Tectonics 2023

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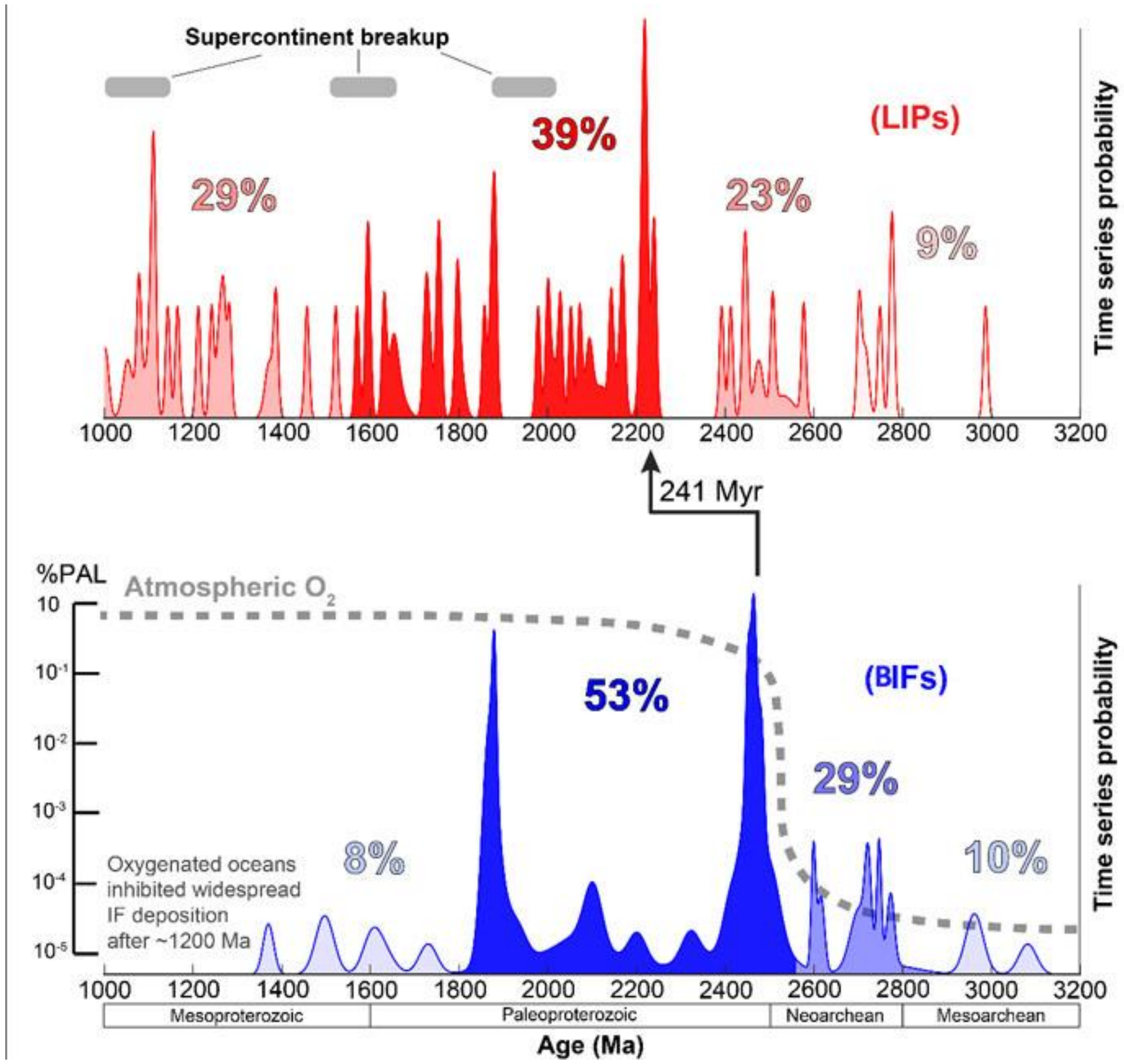
Did Precambrian BIFs 'fall' into the mantle to trigger mantle plumes?

PUBLISHED ON *June 15, 2023*

How the Earth has been shaped has depended to a large extent on a very simple variable among rocks: their density. Contrasts in density between vast rock masses are expressed when gravity attempts to maintain a balance of forces. The abrupt difference in elevation of the solid surface at the boundaries of oceans and continents – the Earth's hypsometry – stems from the contrasted densities of continental and oceanic crust: the one dominated by granitic rocks (~2.8 t m^{-3}) the other by those of basaltic composition (~ 3.0 t m^{-3}). Astronomers have estimated that Earth's overall density is about 5.5 t m^{-3} – it is the densest planet in the Solar System. The underlying mantle makes up 68% of Earth's mass, with a density that increases with depth from 3.3 to 5.4 t m^{-3} in a stepwise fashion, at a number of discontinuities, because mantle minerals undergo changes induced by pressure. The remaining one third of Earth's mass resides in the iron-nickel core at densities between 9.5 to 14.5 t m^{-3}. Such density layering is by no means completely stable. Locally increased temperatures in mantle rocks reduce their density sufficiently for masses to rise convectively to be replaced by cooler ones, albeit slowly. By far the most important form of convection affecting the lithosphere involves the resorption of oceanic lithosphere plates at destructive margins, which results in subduction. This is thought to be due to old, cold oceanic basalts undergoing metamorphism as pressure increases during subduction. They are transformed at depth to a mineral assemblage (eclogite) that is denser (3.4 to 3.5 t m^{-3}) than the enveloping upper mantle. That density contrast is sufficient for gravity to pull slabs of oceanic lithosphere downwards. This **slab-pull force** is transmitted through oceanic lithosphere that remains at the surface to become the dominant driver of modern plate tectonics. As a result, extension of the surface oceanic lithosphere at constructive margins draws mantle upwards to partially melt at reduced pressure, thus adding new basaltic crust at mid-ocean rift systems to maintain a form of mantle convection. Seismic tomography shows that active subducted slabs become ductile about 660 km beneath the surface and below that no earthquakes are detected. Quite possibly, the density of the reconstituted lithospheric slab becomes less than that of the mantle below the 660 km discontinuity. So the subducted slab continues by moving sideways and buckling in response to the 'push' from its rigid upper parts above. But it has been suggested that some subducted slabs do finally sink to the core-mantle boundary, but that is somewhat conjectural.

Typical banded iron formation

There are sedimentary rocks whose density at the surface exceeds that of the upper mantle: banded iron formations (BIFs) that contain up to 60% iron oxides (mainly Fe_2O_3) and have an average density at the surface of around 3.5 t m^{-3}. BIFs formed mainly in the late Archaean and early Proterozoic Eons (3.2 to 1.0 Ga) and none are known from the last 400 Ma. They formed when soluble iron-2 (Fe^{2+}) – being added to ocean water by submarine hydrothermal activity –was precipitated as Fe^{3+} in the form of iron oxide (Fe_2O_3) where oxygen was present in ocean water. With little doubt this happened only in shallow marine basins where cyanobacteria that appeared about 3.5 Ga ago had sufficient sunlight to photosynthesise. Until about 2.4 Ga the atmosphere and thus the bulk of ocean water contained very little oxygen so the oceans were pervaded by soluble iron so that BIFs were able to form wherever such biological activity was going on. Conceivably (but not proven), that BIF-forming biochemical reaction may even have operated far from land in ocean surface water, slowly to deposit Fe_2O_3 on the deep ocean floor. After 2.4 Ga oxygen began to build in the atmosphere after the Great Oxidation Event had begon. That time was also when the greatest production of BIFs took place. Strangely, the amount of BIF in the geological record fell during the next 600 Ma to rise again to a very high peak at 1.8 Ga. Since there must have been sufficient soluble iron and an increasing amount of available oxygen for BIFs to form throughout that 'lean' period the drop in BIF formation is paradoxical. After 1.0 Ga BIFs more or less disappear. By then so much oxygen was present in the atmosphere and from top to bottom in ocean water that soluble iron was mostly precipitated at its hydrothermal source on the ocean floor. Incidentally, modern ocean surface water far from land contains so little dissolved iron that little microbiological activity goes on there: iron is an essential nutrient so the surface waters of remote oceans are effectively 'wet deserts'.



Plots of probability of LIPs and BIFs forming at the Earth's surface during Precambrian times, based on actual occurrences (Credit: Keller, et al., modified Fig 1A)

Spurred by the fact that if a sea-floor slab dominated by BIFs was subducted it wouldn't need eclogite formation to sink into the mantle, Duncan Keller of Rice University in Texas and other US and Canadian colleagues have published a 'thought experiment' using time-series data on LIPs and BIFs compiled by other geoscientists (Keller, D.S. *et al.* 2023. **Links between large igneous province volcanism and subducted iron formations**. *Nature Geoscience*, v. **16**, article; DOI: 10.1038/s41561-023-01188-1.). Their approach involves comparing the occurrences of 54 BIFs through time with signs of activity in the mantle during the Palaeo- and Mesoproterozoic Eras, as marked by **large igneous provinces** (LIPs) during that time span. To do this they calculated the degree of correlation in time between BIFs and LIPs. The authors chose a minimum area for LIPs of 400 thousand km^2 – giving a total of 66 well-dated examples. Because the bulk of Precambrian flood-basalt provinces, such as occurred during the Phanerozoic, have been eroded away, most of their examples are huge, well-dated dyke swarms that almost certainly fed such plateau basalts. Rather than a direct time-correlation, what emerged was a match-up that covered 74% of the LIPs with BIFs that had formed about 241 Ma earlier. They also found a less precise correlation between LIPs associated with 241 Ma older BIFs and protracted periods of stable geomagnetic field, known as 'superchrons'. These are thought by geophysicists to be influenced by heat flow through the core-mantle boundary (CMB).

The high bulk density of BIFs at the surface would be likely to remain about 15 % greater than that of peridotite as pressure increased with depth in the mantle. Such slabs could therefore penetrate the 660 mantle discontinuity. Their subduction would probably result in their eventually 'piling up' in the vicinity of the CMB. The high iron content of BIFs may also have changed the way that the core loses heat, thereby triggering mantle plumes. Certainly, there is a complex zone of ultra-low seismic velocities (ULVZ) that signifies hot, ductile material extending above the CMB. Because BIFs' high iron-content makes them thermally highly conductive compared with basalts and other sediments, they may be responsible. Clearly, Keller *et al's* hypothesis is likely to be controversial and they hope that other geoscientists will test it with new or re-analysed geophysical data. But the possibility of BIFs falling to the base of the mantle spectacularly extends the influence of surface biological processes to the entire planet. And, indeed, it may have shaped the later part of its tectonic history having changed the composition of the deep mantle. The interconnectedness of the Earth system also demands that the consequences – plumes and large igneous provinces – would have fed back to the Precambrian biosphere.

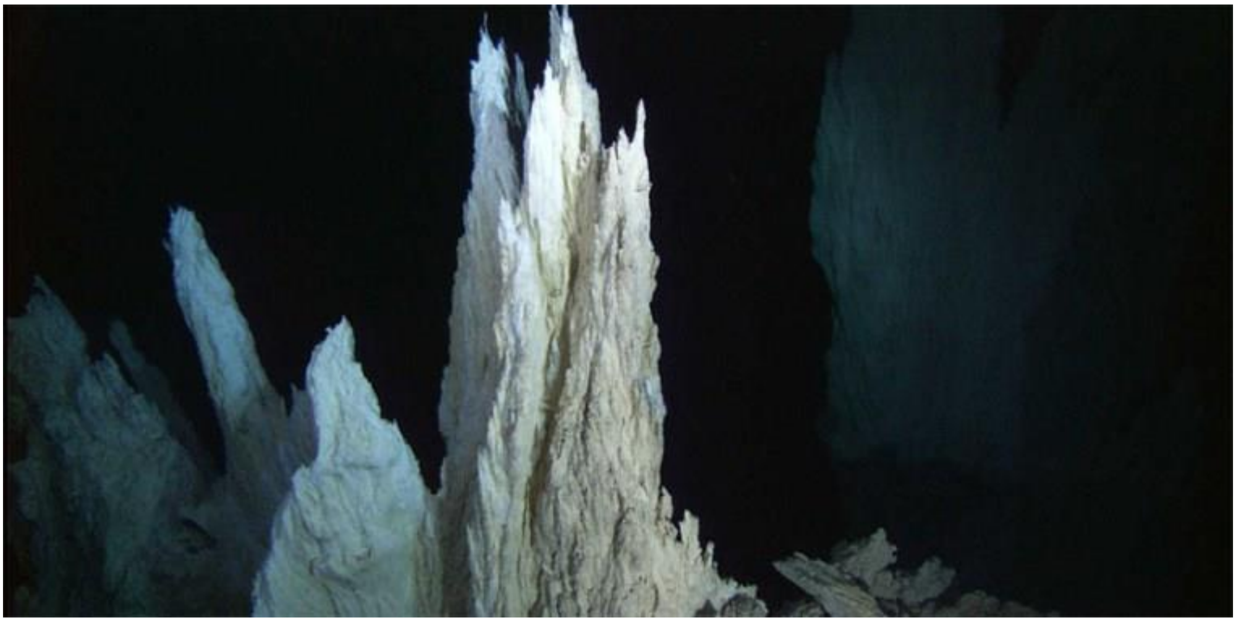
See also: Iron-rich rocks unlock new insights into Earth's planetary history, *Science Daily*, 2 June 2023

New drill core penetrates the Mohorovičić Discontinuity (the 'Moho')

PUBLISHED ON *June 5, 2023*

In 1909 Croatian geophysicist Andrija Mohorovičić examined seismograms of a shallow earthquake that shook the area around Zagreb. To his surprise the by-then familiar time sequence of P-waves followed by the slower S-waves appeared twice on seismic records up to 800 km away. The only explanation that he could come up with was that the first arrivals had travelled directly through the crust to the detector whereas the second set must have followed a longer path: it had travelled downwards to be refracted to reach the surface when it met rocks denser than those at the surface. His analysis revealed a sharp boundary between the Earth's crust and its mantle at a depth of about 54 km below what was then Yugoslavia. Later workers confirmed this discovery and honoured its discoverer by naming it the Mohorovičić Discontinuity. Difficulty with pronouncing his name resulted in a geological nickname: 'the Moho'. It can be detected everywhere: at 20 to 90 km beneath the continental surface and 5 to 10 km beneath the ocean floor, thus distinguishing between continental and oceanic crust.

In the late 1950s accelerating geological and oceanographic research that would culminate in the theory of plate tectonics turned its focus on drilling down to the Moho in much the same way as a lust for space travel spawned getting to the Moon. The difference was that the proposers of what became known as the Mohole Project were members of what amounted to a geoscientific glee club (The American Miscellaneous Society), which included a member of the well-financed US National Science Foundation's Earth Science Panel. The idea emerged shortly after the Soviet Union had launched the Sputnik satellite and rumours emerged that it was proposing deep drilling into the continental crust beneath the Kola Peninsula. The Mohole's initial target was the 3.9 km deep floor of the Caribbean off Guadalupe in Mexico and required advanced methods of stabilisation for a new oceanographic ship that was to host the drilling rig.



Huge (tens of metres high) pillars or 'chimneys' of carbonates formed by the Lost City hydrothermal vent near the mid-Atlantic ridge (Credit: ETH Zurich)

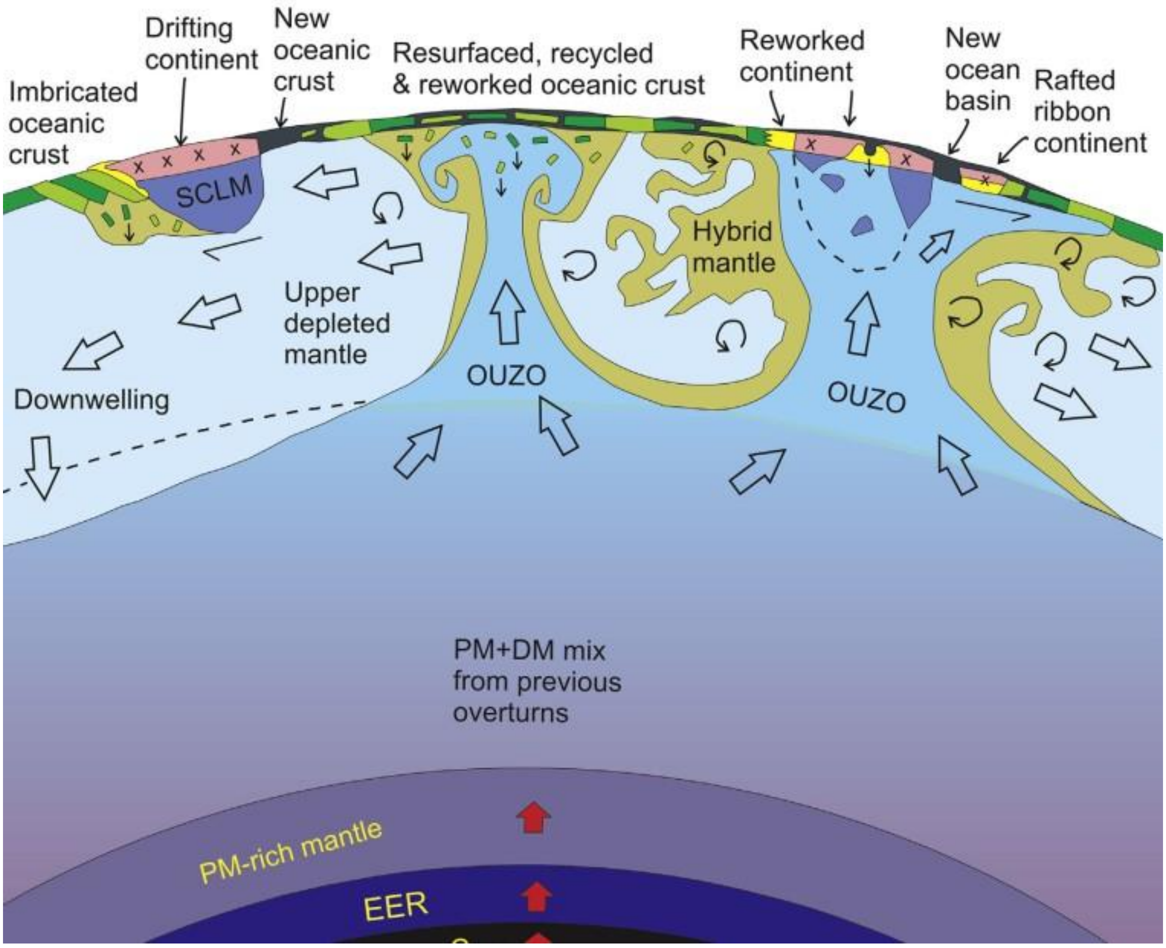
The Mohole was spudded in 1961, but the deepest of five holes reached only 200 m beneath the sea floor. It recovered Miocene sediments and a few metres of basalt. Deep water drilling was somewhat more complicated than expected and about US$ 57 million was spent fruitlessly. The project was disbanded in 1966 with considerable acrimony and schadenfreude. Nonetheless, the Mohole fiasco made technical advances and did demonstrate the feasibility of offshore drilling. The petroleum industry benefitted and so did oceanography with the globe-spanning deep-sea drilling of ocean floor sediments. The sediment cores produced the 200 million-year exquisitely detailed record of climate change and vast amounts of geochemical data from the basaltic oceanic crust. In 2005 JOIDES (the Joint Oceanographic Institutions for Deep Earth Sampling) had another crack at the Moho. That venture centred on the intersection of the Mid-Atlantic Ridge and the Atlantis Fracture Zone close to the 'Lost City' hydrothermal vent. The area around the vent is the site of a huge low-angled extensional fault that has partly dragged the basaltic ocean crust off the mantle beneath causing it to bulge. This provided an excellent opportunity to drill through the Moho. All went well, but 54 days of drilling yielded 1.4 km of basalt but nothing resembling mantle rock. So, again, the Moho had thwarted Science (and research economics). But finally it is beginning to reveal it secrets (see: Voosen, P. 2023. Ocean drillers exhume a bounty of mantle rocks. *Science*, v. **380** (News) p. 876-877; DOI: 10.1126/science.adi9899

The area around the 'Lost City' vent was originally chosen for drilling to examine the chemical processes going on there. Hydrogen emitted by serpentinisation of mantle rocks can combine with carbon monoxide in hydrothermal fluids to create a wide variety of organic compounds, which could be the initial building blocks for the origin of life. As part of the International Ocean Drilling Programme JOIDES decided to launch IODP Expedition 399 to re-examine the area around 'Lost City' in more detail. The expedition first tried to continue drilling the 2005 hole, but failed yet again. Finally a new drill site aimed at penetrating the extensional detachment. Within a few days the drill bit punched into mantle rocks and over a 6-week period the expedition had recovered a kilometre of core. The technical accounts for each week of drilling give a flavour of what it must be like to be a part of such a ship-borne expedition as well as describing what emerged in the drill core. It seems like a bit of a jumble, dominated by the mineral olivine– the principal characteristic of the ultramafic mantle – almost pure in the rock dunite and mixed with pyroxenes in various kinds of peridotite. There are also coarse-grained rocks that contain plagioclase feldspar, which cut through the ultramafic materials – gabbros, troctolites and norites. They are relics of intrusive basaltic magmas that did not make it to the seabed. The samples are variably altered by interaction with watery hydrothermal fluids, with lots of serpentine, talc and even asbestos: the drilling presented a health hazard for a few days. The rocks have been metamorphosed under pressure-temperature conditions of greenschist to amphibolite facies and subject to ductile deformation, probably because of the effect of extensional deformation. Whatever, there is plenty of material to be analysed, including for signs of microbial activity. So, the dreams of a 1950s academic drinking fraternity (they *were* all men!) have finally been realised. But since those pre-plate-tectonic times many geologists have seen and collected much the same, even putting their index fingers on the Moho itself in the time-honoured fashion. Intricate 3-D geology in ophiolite complexes such as that in Oman, provide such opportunities at the much lower cost of air travel, Land Cruiser hire and camping. Indeed what we know of the structure of the oceanic lithosphere – pillow lavas, sheeted dyke complexes, gabbro cumulates and serpentinised ultramafic mantle – has come from such bodies thrust onto continental crust at ancient plate margins. So, why the celebration in this case? They are the first samples of mantle from young oceanic lithosphere; the rocks of ophiolites may not have formed at mid-ocean ridges. These should give clues to the long-term magmatism that has created the vast abyssal basins that the mantle eventually reabsorbs by subduction. Then, of course, there is the link to biogenic processes at constructive margins that underpinned the return to the active hydrothermal venting at 'Lost City'.

News about when subduction began

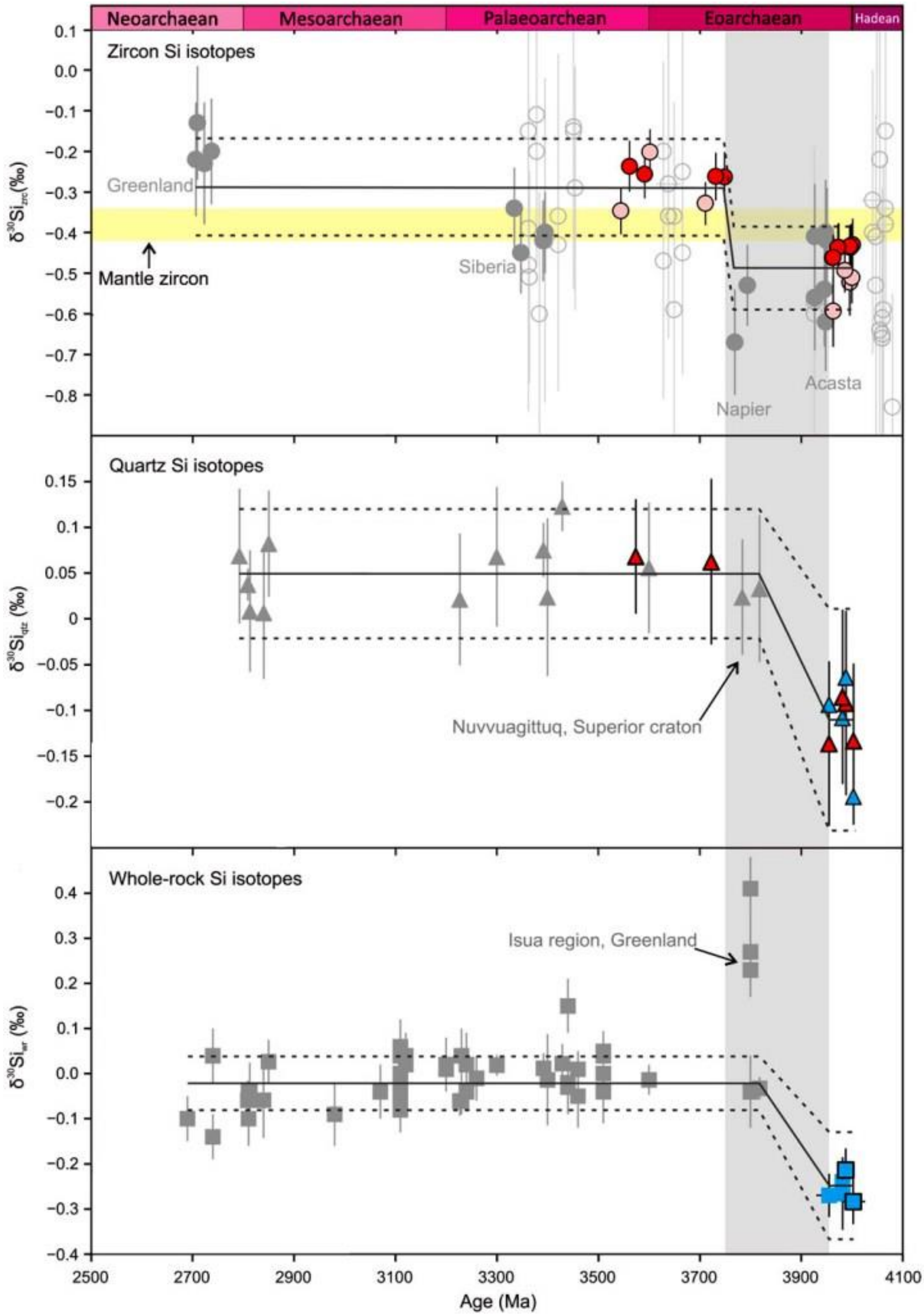
PUBLISHED ON *July 6, 2023*

Tangible signs of past subduction take the form of rocks whose mineralogy shows that they have been metamorphosed under conditions of high pressure and low temperature, and then returned to the surface somehow. Ocean-crust basaltic rocks become blueschist and eclogite. The latter is denser than mantle peridotite so that oceanic lithosphere can sink and be recycled. That provides the slab-pull force, which is the major driver of plate tectonics. Unfortunately, neither blueschists nor eclogites are found in metamorphic complexes older than about 800 Ma. This absence of direct proof of subduction and thus modern style plate tectonics has resulted in lively discussion and research seeking indirect evidence for when it did begin, the progress of which since 2000 you can follow through the index for annual logs about tectonics. An interesting new approach emerged in 2017 that sought a general theory for the evolution of silicate planets, which involves the concept of 'lid tectonics'. A planet in a stagnant-lid phase has a lithosphere that is weak as a result of high temperatures: indeed so weak and warm that subduction was impossible. Stagnant-lid tectonics does not recycle crustal material back to its source in the mantle and it simply builds up the lithosphere. Once planetary heat production wanes below a threshold level that permits a rigid lithosphere, parts of the lid can be driven into the mantle. The beginnings of this mobile-lid phase and thus plate tectonics of some kind involves surface materials in mantle convection: the may be recycled.



Cartoon of possible Hadean stagnant lid tectonics, dominated by mantle plumes. (Credit: Bédard, J.H. 2018, Fig 3B, DOI: 10.1016/j.gsf.2017.01.005)

A group of geochemists from China, Canada and Australia have sought evidence for recycled crustal rocks from silicon and oxygen isotopes in the oldest large Archaean terrane, the 4.0 Ga old Acasta Gneiss Complex in northern Canada (Zhang, Q. and 10 others 2023. No evidence of supracrustal recycling in Si-O isotopes of Earth's oldest rocks 4 Ga ago. *Science Advances*, v.**9**, article eadf0693; DOI: 10.1126/sciadv.adf0693). Silicon has three stable isotopes ^{28}Si, ^{29}Si, and ^{30}Si. As happens with a number of elements, various geochemical processes are able to selectively change the relative proportions of such isotopes: a process known as isotope fractionation. As regards silicon isotopes used to chart lithosphere recycling, the basic steps are as follows: Organisms that now remove silicon from solution in seawater to form their hard parts and accumulate in death as fine sediments like flint had not evolved in the Archaean. Because of that reasonable supposition it has been suggested that seawater during the Archaean contained far more dissolved silicon than it does now. Such a rich source of Si would have entered Archaean oceanic crust and ocean-floor sediments to precipitate silica 'cement'. The heaviest isotope ^{30}Si would have left solution more easily than the lighter two. Should such silicified lithosphere have descended to depths in the mantle where it could partially melt the anomalously high ^{30}Si would be transferred to the resulting magmas.



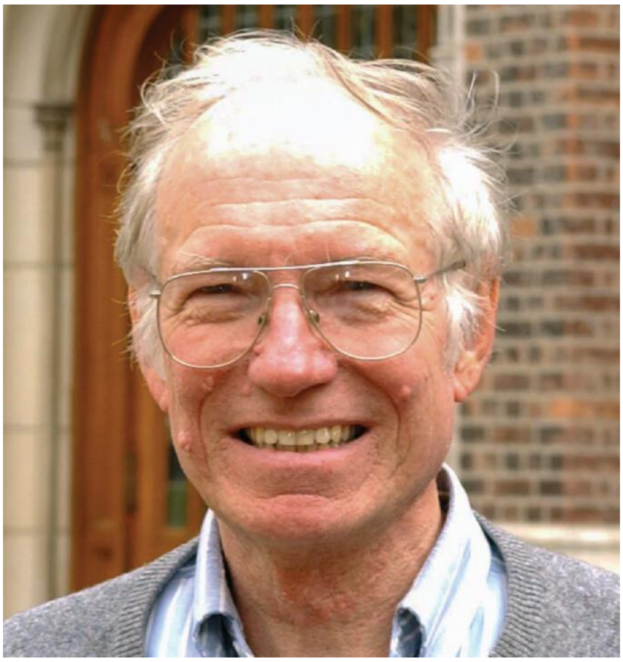
Proportions of 30Si in zircons, quartz and whole rock for Acasta gneisses (coloured), other Archaean areas (grey) and Jack Hills zircons (open circles. Vertical lines are error bars. (Credit: simplified from Zhang et al. Fig 1)

Stable-isotope analyses by Zhang *et al.* revealed that zircon and quartz grains and bulk rock samples from the Acasta gneisses, with undisturbed U-Pb ages, contain ^{30}Si in about the same proportions relative to silicon's other stable isotopes as do samples of the mantle. So it seems that the dominant trondhjemite-tonalite-granodiorite (TTG) rocks that make up the oldest Acasta gneisses were formed by partial melting of a source that **did not** contain rocks from the ocean crust. Yet the Acasta Gneiss Complex also contains younger granitic rocks (3.75 to 3.50 Ga) and they are significantly more enriched in ^{30}Si, as expected from a deep source that contained formerly oceanic rocks. A similar 'heavy' silicon-isotope signature is also found in samples from other Archaean terranes that are less than 3.8 Ga old. Thus a major shift from stagnant-lid tectonics to the mobile-lid form may have occurred at the end of the Hadean. But apart from the Acasta Gneiss Complex only one other, much smaller Hadean terrane has been discovered, the 4.2 Ga Nuvvuagittuq Greenstone Belt. It occupies a mere 20 km^2 on the eastern shore of Hudson Bay in Canada, and appears to be a sample of Hadean oceanic crust. It does include TTG gneisses, but they are about 3.8 Ga old and contain isotopically heavy silicon. So it seems unlikely that testing this hypothesis with silicon-isotope data from other Hadean gneissic terranes will be possible for quite a while, if at all.

Plate tectonics loses another of its pioneers: W. Jason Morgan

PUBLISHED ON *October 25, 2023*

The theory of plate tectonics had a long gestation. Continental drift, one of its central tenets, was first proposed by the meteorologist Alfred Wegener in 1912. Apart from a few enthusiasts of such a dynamic aspect of geology, such as Alex du Toit and Arthur Holmes, the majority of geoscientists remained with the non-revolutionary fixist ideology of their Victorian predecessors. Wegener's stumbling block was his proposed driving mechanism – *polflucht* (flight from the poles) – which assumed that supercontinents had formed in polar regions to be subject to centrifugal force resulting from Earth's rotation. This broke them apart to be driven towards the Equator. Such a mechanism being easily invalidated, most contemporary geologists preferred to 'throw Wegener's baby out with the bathwater'. Yet every piece of his evidence that continents had moved around and most of his ideas about the nature of their movements were steadily verified and amplified over the next six decades, which attracted more curious and flexible scientists. What is now the central paradigm of the Earth Sciences had to wait for a set of major discoveries in the 1950s and '60s enabled by emerging technologies, such as the magnetometers used by Fred Vine and Drummond Matthews to discover sea-floor magnetic striping and thus sea-floor spreading. Their breakthrough presented a plausible mechanism for continental drift and launched a near frenzy of collaborative research among a global milieu of young geoscientists, one of whom being W. Jason Morgan.



W. Jason Morgan Department of Earth Sciences, Princeton University. (Credit: Denise Applewhite, Princeton University)

His initial interest was in the great fracture zones on the floors of the Atlantic and Pacific Oceans. He grasped that each of them was very nearly a great circle. This was a central key to unifying seafloor spreading and continental drift – to move across a spherical surface every point on the seafloor had to follow such a path. Morgan recognised that the fracture zones could only result from *rigid* plates having to fracture to accommodate that motion. Using spherical geometry he was able to link together ridges, trenches and these huge transform faults with poles of rotation and triple junctions to predict plate motions in a quantitative manner. That insight provided a key to active earthquakes, mountain belts and volcanoes. His scientific unification was a result of genius: in just a few weeks Morgan established the fundamentals of what became known as plate tectonics.

W. Jason Morgan was one of the revolutionaries who made geology dynamic and launched its resurrection from the boring province of damp field workers in anoraks tramping across tracts of extremely puzzling rocks and structures, noses to the ground. He died at the age of 87 on 31 July 2023.

You can read an obituary by his former research student Richard Hey and his son Jason Phipps Morgan together with a fuller account of his career on Wikipedia.