography**

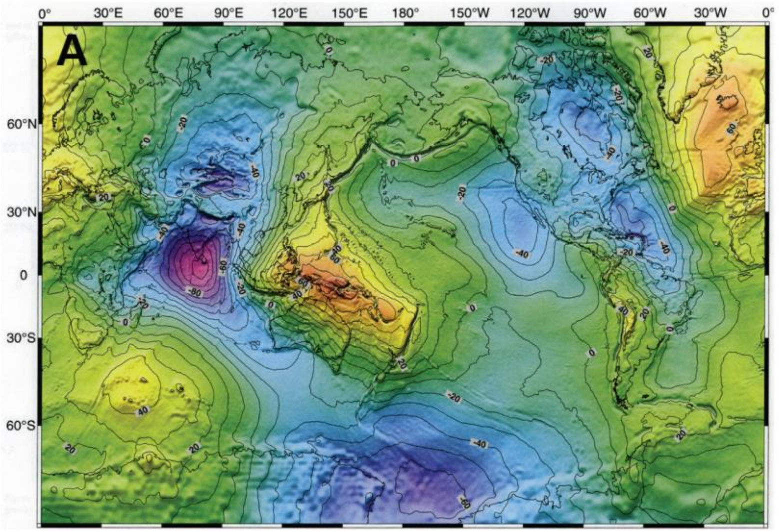


Fig. 29. Earth geoid compared to Venus topography and geoid. A, terrestrial geoid, 10m contours, blue and purple low, green/yellow/brown high. Earth's topography is mostly compensated isostatically at upper-mantle depths and shows almost no correlation with the geoid except at very short wavelengths. B, Venusian topography, and C, geoid correlate directly over a broad range of wavelengths. Thus, topography cannot be compensated primarily by earthlike variations in upper mantle structure and density. Venusian geoid height shown by 10 m contours, 0 not shown, red positive, blue negative; spherical harmonic degrees 2–30 are fully retained but a roll-off is applied to degrees 30–60. Venus maps are centered on the equator and longitude 180 . Dots on Venus maps mark the small proportion of large rimmed circular structures designated as “coronae” in conventional reports and assumed to be pushed up by plumes. Nearly all of the more abundant similar structures in lowland areas are omitted. A provided by David Sandwell, and B and C by Catherine Johnson, who also supplied the topographic altitude scale for B, corrected from that published by Johnson and Richards (2003).

All photographs we have of Venus' surface appear to show flat, thinbedded, fine-grained sediments, not lava flows.

Fig. 24. Optical-scanner image of Venusian plains made by Soviet lander Venera (Venus) 14. Scan rotates from distant left horizon to distant right horizon (visible in top corners) via steeply downward look at foot of lander on which teeth are 2 cm apart. Russian observers interpreted this and other lander images to depict flat, thinbedded, fine-grained sediments, recrystallized under the hot atmosphere (Basilevsky et al., 1985) and I concur. However, most current literature contends that the rocks are non-earthlike, very smooth basalt flows. Image provided by Russian Academy of Sciences.

Magellan radar backscatter (A) poorly registers topography. Nadir-radar altimetry (B) reveals ancient landscape with *1,000s of sediment-filled craters*.

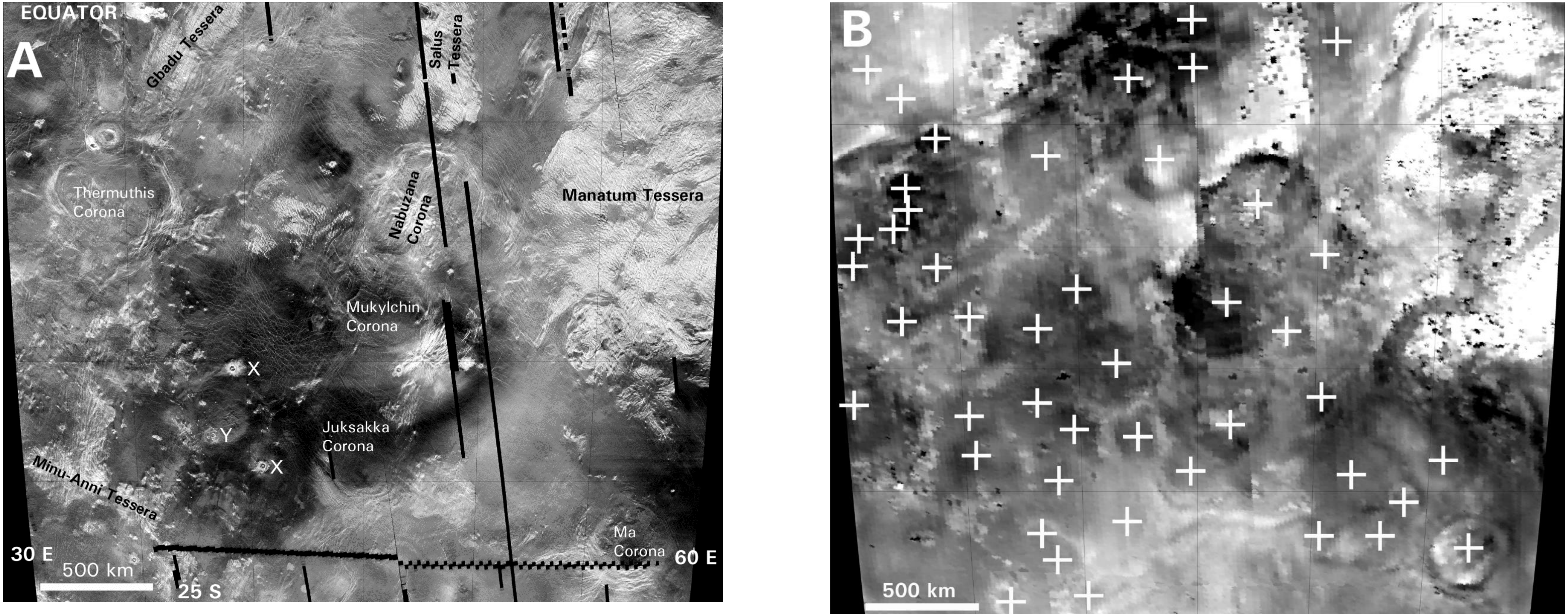
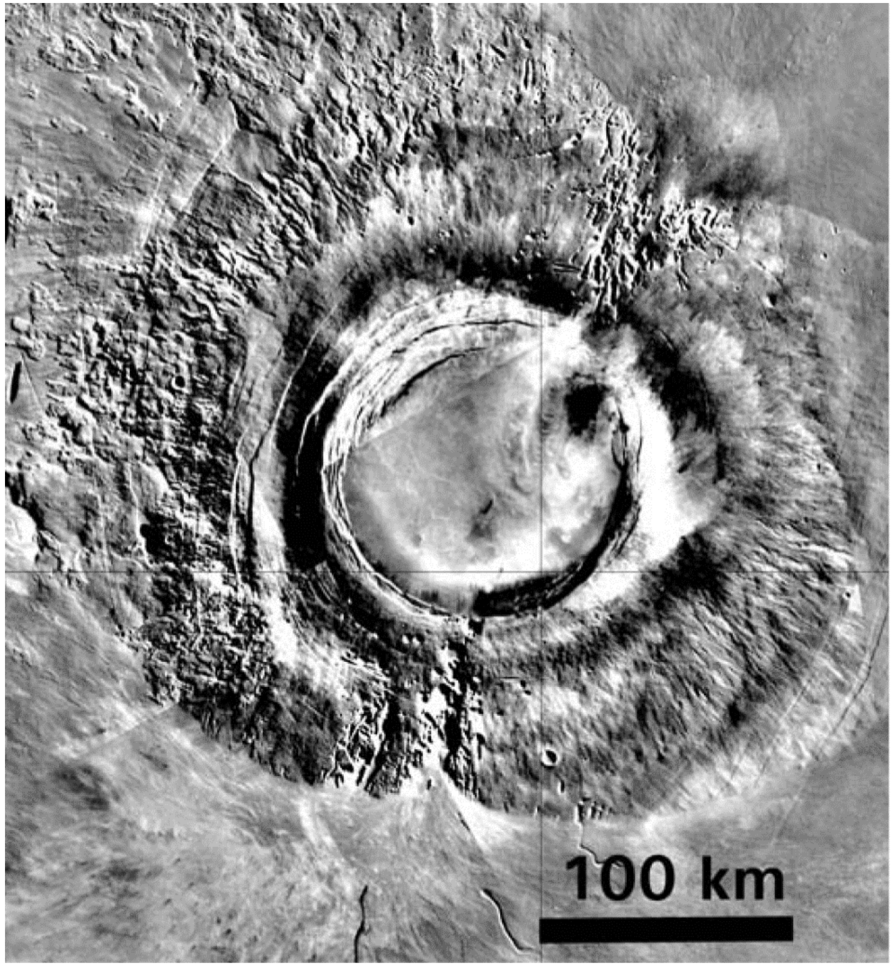


Fig. 27. Contrasted visibility of ancient Venusian lowland impact structures on maps of A, radar backscatter brightness (rough surfaces are light, smooth are dark; topography registers poorly; shows little structure) and B, nadir-radar topography (dark is low, white is high; shows much more information) of same area. My interpretation is that ancient crust was saturated by overlapping large and small impact craters before about 3.9 Ga, cratered landscape was flooded by water released by volatile-bolides bombardment and marine sediments mostly covered old craters and were compressed into them. White crosses mark many craters. Upland in NE, an impact-melt construct(?) is only indented by impacts, not saturated by them, so is younger than plains basement. Magellan mosaics by USGS of area from 0° to 25°S, and 30° to 60°E; total relief ~3 km.

Martian “volcanoes” are often said to resemble Hawaii. But these broad, circular, single-peak structures *do not resemble Hawaii at all*.



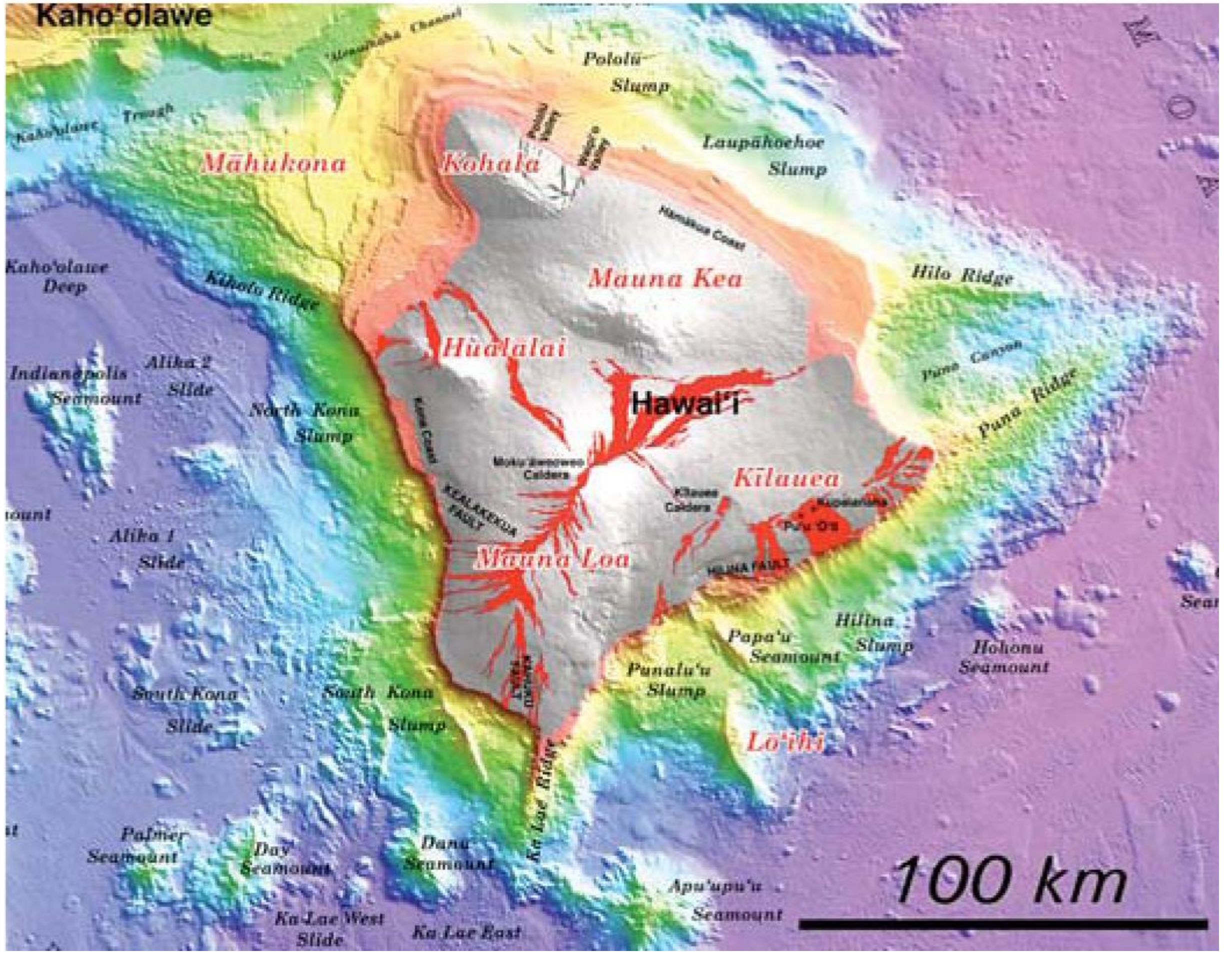


Fig. 23. Martian impact-melt construct Arsia Mons compared with Hawaii. Each rises ~9 km from its base, Arsia from Tharsis plateau, Hawaii from Pacific Ocean floor. Top: Arsia Mons “volcano”. Its huge, shallow, circular caldera is as large as irregular Hawaii is above sea level and sagged into an enormous mass of shallow melt. Arsia is centered at ~9°S, 239°E; composite Viking Orbiter imagery by USGS. Bottom: island of Hawaii, gray above sea level; historic lava flows, mostly erupted from dikes along gravitationally widening lateral rifts, are in red; ocean depths are colored deepening to magenta and are ~5.5 km deep. Hawaii is a composite of five volcanoes at the surface and grew by frequent small increments of magma over a few million years. Shallow subsurface melt never covered a large area and the largest caldera is only ~4 km across. Edges of map: 154° and 157°W, and 18.5° and 20.5°N; map from Eakins et al. (2003). The assumptions that Martian “volcanoes” closely resemble Hawaii, and that Hawaii sits atop a deep-mantle plume, provide the basis for the popular model of Mars geodynamics.

Known ages of some features associated with plate tectonics (after Stern et al. 2016), provide evidence that *plate tectonics began about 600 Ma*.

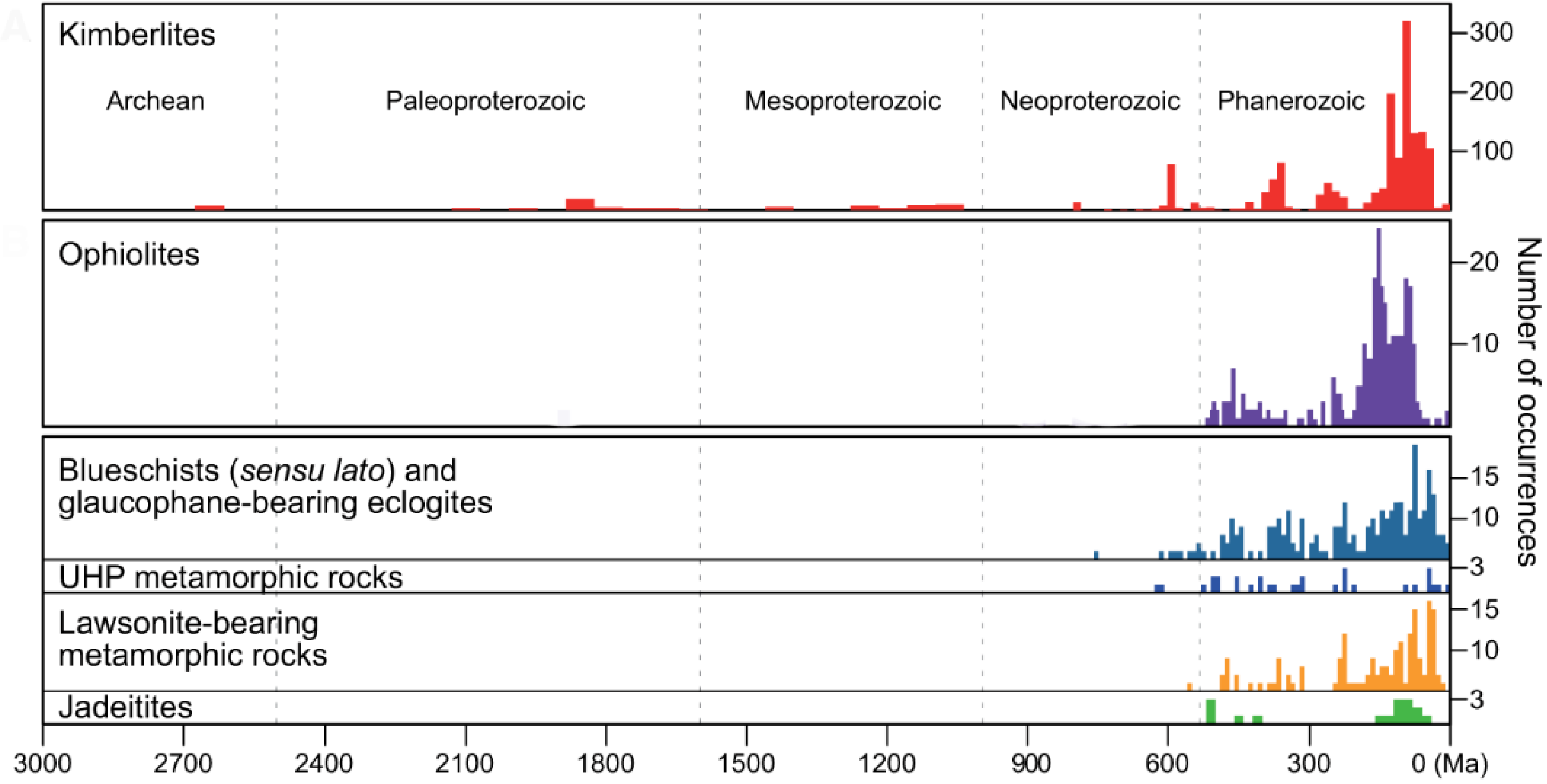
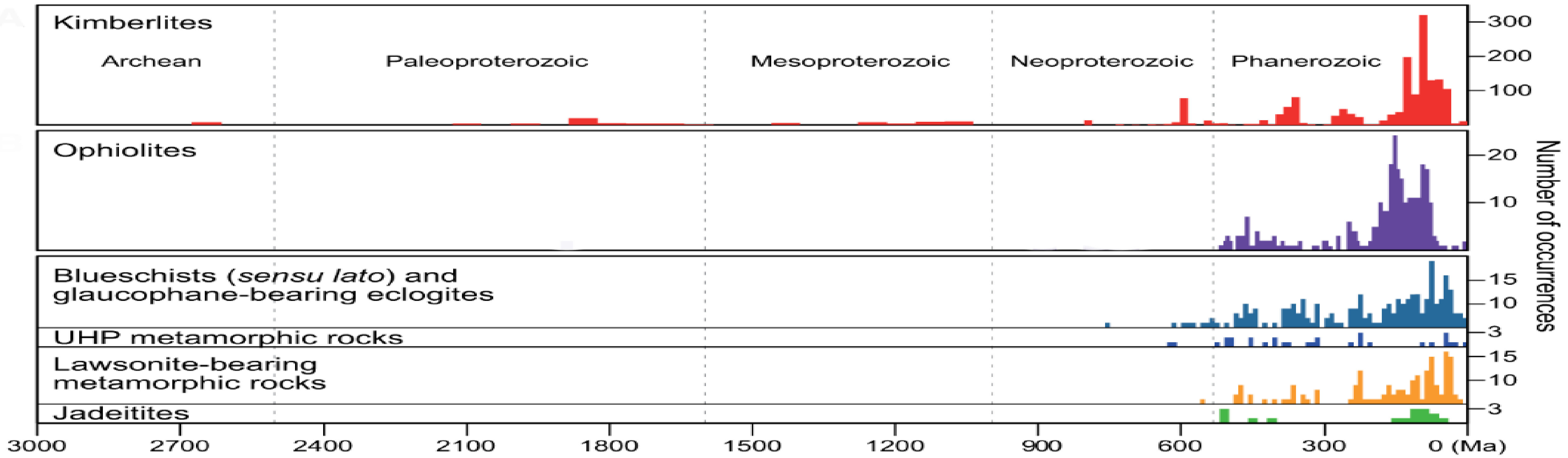
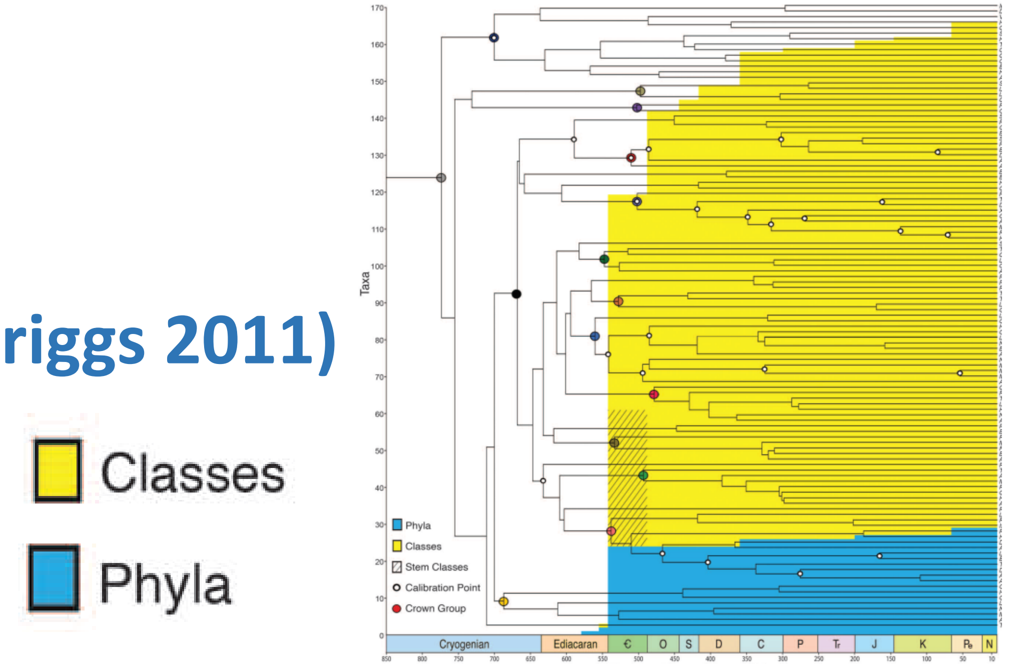


Fig. 1. Known ages of some features associated with plate tectonics, after Stern et al. (2016), provide powerful evidence that plate tectonics began about 600 m.y. ago. Kimberlites formed mostly after plate-tectonic recycling was well underway and likely mostly record top-down re-fertilization of early-fractionated lithospheric mantle by hydrated slabs subducted to or beneath the asthenosphere. All classical ophiolites are included. Stern et al.'s published diagram applied a dubious locally-expanded definition of “ophiolite” to add several very different Meso- and Neo-Proterozoic assemblages which I have removed here.



Indicators of plate tectonics (modified/Stern et al. 2016)

Origin & diversification of animals (Briggs 2011)



- The approximate coincidence of the Ediacaran biological leap with the onset of plate tectonics makes a connection between them possible.
- The link may be that Earth's asthenosphere and strong dipolar magnetic field both originated then, as a result of torques and frictional heating from Sun/Earth/Moon orbital mechanics.
- Asthenosphere enabled plate tectonics, and influenced convection in the outer core.
- This in turn allowed differential core motions and development of an inner core and internal strong dipolar magnetic field, shielding Earth's surface and enabling evolution.

Recent advances in orbital understanding and paleomagnetic evidence suggest such speculative ideas.

But much more information of course is needed to test them.

Why does Earth have plate tectonics, while Venus and Mars do not? In this paper he was coming around to a view that *the elephant in the room is the Moon.*

Also: If Earth, Venus & Mars received oceanic quantities of water through impacts ~4 Ga, the Moon likely did so as well —
giving rise to its own short-lived seas.