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Evidence for an early Archaean transition to subduction

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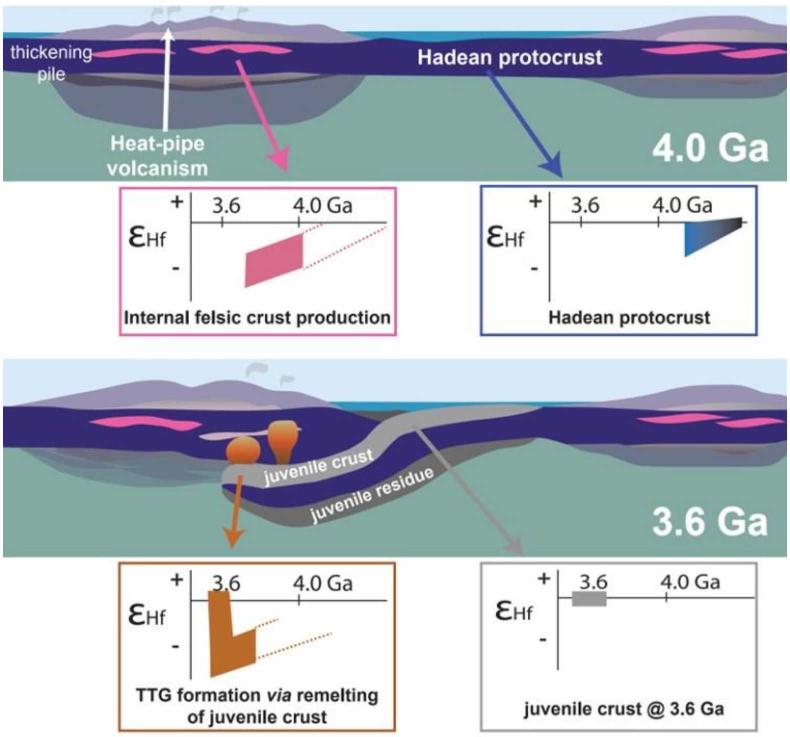
Modern plate tectonics is largely driven by slab-pull: a consequence of high-pressure, low-temperature metamorphism of the oceanic crust far from its origin at an oceanic ridge. As it ages, basaltic crust cools, become increasingly hydrated by hydrothermal circulation of seawater through it and its density increases. That is why the abyssal plains of the ocean floor are so deep relative to the shallower oceanic ridges where it formed. Due to the decrease in the Earth's internal heat production by decay of radioactive isotopes, once oceanic lithosphere breaks and begins to descend high-P low-T metamorphism transforms the basaltic crust to a denser form: eclogite, in which the dense, anhydrous minerals garnet and sodium-rich pyroxene (omphacite) form. Depending on local heat flow, the entire oceanic slab may then exceed the density of the upper mantle to drag the plate downwards under gravity. Metamorphic reactions of any P-T regime creates minerals less capable of holding water and drive H_2O-rich fluids upwards into the overriding lithosphere, thus inducing it to partially melt. Magmas produced by this create volcanism at the surface, either at oceanic island arcs or near to continental margins, depending on the initial position of the plate subduction.

A direct proof of active subduction in the geological record is the presence of eclogite and related blueschists. Such rocks are unknown before 2100 Ma ago (mid-Palaeoproterozoic of the Democratic Republic of Congo) but there are geochemical means of 'sensing' plate tectonic control over arc magmatism (**See:** So, when did plate tectonics start up? February 2016). The relative proportions of rare-earth elements in ancient magmatic rocks that make up the bulk of continental crust once seemed to suggest that plate tectonics started at the end of the Archaean Eon (~2500 Ma). That method, however, was quite crude and has been superseded by looking in great detail at the geochemistry of the Earth's most durable mineral: zircon ($ZrSiO_4$), which began more than two decades ago. Minute grains of that mineral most famously have pushed back the geological record into what was long believed to be half a billion years with no suggestion of a history: the Hadean. Zircon grains extracted from a variety of ancient sediments have yielded U-Pb ages of their crystallisation from igneous magma that extend back 4.4 billion years (Ga) (**see:** Pushing back the "vestige of a beginning" ;January 2001).

Though simple in their basic chemical formula, zircons sponge-up a large range of other trace elements from their parent magma. So, in a sense, each tiny grain is a capsule of their geochemical environment at the time they crystallised. In 2020 Australian geochemists presented the trace-element geochemistry of 32 zircons extracted from a 3.3 Ga old sedimentary conglomerate in the Jack Hills of Western Australia, which lie within an ancient continental nucleus or craton. They concluded that those zircons mainly reveal that they formed in andesitic magmas, little different from the volcanic rocks that are erupted today above subduction zones. From those data it might seem that some form of plate tectonics has been present since shortly after the Earth's formation. Oxygen-isotope data from zircons are useful in checking whether zircons had formed in magmas derived directly from partial melting of mantle rocks or by recycling of crustal magmatic rocks through subduction. Such a study in 2012 (**see:** Charting the growth of continental crust; March 2012) that used a very much larger number of detrital zircon grains from Australia, Eurasia, North America, and South America seemed, in retrospect, to contradict a subduction-since-the-start view of Earth dynamics and crust formation. Instead it suggested that recycling of crust, and thus plate-tectonic subduction, first showed itself in zircon geochemistry at about 3 Ga ago.

Detailed chemical and isotopic analysis of zircons using a variety of instruments has steadily become faster and cheaper. Actually finding the grains is much easier than doing interesting things with them. It is a matter of crushing the host rock to 'liberate' the grains. Sedimentary hosts that have not been strongly metamorphosed are much more tractable than igneous rocks. Being denser than quartz, the dominant sedimentary mineral, zircon can be separated from it along with other dense, trace minerals, and from them in turn by various methods based on magnetic and electrical properties. Zircons can then be picked out manually because of their distinctive colours and shapes. A tedious process, but there are now several thousand fully analysed zircons aged between 3.0 to 4.4 Ga, from eleven cratons that underpin Australia, North America, India, Greenland and southern Africa. The latest come from a sandstone bed laid down about 3.31 Ga ago in the Barberton area of South Africa (Drabon, N. et al. 2022. Destabilization of Long-Lived Hadean Protocrust and the Onset of Pervasive Hydrous Melting at 3.8 Ga. *AGU Advances*, v. **3**, article e2021AV000520; DOI: 10.1029/2021AV000520). The authors measured lutetium (Lu), hafnium (Hf) and oxygen isotopes, and concentrations of a suite of trace element in 329 zircons from Barberton dated between 3.3 to 4.15 Ga.



A schematic model of transition from Hadean-Eoarchaean lid tectonics to a type of plate tectonics that subsequently evolved to its current form, based on hafnium isotope data in ancient zircons (credit: Bauer et al. 2020; Fig 3)

The Hf isotopes show two main groups relative to the values for chondritic meteorites (assumed to reflect the composition of the bulk Earth). Zircons dated between 3.8 and 4.15 Ga all show values below that expected for the whole Earth. Those between 3.3 and 3.8 Ga show a broader range of values that extend above chondritic levels. The transition in data at around 3.8 Ga is also present in age plots of uranium relative to niobium and scandium relative to ytterbium, and to a lesser extent in the oxygen isotope data. On the basis of these data, something fundamentally changed in the way the Earth worked at around 3.8 Ga. Nadja Drabon and colleagues ascribe the chemical features of Hadean and Eoarchaean zircons to an early protocrust formed by melting of chemically undepleted mantle. This gradually built up and remained more or less stable for more than 600 Ma, without being substantially remelted through recycling back to mantle depths. After 3.8 billion years ago, geochemical signatures of the zircons start showing similarities to those of zircons derived from modern subduction zones. Hf isotopes and trace-element geochemistry in 3.6 to 3.8 Ga-old detrital zircons from other cratons are consistent with a 200 Ma transition from 'lid' tectonics (**see:** Lid tectonics on Earth; December 2017) to the familiar tectonics of rigid plates whose basalt-capped lithosphere ultimately returns to the mantle to be involved in formation of new magmas from which continental crust stems. Parts of plates bolstered by this new, low density crust largely remain at the surface.

While Drabon *et al*. do provide new data from South Africa's Kaapvaal craton, their conclusions are similar to earlier work by other geochemists based on data from other area (e.g. Bauer, A.M. *et al*. 2020. Hafnium isotopes in zircons document the gradual onset of mobile-lid tectonics. *Geochemical Perspectives Letters*, v. **14**; DOI: 10.7185/geochemlet.2015), which the accompanying figure illustrates.

See also: Earliest geochemical evidence of plate tectonics found in 3.8-billion-year-old crystal. *Science Daily*, 21 April 2022. 3.8-Billion-Year-Old Zircons Offer Clues to When Earth's Plate Tectonics Began. *SciNews*, 26 April 2022

The Earth System in action: land plants affected composition of continental crust

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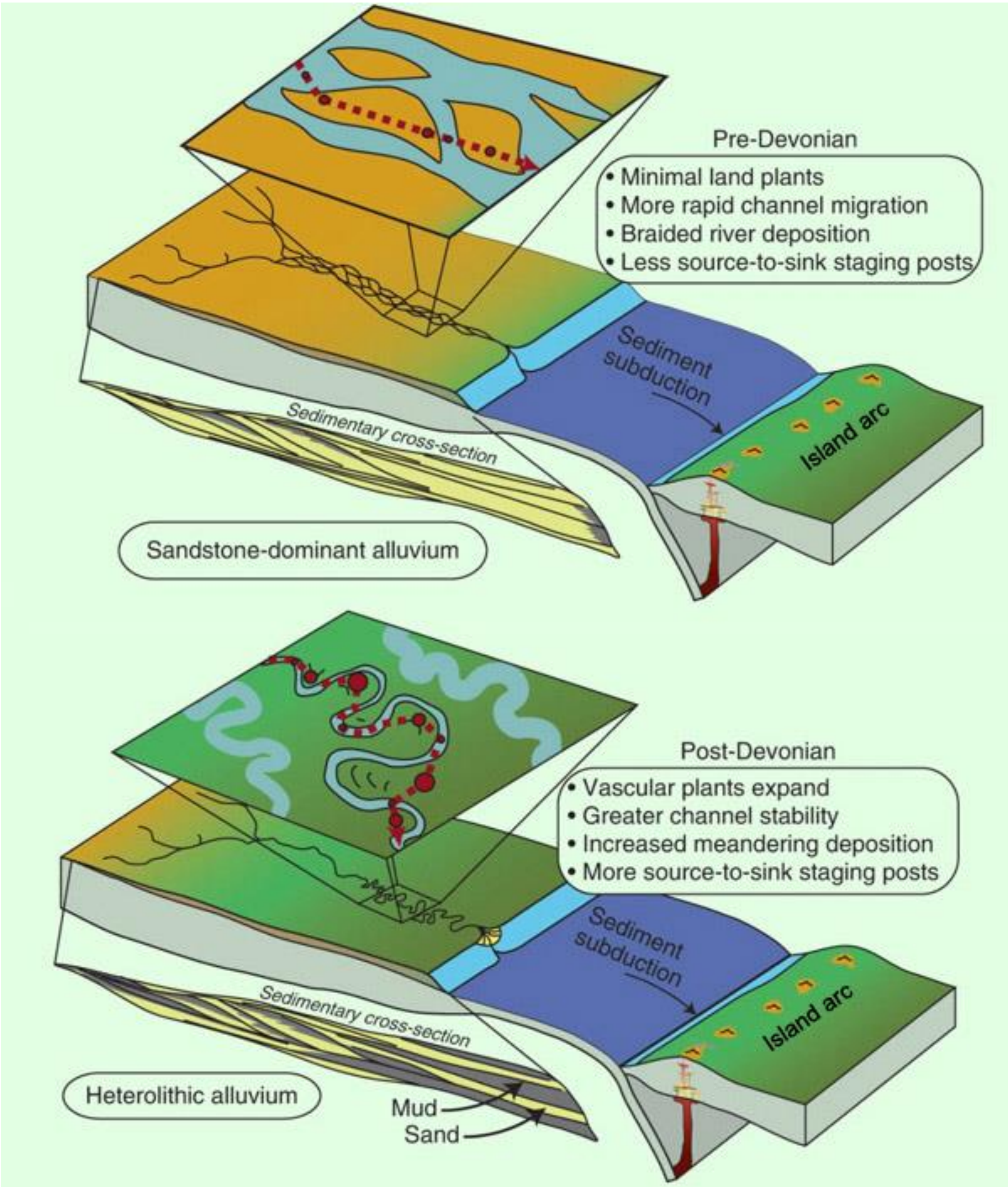
The essence of the Earth System is that all processes upon, above and beneath the surface interact in a bewildering set of connections. Matter and energy in all their forms are continually being exchanged, deployed and moved through complex cycles: involving rocks and sediments; water in its various forms; gases in the atmosphere; magmas; moving tectonic plates and much else besides. The central and massively dominant role of plate tectonics connects surface processes with those of our planet's interior: the lithosphere, mantle and, arguably, the core. Interactions between the Earth System's components impose changes in the dynamics and chemical processes through which it operates. Living processes have been a part of this for at least 3.5 billion years ago, in part through their role in the carbon cycle and thus the Earth's climatic evolution. During the Silurian Period life became a pervasive component of the continental surface, first in the form of plants, to be followed by animals during the Devonian Period. Those novel changes have remained in place since about 430 Ma ago, plants being the dominant base of continental ecosystems and food chains.



Schematic diagram showing changes in river systems and their alluvium before and after the development of land plants. (Credit: Based on Spencer et al. 2022, Fig 4)

Land plants exude a variety of chemicals from their roots that break down rock to yield nutrient elements. So they play a dominant role in the formation of soil and are an important means of rock weathering and the production of clay minerals from igneous and metamorphic minerals. Plant root systems bind near-surface sediments thus increasing their resistance to erosion by wind and water, and to mass movement under gravity. This binding and plant canopies efficiently reduce dust transport, slow water flow on slopes and decrease the sediment load of flowing water. Plants and their roots also stabilise channels systems. There is much evidence that before the Devonian most rivers comprised continually migrating braided channels in which mainly coarse sands and gravels were rapidly deposited while silts and muds in suspension were shifted to the sea. Thereafter flow became dominated by larger and fewer channels meandering across wide tracts on which fine sediment could accumulate as alluvium on flood plains when channels broke their banks. Land plants more efficiently extract CO_2 from the atmosphere through photosynthesis and the new regime of floodplains could store dead plant debris in the muds and also in thick peat deposits. As a result, greenhouse warming had dwindled by the Carboniferous, encouraging global cooling and glaciation.

Judging the wider influence of the 'greening of the land' on other parts of the Earth system, particularly those that depend on internal magmatic processes, relies on detecting geochemical changes in minerals formed as direct outcomes of plate tectonics. Christopher Spencer of Queen's University in Kingston, Canada and co-workers at the Universities of Southampton, Cambridge and Aberdeen in the UK, and the China University of Geosciences in Wuhan set out to find and assess such a geochemical signal (Spencer, C., Davies, N., Gernon, T. *et al.* 2022. Composition of continental crust altered by the emergence of land plants. *Nature Geoscience*, v. **15** online publication; DOI: 10.1038/s41561-022-00995-2). Achieving that required analyses of a common mineral formed when magmas crystallise: one that can be precisely dated, contains diverse trace elements and whose chemistry remains little changed by later geological events. Readers of Earth-logs might have guessed that would be zircon ($ZrSiO_4$). Being chemically unreactive and hard, small zircon grains resist weathering and the abrasion of transport to become common minor minerals in sediments. Thousands of detrital zircon grains teased out from sediments have been dated and analysed in the last few decades. They span almost the entirety of geological history. Spencer *et al*. compiled a database of over 5,000 zircon analyses from igneous rocks formed at subduction zones over the last 720 Ma, from 183 publications by a variety of laboratories.

The approach considered two measures: the varying percentages of mudrocks in continental sedimentary sequences since 600 Ma ago; aspects of the hafnium- (Hf) and oxygen-isotope proportions measured in the zircons using mass spectrometry and their changes over the same time. Before ~430 Ma the proportion of mudrocks in continental sedimentary sequences is consistently much lower than it is in post post-Silurian, suggesting a link with the rise of continental plant cover (see second paragraph). The deviation of the $^{176}Hf/^{177}Hf$ ratio in an igneous mineral from that of chondritic meteorites (the mineral's εHf value) is a guide to the source of the magma, negative values indicating a crustal source, whereas positive values suggest a mantle origin. The relative proportions of two oxygen isotopes ^{18}O and ^{16}O in zircons, expressed as $\delta^{18}O$, indicates the proportion of products of weathering, such as clay minerals, involved in magma production – ^{18}O selectively moves from groundwater to clay minerals when they form, increasing their $\delta^{18}O$.

While the two geochemical parameters express very different geological processes, the authors noticed that before ~430 Ma the two showed low correlation between their values in zircons. Yet, surprisingly, the parameters showed a considerable and consistent increase in their correlation in younger zircons, directly paralleling the 'step change' in the proportions of mudstones after the Silurian. Complex as their arguments are, based on several statistical tests, Spencer *et al*. conclude that the geologically sudden change in zircon geochemistry ultimately stems from land plants' stabilisation of river systems. As a result more clay minerals formed by protracted weathering, increasing the $\delta^{18}O$ in soils when they were eroded and transported. When the resulting marine mudrocks were subducted they transferred their oxygen-isotope proportions to magmas when they were partially melted.

That bolsters the case for dramatic geological consequences of the 'greening of the land'. But did its effect on arc magmatism fundamentally change the bulk composition of post-Silurian additions to the continental crust? To be convinced of that I would like to see if other geochemical parameters in subduction-related magmas changed after 430 Ma. Many other elements and isotopes in broadly granitic rocks have been monitored since the emergence of high-precision rock-analysing technologies around 50 years ago. There has been no mention, to my knowledge, that the late-Silurian involved a magmatic game-changer to match that which occurred in the Archaean, also revealed by hafnium and oxygen isotopes in much more ancient zircons.

See also: https://www.sci.news/othersciences/geoscience/land-plants-continental-crust-composition-11151.html; https://www.eurekalert.org/news-releases/963296