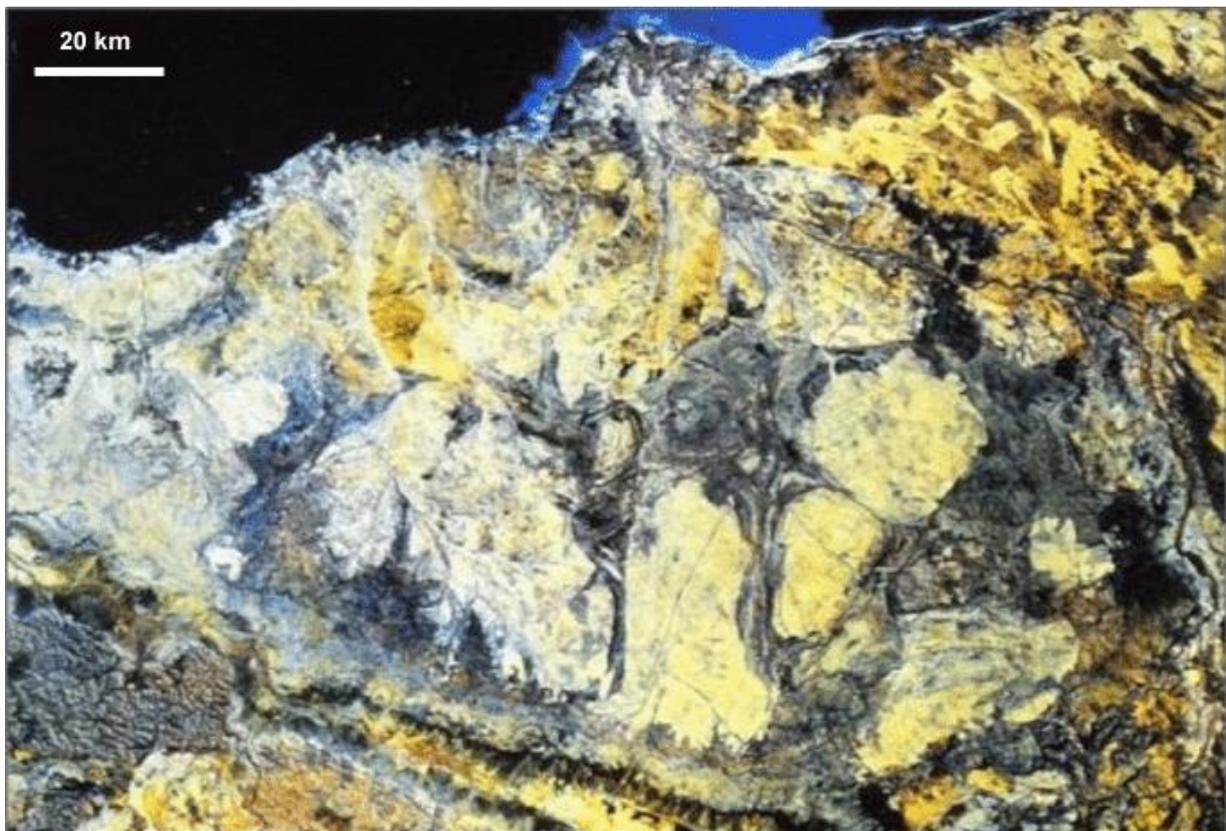


Tectonics 2025

How the earliest continental crust may have formed

PUBLISHED ON *May 28, 2025*

Detrital zircon grains extracted from sandstones deposited ~3 billion year (Ga) ago in Western Australia yield the ages at which these grains crystallised. The oldest formed at about 4.4 Ga; only 150 Ma after the origin of the Earth (4.55 Ga). Various lines of evidence suggest that they originally crystallized from magmas with roughly andesitic compositions, which some geochemists suggest to have formed the first continental crust (see: [Zircons and early continents no longer to be sneezed at](#); February 2006). So far, no actual rocks of that age and composition have come to light. The oldest of these zircon grains also contain anomalously high levels of ^{18}O , a sign that [water played a role in the formation of these silicic magmas](#). Modern andesitic magmas – ultimately the source of most continental crust – typically form above steeply-dipping subduction zones where fluids expelled from descending oceanic crust encourage partial melting of the overriding lithospheric mantle. Higher radiogenic heat production in the Hadean and the early Archaean would probably have ensured that the increased density of later oceanic lithosphere needed for steep subduction could not have been achieved. If subduction occurred at all, it would have been at a shallow angle and unable to exert the slab-pull force that perpetuated plate tectonics in later times (see: [Formation of continents without subduction](#), March, 2017).



Landsat image mosaic of the Palaeoarchaean granite-greenstone terrain of the Pilbara Craton, Western Australia. Granite bodies show as pale blobs, the volcanic and sedimentary greenstone belts in shades of grey.

Geoscientists have been trying to resolve this paradox for quite a while. Now a group from Australia, Germany and Austria have made what seems to be an important advance (Hartnady, M. I. H and 8 others 2025. [Incipient continent formation by shallow melting of an altered mafic protocrust](#). *Nature Communications*, v. 16, article 4557; DOI: 10.1038/s41467-025-59075-9). It emerged from their geochemical studies of rocks in the Pilbara Craton of Western Australia that are about a billion years younger than the aforementioned ancient zircon grains. These are high-grade Palaeoarchaeon metamorphic rocks known as migmatites that lie beneath lower-grade 'granite-greenstone' terrains that dominate the Craton, which Proterozoic deformation has forced to the surface. Their bulk composition is that of basalt which has been converted to amphibolite by high temperature, low pressure metamorphism (680 to 730°C at a depth of about 30 km). These metabasic rocks are laced with irregular streaks and patches of pale coloured rock made up mainly of sodium-rich feldspar and quartz, some of which cut across the foliation of the amphibolites. The authors interpret these as products of partial melting during metamorphism, and they show signs of having crystallised from a water-rich magma; i.e. their parental basaltic crust had been hydrothermally altered, probably by seawater soon after it formed. The composition of the melt rocks is that of [trondhjemite](#), one of the most common types of granite found in Archaean continental crust. Interestingly, small amounts of trondhjemite are found in modern oceanic crust and ophiolites.



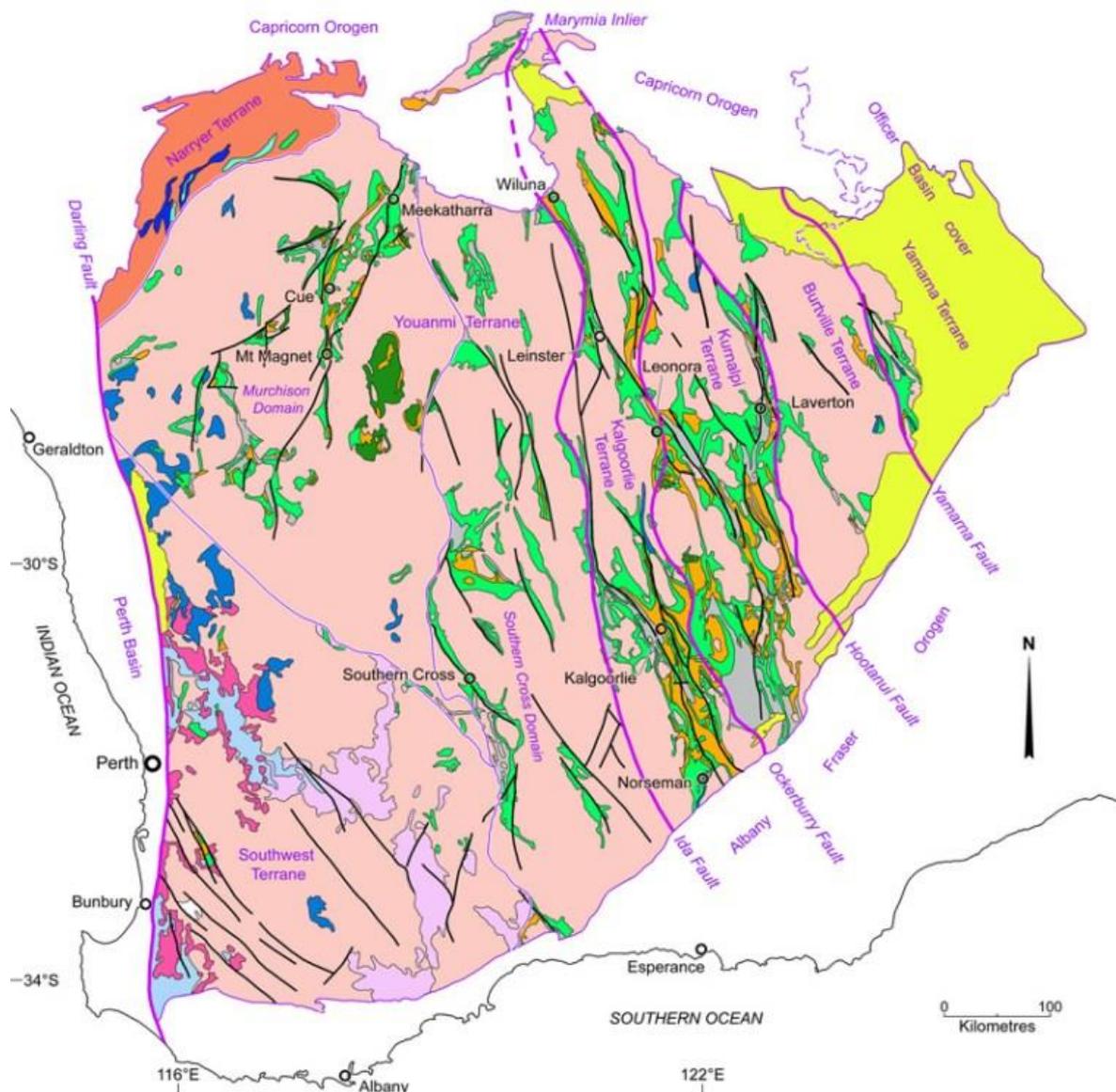
A typical migmatite from Antarctica showing dark amphibolites laced with quartzofeldspathic products of partial melting. Credit: Lunar and Planetary Laboratory, University of Arizona

The authors radiometrically dated zircon and titanite (CaTiSiO_5) – otherwise known as sphene – in the trondhjemites, to give an age of 3565 Ma. The metamorphism and partial melting took place around 30 Ma before the overlying granite-greenstone assemblages formed. They regard the

amphibolites as the Palaeoarchaean equivalent of basaltic oceanic crust. Under the higher heat production of the time such primary crust would probably have approached the thickness of that at modern oceanic plateaux, such as Iceland and Ontong-Java, that formed above large mantle plumes. Michael Hartnady and colleagues surmise that this intracrustal partial melting formed a nucleus on which the Pilbara granite-greenstone terrain formed as the oldest substantial component of the Australian continent. The same nucleation may have occurred during the formation of similar early Archaean terrains that form the cores of most [cratons](#) that occur in all modern continents.

Sagduction of greenstone belts and formation of Archaean continental crust

PUBLISHED ON *July 11, 2025*



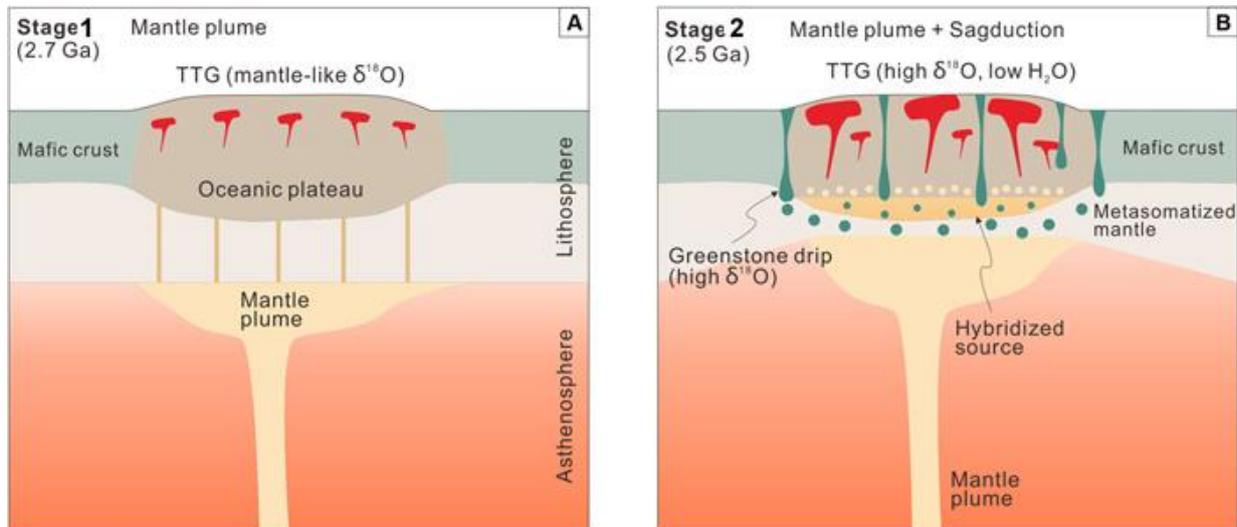
Simplified geological map of the Archaean Yilgarn Craton in Western Australia, greenstone belts in green and orange. Credit: Geological Survey of Western Australia

Every ancient craton seen from space shows patterns that are unique to Archaean continental crust: elongated, 'canoe-shaped' greenstone belts enveloped by granitic gneisses, both of which are punctured by domes of younger, less deformed granites. The Yilgarn Craton of Western Australia is a typical granite-greenstone terrain. Greenstone belts contain lavas of ultramafic, basaltic and andesitic compositions, which in undeformed settings show the typical pillow structures formed by submarine volcanic extrusion. There are also layered mafic to ultramafic complexes, formed by fractional crystallisation, minor sedimentary sequences and occasionally more felsic lavas and ashes. The enveloping grey gneisses are dominantly highly deformed tonalite-trondhjemite-granodiorite (TTG) composition that suggest that they formed from large volumes of sodium-rich, silicic magmas, probably generated at depth by partial melting of hydrated basaltic rocks.

The heat producing radioactive isotopes of potassium, uranium and thorium in both the Archaean mantle and crust would have been more abundant before 2.5 Ga ago, because they decay over time. Consequently the Earth's interior would have then generated more heat than now, gradually to escape by thermal conduction towards the cooler surface. The presence of pillow lavas and detrital sediments in greenstone belts indicate that surface temperatures during the Archaean Eon were below the boiling point of water; in fact probably much the same as in the tropics at present. Indeed there is evidence that [Earth was then a water world](#). It may even have been so [during the Hadean](#), as revealed by the oxygen-isotope data in 4.4 Ga zircon grains. The broad conclusion from such findings is that the Archaean geothermal gradient was much steeper; there would have been a greater temperature increase with depth than now and new crust would have cooled more slowly. Subduction of cool lithosphere would have been less likely than in later times, especially as higher mantle heat production would have generated new crust more quickly. Another likely possibility is that far more heat would have been moved by convection: there would have been more mantle-penetrating plumes and they would have been larger. Large mantle plumes of the Phanerozoic have generated vast ocean floor plateaus, such as the Kerguelen and Ontong Java Plateau.

A group of geoscience researchers at The University of Hong Kong and international colleagues recently completed a geological and geochemical study of the North China Craton, analysing their data in the light of recently emerging views on Archaean processes (Dingyi Zhao et al, [A two-stage mantle plume-sagduction origin of Archean continental crust revealed by water and oxygen isotopes of TTGs](#), *Science Advances*, v. 11, article eadr9513 ; DOI: 10.1126/sciadv.adr9513). They found compelling evidence that ~2.5 Ga-old Neoarchean TTG gneisses in the North China granite-greenstone terrain formed by partial melting of an earlier mafic-ultramafic greenstone crust with high water content. They consider this to support a two-stage model for the generation of the North China Craton's crust above a vast mantle plume. The first stage at around 2.7 Ga was the arrival of the plume at the base of the lithosphere, which partially melted as a result of the decompression of the rising ultramafic plume. The resulting mafic magma created an oceanic plateau partly by underplating the older lithosphere, intruding it and erupting onto the older ocean floor. This created the precursors of the craton's greenstones, the upper part of which interacted directly with seawater to become hydrothermally altered. They underwent minor partial melting to produce small TTG intrusions. A second plume arriving at ~2.5 Ga resulted in sinking of the greenstones under their own weight to mix or 'hybridise' with the re-heated lower crust. This caused the greenstones substantially to partially melt and so generate voluminous TTG magmas that rose as the greenstones subsided. . It seems likely that this dynamic, hot environment deformed the TTGs as they rose to create the grey gneisses so typical of Archaean granite-greenstone terranes. [**Note:** The key evidence

for Dingyi Zhao et al.'s conclusions is that the two TTG pulses yielded the 2.7 and 2.5 Ga ages, and show significantly different oxygen isotope data ($\delta^{18}\text{O}$).



Two stages of TTG gneiss formation in the North China Craton and the sinking (sagduction) of greenstone belts in the second phase. Credit: Dingyi Zhao et al., Fig 4)

Such a petrogenetic scenario, termed sagduction by Dingyi Zhao and colleagues, also helps explain the unique keel-like nature of greenstone belts, and abundant evidence of vertical tectonics in many Archaean terrains (see: [Vertical tectonics and formation of Archaean crust](#); January 2002). Their model is not entirely new, but is better supported by data than earlier, more speculative ideas. That such processes have been recognised in the Neoproterozoic – the North China Craton is one of the youngest granite-greenstone terrains – may well apply to far older Archaean continental crust generation. It is perhaps the last of a series of such events that began in the Hadean, [as summarised in the previous Earth-logs post](#).

The final closure of the Iapetus Ocean

PUBLISHED ON [October 16, 2025](#)

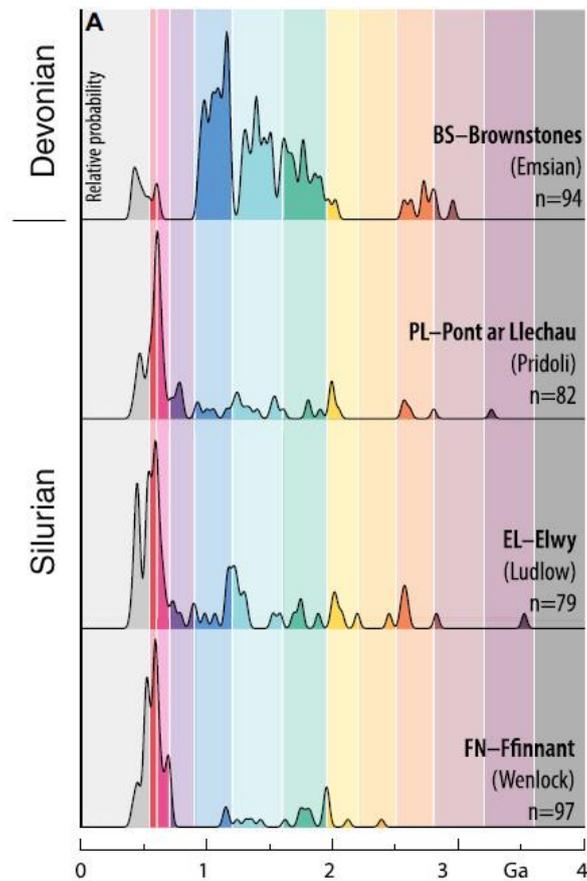
A symposium hosted by the Royal Society in 1965 aimed at resurrecting Alfred Wegener's hypothesis of continental drift. During the half century since Wegener made his proposal in 1915, it had been studiously ignored by most geologists. The majority had bumbled along with the fixist ideology of their Victorian predecessors. The symposium launched what can only be regarded as a revolution in the Earth Sciences. In the three years following the symposium, the basic elements of plate tectonics had emerged from a flurry of papers, mainly centred on geophysical evidence. Geology itself became part of this *cause célèbre* through young scientists eager to make a name for themselves. The geological history of Britain, together with that of the eastern North America, became beneficiaries only four years after the Royal Society meeting (Dewey, J. 1969. Evolution of the Appalachian/Caledonian Orogen. *Nature* **222**, 124–129; DOI: 10.1038/222124a0).

In Britain John Dewey, like a few other geologists, saw plate theory as key to understanding the many peculiarities revealed by geological structure, igneous activity and stratigraphy of the early Palaeozoic. These included very different Cambrian and Ordovician fossil assemblages in Scotland

and Wales, now only a few hundred kilometres apart. The Cambro-Ordovician of NW Scotland was bounded to the SE by a belt of highly deformed and metamorphosed Proterozoic to Ordovician sediments and volcanics forming the Scottish Highlands. That was terminated to the SE by a gigantic fault zone containing slivers of possible oceanic lithosphere. The contorted and 'shuffled' Ordovician and Silurian sediments of the Southern Uplands of Scotland. The oldest strata seemed to have ocean-floor affinities, being deposited on another sliver of ophiolites. A few tens of km south of that there was a very different Lower Palaeozoic stratigraphy in the Lake District of northern England. It included volcanic rocks with affinities to those of modern island arcs. A gap covered by only mildly deformed later Palaeozoic shelf and terrestrial sediments, dotted by inliers of Proterozoic sediments and volcanics separated the Lake District from yet another Lower Palaeozoic assembly of arc volcanics and marine sediments in Wales. Intervening in Anglesey was another Proterozoic block of deformed sediments that also included ophiolites.

Dewey's tectonic assessment from this geological hodge-podge, which had made Britain irresistible to geologists through the 19th and early 20th centuries, was that it had resulted from blocks of crust (terrane), once separated by thousands of kilometres, being driven into each other. Britain was thus formed by the evolution and eventual destruction of an early Palaeozoic ocean, Iapetus: a product of plate tectonics. Scotland had a fundamentally different history from England and Wales; the unification of several terranes having taken over 150 Ma of diverse tectonic processes. Dewey concluded that the line of final convergence lay at a now dead, major subduction zone – the Iapetus Suture – roughly beneath the Solway Firth. During the 56 years since Dewey's seminal paper on the Caledonian-Appalachian Orogeny details and modifications have been added at a rate of around one to two publications per year. The latest seeks to date when and where the accretion of 6 or 7 terranes was finally completed (Waldron, J.W.F. *et al.* 2025. [Is Britain divided by an Acadian suture?](#) *Geology*, v. 53, p. 847–852; DOI: 10.1130/G53431.1).

John Waldron and colleagues from the University of Alberta and Acadia University in Canada and the British Geological Survey addressed this issue by extracting zircons from four late Silurian and early Devonian sandstones in North and South Wales. These sediments had been deposited between 433 and 393 Ma ago at the southernmost edge of the British Caledonide terrane assemblage towards the end of terrane assembly. The team dated roughly 250 zircons from each sandstone using the $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$ methods. Each produced a range of ages, presumed to be those of igneous rocks from whose magma the zircon grains had crystallised. These data are expressed as plots of probable frequency against age. Each pattern of ages is assumed to be a 'fingerprint' for the continental crust from which the zircons were eroded and transported to their resting place in their host sediment. In this case, the researchers were hoping to see signs of continental crust from the other side of the Caledonian orogen; i.e. from the Precambrian basement of the Laurentia continent.



Kernel density plots – smoothed versions of histograms – of detrital zircon ages in Silurian and Devonian sandstones from Wales. The bracketed words are stratigraphic epochs. Credit: Waldron *et al.* 2025, Fig 3A

The three late-Silurian sediments showed distinct zircon-age peaks around 600 Ma and a spread of smaller peaks extending to 2.2 Ga. This tallied with a sediment source in Africa, from which the southernmost Caledonian terrane was said to have split and moved northwards. The Devonian sediment lacked signs of such an African ‘heritage’ but had a prominent age peak at about 1.0 Ga, absent from the Welsh Silurian sediments. Not only is this a sign of different sediment provenance but closely follows the known age of a widespread magmatic pulse in the Laurentian continent. So, sediment transport from the opposite side of the Iapetus Ocean across the entire Caledonian orogenic belt was only possible after the end of the Silurian Period at around 410 Ma. There must have been an intervening barrier to sediment movement from Laurentia before that, such as deep ocean water further north. Previous studies from more northern Caledonian terranes show that Laurentian zircons arrived in the Southern Uplands of Scotland and the English Lake District around 432 Ma in the mid-Silurian. Waldron *et al.* suggest, on these grounds that the suture marking the final closure of the Iapetus Ocean lies between the English Lake District and Anglesey, rather than beneath the Solway. They hint that the late-Silurian to early Devonian granite magmatism that permeated the northern parts of the Caledonian-Appalachian orogen formed above northward subduction of the last relics of Iapetus, which presaged widespread crustal thickening known as the [Acadian](#) orogeny in North America.

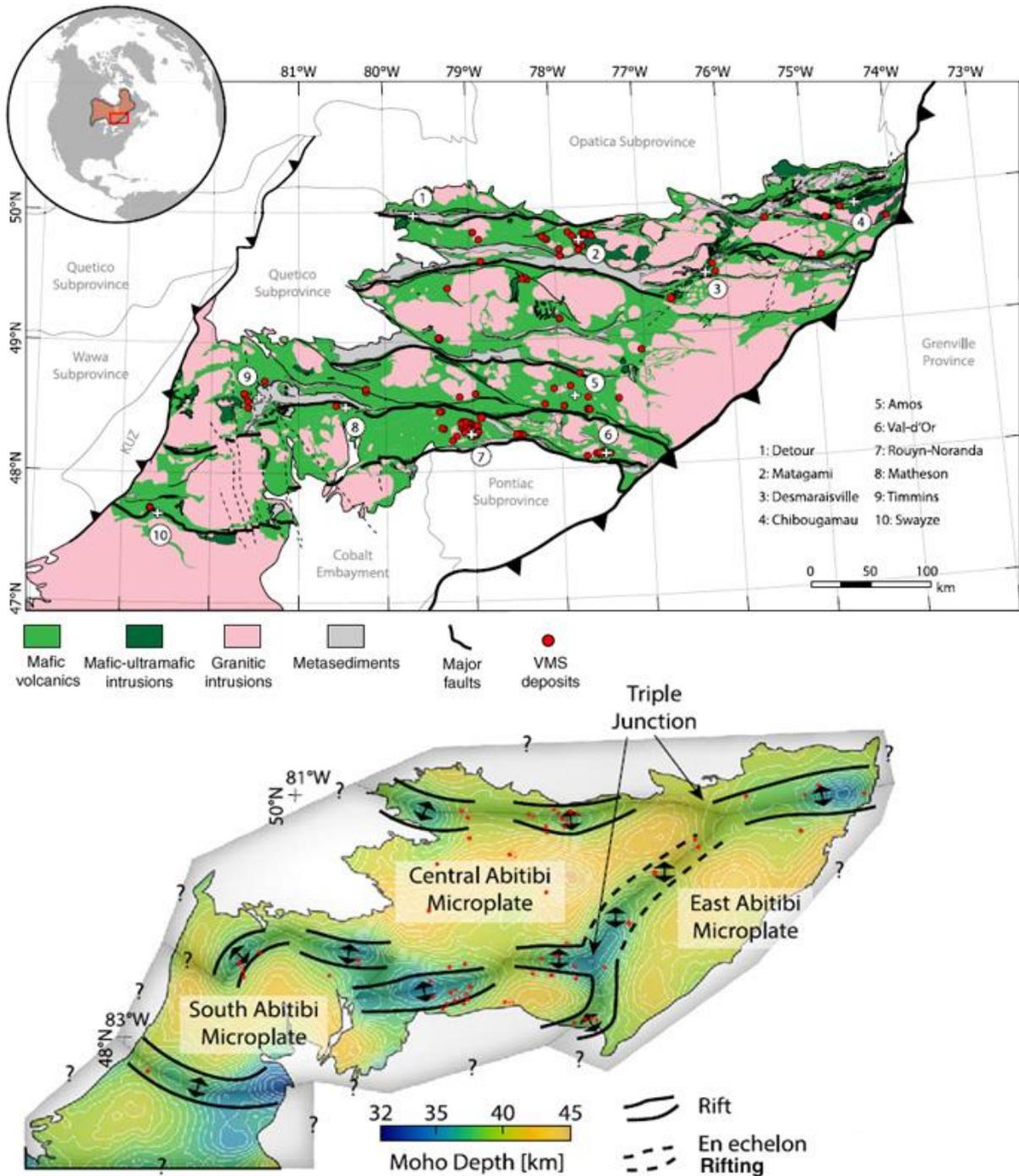
Readers interested in this episode of Earth history should download Waldron *et al.*'s paper for its excellent graphics, which cannot be reproduced adequately here.

Gravity survey reveals signs of Archaean tectonics in Canadian Shield

PUBLISHED ON *October 10, 2025*

Much of the Archaean Eon is represented by cratons, which occur at the core of continental parts of tectonic plates. Having low geothermal heat flow they are the most rigid parts of the continental crust. The Superior Craton is an area that makes up much of the eastern part of the Canadian Shield, and formed during the Late Archaean from ~4.3 to 2.6 billion years (Ga) ago. Covering an area in excess of 1.5 million km², it is the world's largest [craton](#). One of its most intensely studied components is the Abitibi Terrane, which hosts many mines. A granite-greenstone terrain, it consists of volcano-sedimentary supracrustal rocks in several typically linear greenstone belts separated by areas of mainly intrusive granitic bodies. Many Archaean terrains show much the same 'stripy' aspect on the grand scale. [Greenstone belts](#) are dominated by metamorphosed basaltic volcanic rock, together with lesser proportions of ultramafic lavas and intrusions, and overlying metasedimentary rocks, also of Archaean age. Various hypotheses have been suggested for the formation of granite-greenstone terrains, the latest turning to a process of '[sagduction](#)'. However the relative flat nature of cratonic areas tells geologists little about their deeper parts. They tend to have resisted large-scale later deformation by their very nature, so none have been tilted or wholly obducted onto other such stable crustal masses during later collisional tectonic processes. Geophysics does offer insights however, using seismic profiling, geomagnetic and gravity surveys.

The Geological Survey of Canada has produced masses of geophysical data as a means of coping with the vast size and logistical challenges of the Canadian Shield. Recently five Canadian geoscientists have used gravity data from the Canadian Geodetic Survey to model the deep crust beneath the huge Abitibi granite-greenstone terrain, specifically addressing variations in its density in three dimensions. They also used cross sections produced by seismic reflection and refraction data along 2-D survey lines (Galley, C. *et al.* 2025. [Archean rifts and triple-junctions revealed by gravity modelling of the southern Superior Craton](#). *Nature Communications*, v. **16**, article 8872; DOI: 10.1038/s41467-025-63931-z). The group found that entirely new insights emerge from the variation in crustal density down to its base at the Moho (Mohorovičić discontinuity). These data show large linear bulges in the Moho separated by broad zones of thicker crust.



Geology of the Abitibi Terrane (upper); Depth to the Moho beneath the Abitibi Terrane with rifts and VMS deposits superimposed (lower). Credit: After Galley et al. Figs 1 and 5.

Galley *et al.* suggest that the zones are former sites of lithospheric extensional tectonics and crustal thinning: rifts from which ultramafic to mafic magmas emerged. They consider them to be akin to modern mid-ocean and continental rifts. Most of the rifts roughly parallel the trend of the greenstone belts and the large, long-lived faults that run west to east across the Abitibi Terrain. This suggests that rifts formed under the more ductile lithospheric condition of the Neoproterozoic set the gross fabric of the granites and greenstones. Moreover, there are signs of two triple junctions where three rifts converge: fundamental features of modern plate tectonics. However, both rifts and junctions are on a smaller scale than those active at present. The rift patterns suggest plate tectonics in miniature, perhaps indicative of more vigorous mantle convection during the Archaean Eon.

There is an interesting spin-off. The Abitibi Terrane is rich in a variety of mineral resources, especially volcanic massive-sulfide deposits (VMS). Most of them are associated with the suggested rift zones. Such deposits form through sea-floor hydrothermal processes, which Archaean rifting and triple junctions would have focused to generate clusters of 'black smokers' precipitating large amounts of metal sulfides. Galley *et al*'s work is set to be applied to other large cratons, including those that formed earlier in the Archaean: the Pilbara and Kaapvaal cratons of Australia and South Africa. That could yield better insights into earlier tectonic processes and test some of the hypotheses proposed for them

See also: [Archaean Rifts, Triple Junctions Mapped via Gravity Modeling](#). *Scienmag*, 6 October 2025

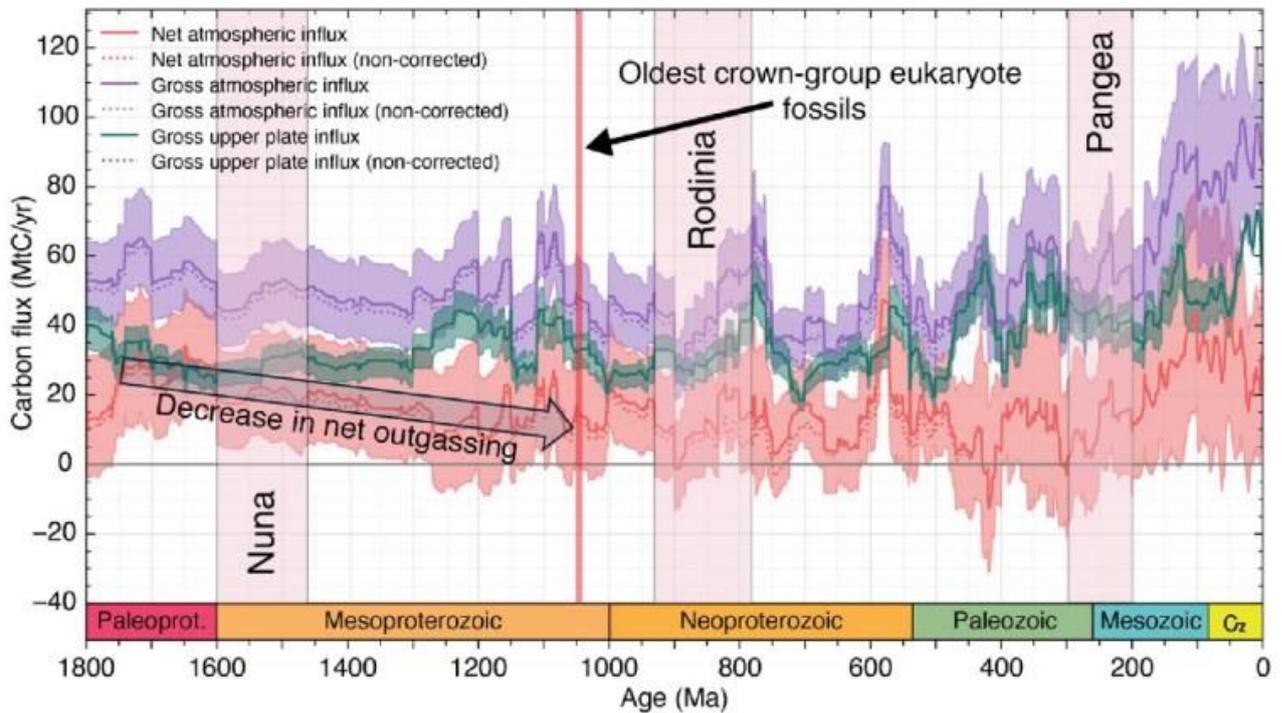
The 'boring billion' years of the Mesoproterozoic: plate tectonics and the eukaryotes

PUBLISHED ON [December 10, 2025](#)

The emergence of the eukaryotes – of which we are a late-entry member – has been debated for quite a while. In 2023 *Earth-logs* reported that a study of 'biomarker' [organic chemicals in Proterozoic sediments](#) suggests that eukaryotes cannot be traced back further than about 900 Ma ago using such an approach. At about the same time another biomarker study showed signs of a eukaryote presence at around 1050 Ma. Both outcomes seriously contradicted a 'molecular-clock' approach based on the DNA of modern members of the Eukarya and estimates of the rate of genetic mutation. That method sought to deduce the time in the past when the [last eukaryotic common ancestor](#) (LECA) appeared. It pointed to about 2 Ga ago, i.e. a few hundred million years after the Great Oxygenation Event got underway. Since eukaryote metabolism depends on oxygen, the molecular-clock result seems reasonable. The biomarker evidence does not. But were the Palaeo- and Mesoproterozoic Eras truly 'boring'? A recent paper by Dietmar Müller and colleagues from the Universities of Sydney and Adelaide, Australia definitely shows that geologically they were far from that (Müller, R.D. *et al.* 2025. [Mid-Proterozoic expansion of passive margins and reduction in volcanic outgassing supported marine oxygenation and eukaryogenesis](#). *Earth and Planetary Science Letters*, v. **672**; DOI: 10.1016/j.epsl.2025.119683).

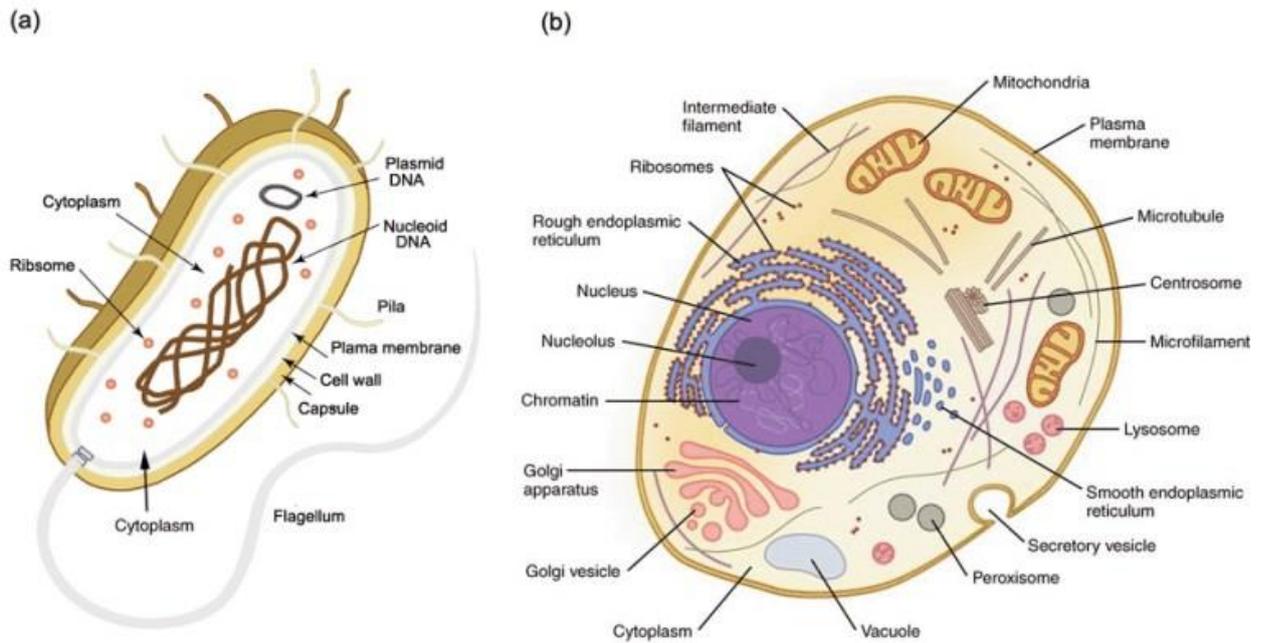
From 1800 to 800 Ma two supercontinents – [Nuna-Columbia](#) and [Rodinia](#) – aggregated nearly all existing continental masses, and then broke apart. Continents had collided and then split asunder to drift. So plate tectonics was very active and encompassed the entire planet, as Müller *et al*'s [palaeogeographic animation](#) reveals dramatically. Tectonics behaved in much the same fashion through the succeeding Neoproterozoic and Phanerozoic to build-up then fragment the more familiar supercontinent of Pangaea. Such dynamic events emit magma to form new oceanic lithosphere at oceanic rift systems and arc volcanoes above subduction zones, interspersed with plume-related large igneous provinces and they wax and wane. Inevitably, such partial melting delivered carbon dioxide to the atmosphere. Reaction on land and in the rubbly flanks of spreading ridges between new lithosphere and dissolved CO₂ drew down and sequestered some of that gas in the form of solid carbonate minerals. Continental collisions raised the land surface and the pace of weathering, which also acted as a carbon sink. But they also involved metamorphism that released carbon dioxide from limestones involved in the crustal transformation. This protracted and changing

tectonic evolution is completely bound up through the rock cycle with geochemical change in the carbon cycle.



Carbon influx (million tons per year) into tectonic plates and into the ocean-atmosphere system from 1800 Ma to present. The colour bands represent: total carbon influx into the atmosphere (mauve); sequestered in tectonic plates (green); net atmospheric influx i.e. total minus carbon sequestered into plates (orange). The widths of the bands show the uncertainties of the calculated masses shown as darker coloured lines.

From the latest knowledge of the tectonic and other factors behind the accretion and break-up of Nuna and Rodinia, Müller *et al.* were able to model the changes in the carbon cycle during the 'boring billion' and their effects on climate and the chemistry of the oceans. For instance, about 1.46 Ga ago, the total length of continental margins doubled while Nuna broke apart. That would have hugely increased the area of shallow shelf seas where living processes would have been concentrated, including the photosynthetic emission of oxygen. In an evolutionary sense this increased, diversified and separated the ecological niches in which evolution could prosper. It also increased the sequestration of greenhouse gas through reactions on the flanks of a multiplicity of oceanic rift systems, thereby cooling the planet. Translating this into a geochemical model of the changing carbon cycle (see figure) suggests that the rate of carbon addition to the atmosphere (outgassing) halved during the Mesoproterozoic. The carbon cycle and probable global cooling bound up with Nuna's breakup ended with the start of Rodinia's aggregation about 1000 Ma ago and the time that biomarkers first indicate the presence of eukaryotes.



Simplified structures of (a) a prokaryote cell; (b) a simple eukaryote animal cell. Plants also contain organelles called chloroplasts

So, did tectonics play a major role in the rise of the Eukarya? Well, of course it did, as much as it was subsequently the changing background to the appearance of the Ediacaran animals and the evolutionary carnival of the Phanerozoic. But did it affect the billion-year delay of ‘eukaryogenesis’ during prolonged availability of the oxygen that such a biological revolution demanded? Possibly not. Lyn Margulis’s hypothesis of the [origin of the basic eukaryote cell by a process of ‘endosymbiosis’](#) is still the best candidate 50 years on. She suggested that such cells were built from various forms of bacteria and archaea successively being engulfed within a cell wall to function together through symbiosis. Compared with prokaryote cells those of the eukaryotes are enormously complex. At each stage the symbionts had to be or become compatible to survive. It is highly unlikely that all components entered the relationship together. Each possible kind of cell assembly was also subject to evolutionary pressures. This clearly was a slow evolutionary process, probably only surviving from stage to stage because of the global presence of a little oxygen. But the eukaryote cell may also have been forced to restart again and again until a stable form emerged.

See also: [New Clues Show Earth’s “Boring Billion” Sparked the Rise of Life](#). *SciTechDaily*, 3 November 2025