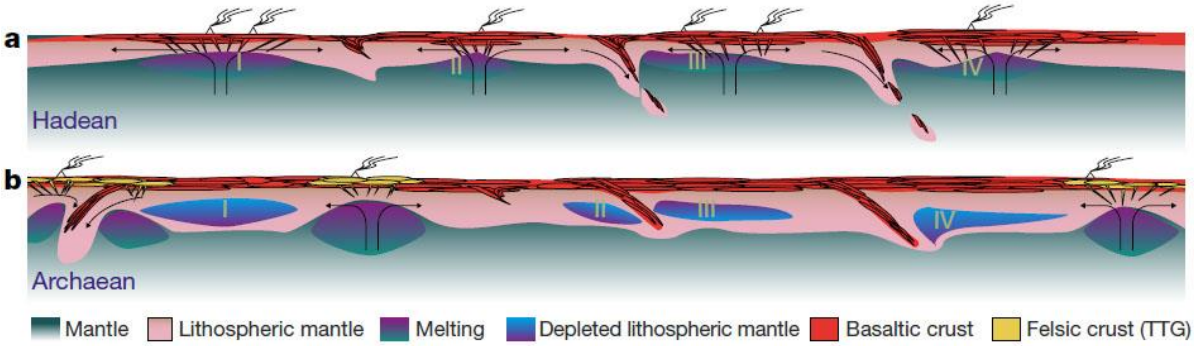
Tectonics

Weak lithosphere delayed the formation of continents (January 2021)

There are very few tangible signs that the Earth had continents at the surface before about 4 billion years (Ga) ago. The most cited evidence that they may have existed in the Hadean Eon are zircon grains with radiometric ages up to 4.4 Ga that were recovered from much younger sedimentary rocks in Western Australia. These tiny grains also show isotopic anomalies that support the existence of continental material, i.e. rocks of broadly granitic composition, only 100 Ma after the Earth formed (see: Zircons and early continents no longer to be sneezed at; February 2006). So, how come relics of such early continents have yet to be discovered in the geological record? After all granitic rocks – in the broad sense – which form continents are so less dense than the mantle that modern subduction is incapable of recycling them en masse. Indeed, mantle convection of any type in the hotter Earth of the Hadean seems unlikely to have swallowed continents once they had formed. Perhaps they are hiding in another guise among younger rocks of the continental crust. But, believe me; geologists have been hunting for them, to no avail, in every scrap of existing continental crust since 1971 when gneisses found in West Greenland by New Zealander Vic McGregor turned out to be almost 3.8 Ga old. This set off a grail-quest, which still continues, to negate James Hutton's 'No vestige of a beginning …' concept of geological time.

There is another view. Early continental lithosphere may have returned to the mantle piece by piece by other means. One that has been happening since the Archaean is as debris from surface erosion and its transportation to the ocean floor, thence to be subducted along with denser material of the oceanic lithosphere. Another possibility is that before 4 Ga continental lithosphere had far less strength than characterised it in later times; it may have been continually torn into fragments small enough for viscous drag to defy buoyancy and consign them into the mantle by convective processes. Two things seem to confer strength on continental lithosphere younger than 4 billion years: its depleted surface heat flow and heat-production that stem from low concentrations of radioactive isotopes of uranium, thorium and potassium in the lower crust and sub-continental mantle; bolstering by cratons that form the cores of all major continents. Three geoscientists at Monash University in Victoria, Australia have examined how parts of early convecting mantle may have undergone chemical and thermal differentiation (Capitanio, F.A. *et al*. 2020. Thermochemical lithosphere differentiation and the origin of cratonic mantle. *Nature*, v. **588**, p. 89-94; DOI: 10.1038/s41586-020-2976-3). These processes are an inevitable outcome of the tendency for mantle melting to begin as it becomes decompressed when pressure decreases when it rises during convection. Continual removal of the magmas produced in this way would remove not only much of the residue's heat-producing capacity – U, Th and K preferentially enter silicate melts – but also its content of volatiles, especially water. Even if granitic magmas were completely recycled back to the mantle by the greater vigour of the hot, early Earth, at least some of the residue of partial melting would remain. Its dehydration would increase its viscosity (strength). Over time this would build what eventually became the highly viscous thick mantle roots (tectosphere) on which increasing amounts of the granitic magmas could stabilise to establish the oldest cratons. Over time more and more such cratonised crust would accumulate, becoming increasingly unlikely to be resorbed into the mantle. Although cratons are not zoned in terms of the age of their constituent rocks, they do jumble together several billion years' worth of continental crust in what used to be called 'the Basement Complex'.



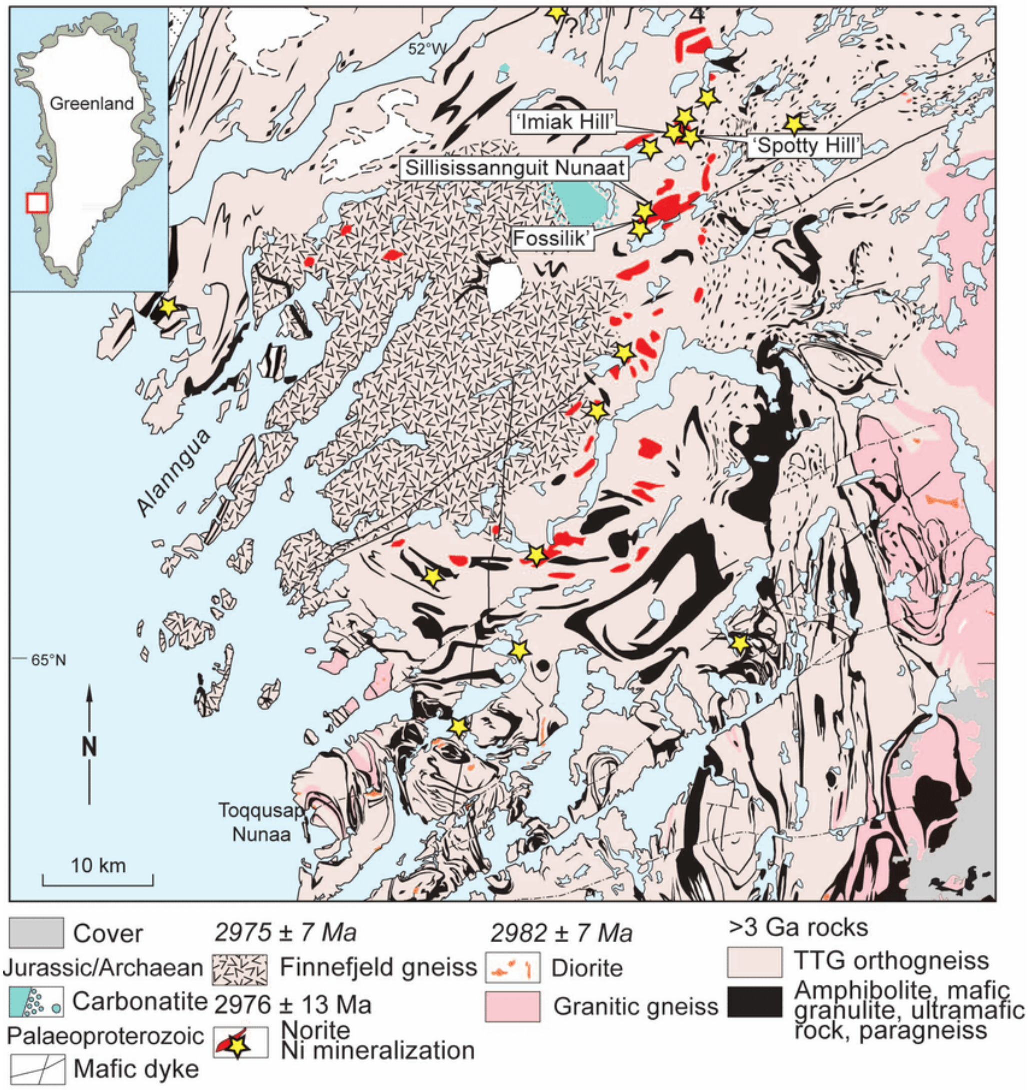
Development of depleted and viscous sub-continental mantle on the early Earth – a precedes b – TTG signifies tonalite-trondhjemite-granodiorite rocks typical of Archaean cratons (Credit, Capitanio et al.; Fig 5)

Early in this process, heat would have made much of the lithosphere too weak to form rigid plates and the tectonics with which geologists are so familiar from the later parts of Earth's history. The evolution that Capitanio *et al*. propose suggests that the earliest rigid plates were capped by Archaean continental crust. That implies subduction of oceanic lithosphere starting at their margins, with intra-oceanic destructive plate margins and island arcs being a later feature of tectonics. It is in the later, Proterozoic Eon that evidence for accretion of arc terranes becomes obvious, plastering their magmatic products onto cratons, further enlarging the continents.

The oldest known impact structure (?) (January 2021)

That large, rocky bodies in the Solar System were heavily bombarded by asteroidal debris at the end of the Hadean Eon (between 4.1 to 3.8 billion years ago) is apparent from the ancient cratering records that they still preserve and their matching with dating of impact-melt rocks on the Moon. Being a geologically dynamic planet, the Earth preserves no tangible, indisputable evidence for this Late Heavy Bombardment (LHB), and until quite recently could only be *inferred* to have been battered in this way. That it actually did happen emerged from a study of tungsten isotopes in early Archaean gneisses from Labrador, Canada (see: Tungsten and Archaean heavy bombardment, August 2002; and Did mantle chemistry change after the late heavy bombardment? September 2009). Because large impacts deliver such vast amounts of energy in little more than a second (see: Graveyard for asteroids and comets, Chapter 10 in *Stepping Stones*) they have powerful consequences for the Earth System, as witness the Chicxulub impact off the Yucatán Peninsula of Mexico that resulted in a mass extinction at the end of the Cretaceous Period. That seemingly unique coincidence of a large impact with devastation of Earth's ecosystems seems likely to have resulted from the geology beneath the impact; dominated by thick evaporite beds of calcium sulfate whose extreme heating would have released vast amounts of SO_2 to the atmosphere. Its fall-out as acid rain would have dramatically affected marine organisms with carbonate shells. Impacts on land would tend to expend most of their energy throughout the lithosphere, resulting in partial melting of the crust or the upper mantle in the case of the largest such events.

The further back in time, the greater the difficulty in recognising visible signs of impacts because of erosion or later deformation of the lithosphere. With a single, possible exception, every known terrestrial crater or structure that may plausibly be explained by impact is younger than 2.5 billion years; i.e. they are post-Archaean. Yet rocky bodies in the Solar System reveal that after the LHB the frequency and magnitude of impacts steadily decreased from high levels during the Archaean; there must have been impacts on Earth during that Eon and some may have been extremely large. In the least deformed Archaean sedimentary sequences there is indirect evidence that they did occur, in the form of spherules that represent droplets of silicate melts (see: Evidence builds for major impacts in Early Archaean; August 2002, and Impacts in the early Archaean; April 2014), some of which contain unearthly proportions of different chromium isotopes (see: Chromium isotopes and Archaean impacts; March 2003). As regards the search for very ancient impacts, rocks of Archaean age form a very small proportion of the Earth's continental surface, the bulk having been buried by younger rocks. Of those that we can examine most have been subject to immense deformation, often repeatedly during later times.



The Archaean geology of part of the Akia Terrane (Manitsoq area) in West Greenland. The suggested impact structure is centred on the Finnefjeld Gneiss (V symbols) surrounded by highly deformed ultramafic to mafic igneous rocks. (Credit: Jochen Kolb, Karlsruhe Institute of Technology, Germany)

There is, however, one possibly surviving impact structure from Archaean times, and oddly it became suspected in one of the most structurally complex areas on Earth; the Akia Terrane of West Greenland. Aeromagnetic surveys hint at two concentric, circular anomalies centred on a 3.0 billion years-old zone of grey gneisses (see figure) defining a cryptic structure. It is is surrounded by hugely deformed bodies of ultramafic and mafic rocks (black) and nickel mineralisation (red). In 2012 the whole complex was suggested to be a relic of a major impact of that age, the ultramafic-mafic bodied being ascribed to high degrees of impact-induced melting of the underlying mantle. The original proposers backed up their suggestion with several associated geological observations, the most crucial being supposed evidence for shock-deformation of mineral grains and anomalous concentrations of platinum-group metals (PGM).

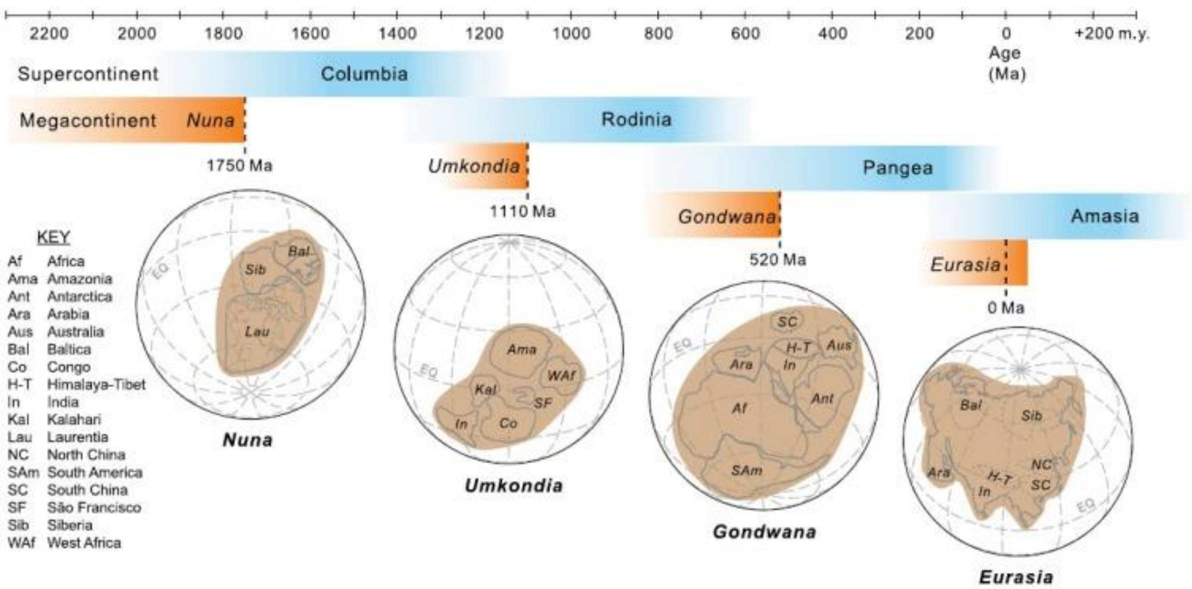
A multinational team of geoscientists have subjected the area to detailed field surveys, radiometric dating, oxygen-isotope analysis and electron microscopy of mineral grains to test this hypothesis (Yakymchuck, C. and 8 others 2020. Stirred not shaken; critical evaluation of a proposed Archean meteorite impact in West Greenland. *Earth and Planetary Science Letters*, v. **557**, article 116730 (advance online publication); DOI: 10.1016/j.epsl.2020.116730). Tectonic fabrics in the mafic and ultramafic rocks are clearly older than the 3.0 Ga gneisses at the centre of the structure. Electron microscopy of ~5500 zircon grains show not a single example of parallel twinning associated with intense shock. Oxygen isotopes in 30 zircon grains fail to confirm the original proposers' claims that the whole area has undergone hydrothermal metamorphism as a result of an impact. All that remains of the original suggestion are the nickel deposits that do contain high PGM concentrations; not an uncommon feature of Ni mineralisation associated with mafic-ultramafic intrusions, indeed much of the world's supply of platinoid metals is mined from such bodies. Even if there had been an impact in the area, three phases of later ductile deformation that account for the bizarre shapes of these igneous bodies would render it impossible to detect convincingly.

The new study convincingly refutes the original impact proposal. The title of Yakymchuck *et al.'s* paper aptly uses Ian Fleming's recipe for James Bond's tipple of choice; multiple deformation of the deep crust does indeed stir it by ductile processes, while an impact definitely provides a big shake. For the southern part of the complex (Toqqusap Nunaa), tectonic stirring was amply demonstrated in 1957 by Asger Berthelsen of the Greenland Geological Survey (Berthelsen, A. 1957. The structural evolution of an ultra- and polymetamorphic gneiss-complex, West Greenland. *Geologische Rundschau*, v. **46**, p. 173-185; DOI: 10.1007/BF01802892). Coming across his paper in the early 1960s I was astonished by the complexity that Berthelsen had discovered, which convinced me to emulate his work on the Lewisian Gneiss Complex of the Inner Hebrides, Scotland. I was unable to match his efforts. The Akia Terrane has probably the most complicated geology anywhere on our planet; the original proposers of an impact there should have known better …

When did supercontinents start forming? (April 2021)

Plate tectonics is easily thought of as being dominated by continental drift, the phenomenon that Alfred Wegener recognised just over a century ago. So it is at present, the major continents being separated by spreading oceans. Yet, being placed on a nearspherical planet, continents also move closer to others; eventually to collide and weld together. Part of Wegener's concept was that modern continents formed from the breakup of a single large one that he called Pangaea; a supercontinent. The current drifting apart began in earnest around the end of the Triassic Period (~200 Ma), after 200 Ma of Pangaea's dominance of the planet along with a single large ocean (Panthalassa) covering 70% of the Earth's surface. Wegener was able to fit Pangaea together partly on the basis of evidence from the continents' earlier geological history. In particular the refit joined up zones of intense deformation from continent to continent. Although he did not dwell on their origin, subsequent research has shown these zones were the lines of earlier collisions between older continental blocks, once subduction had removed the intervening oceanic lithosphere; Pangaea had formed from an earlier round of continental drift. Even older collision zones within the pre-Pangaea continental blocks suggested the former existence of previous supercontinents.

Aided by the development of means to divine the [position of the magnetic poles] relative to differently aged blocks on the continents, Wegener's basic methods of refitting have resulted in the concept of supercontinent cycles of formation and break-up. It turns out that supercontinents did not form by all earlier continental clanging together at one time. The most likely scenario is that large precursors or 'megacontinents' (Eurasia is the current example) formed first, to which lesser entities eventually accreted A summary of the latest ideas on such global tectonic cycles appeared in the November 2020 issue of *Geology* (Wang, c. *et al*. 2020. [The role of megacontinents in the supercontinent cycle]. *Geology*, v. **49** p. 402-406; DOI: 10.1130/G47988.1). Chong Wang of the Chinese Academy of Sciences and colleagues from Finland and Canada identify three such cycles of megacontinent formation and the accretion around them of the all-inclusive supercontinents of Columbia, Rodinia and Pangaea since about 1750 Ma (Mesoproterozoic). They also suggest that a future supercontinent (Amasia) is destined to agglomerate around Eurasia.



Known megacontinents in relation to suggested supercontinents since the Mesoproterozoic (credit: Wang et al.; Fig 2)

The further back in time, the more cryptic are ancient continent-continent collision zone or sutures largely because they have been re-deformed long after they formed. In some cases younger events that involved heating have reset their radiometric ages. The oldest evidence of crustal deformation lies in cratons, where the most productive source of evidence for clumping of older continental masses is the use of palaeomagnetic pole positions. This is not feasible for the dominant metamorphic rocks of old suture zones, but palaeomagnetic measurements from old rocks that have been neither deformed nor metamorphosed offer the possibility of teasing out ancient supercontinents. Commonly cratons show signs of having been affected by brittle extensional deformation, most obviously as swarms of vertical sheets or dykes of often basaltic igneous rocks. Dykes can be dated readily and do yield reliable palaeomagnetic pole positions. Some cratons have multiple dyke swarms. For example the Archaean Yilgarn Craton of Western Australia, founded on metamorphic and plutonic igneous crust that formed by tectonic accretion between 3.8 to 2.7 Ga, has five of them spanning 1.4 billion years from late-Archaean (2.6 Ga) to Mesoproterozoic (1.2 Ga). Throughout that immense span of time the Yilgarn remained as a single continental block. Also, structural trends end abrubtly at the craton margins, suggesting that it was once part of a larger 'supercraton' subsequently pulled apart by extensional tectonics. The eleven known cratons show roughly the same features.

On the strength of new, high quality pole positions from dykes of about the same ages (2.62 and 2.41 Ga) cutting the Yilgarn and Zimbabwe cratons, geoscientists from Australia, China, Germany, Russia and Finland, based at Curtin University in Western Australia, have attempted to analyse all existing Archaean and Palaeoproterozoic pole positions (Liu, Y. *et al*. 2021. Archean geodynamics: Ephemeral supercontinents or long-lived supercratons. *Geology*, v. **49** ; DOI: 10.1130/G48575.1). The Zimbabwe and Yilgarn cratons, though now very far apart, were part of the same supercraton from at least 2.6 Ga ago. Good cases can be made for several other such large entities, but attempting fit them all together as supercontinents by modelling is unconvincing. The modelled fit for the 2.6 Ga datum is very unlike that for 2.4 Ga; in the intervening 200 Ma all the component cratons ould have had to shuffle around dramatically, without the whole supercontinent edifice breaking apart. However, using the data to fit cratons together at two supercratons does seem to work, for the two assemblies remain in the same configurations for both the 2.6 and 2.4 Ga data.

Interestingly, all cratonic components of one of the supercratons show geological evidence of the major 2.4 Ga glaciation, whereas those of the other show no such climatic indicator. Yet the entity with glacial evidence was positioned at low latitudes around 2.4 Ga, the ice-free one spanning mid latitudes. This may imply that the Earth's axial tilt was far higher than at present. The persistence of two similar sized continental masses for at least 200 Ma around the end of the Archaean Eon also hints at a different style of tectonics from that with which geologists are familiar. Only palaeomagnetic data from the pre 2.6 Ga Archaean can throw light on that possibility. That requires older, very lightly or unmetamorphosed rocks to provide palaeopole positions. Only two cratons, the Pilbara of Western Australia and the Kaapvaal of South Africa, are suitable. The first yielded the oldest-known pole dated at 3.2 Ga, the oldest from the second is 2.7 Ga. A range of evidence suggests that Pilbara and Kaapvaal cratons were united during at least the late Archaean.

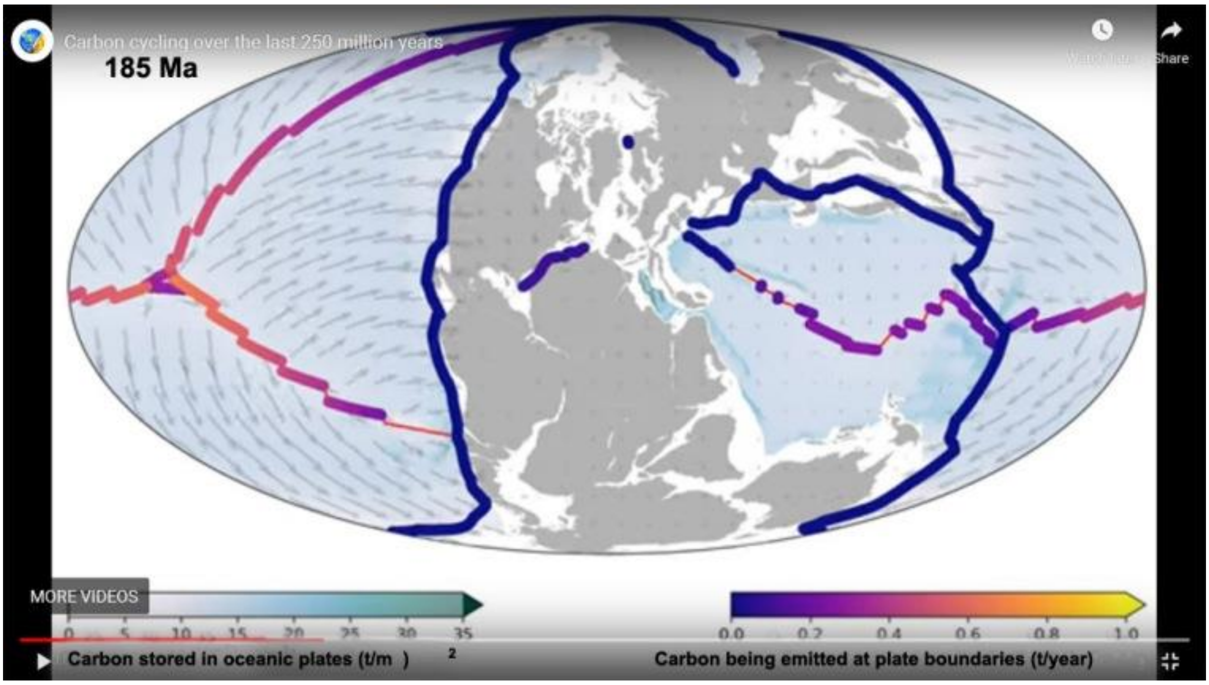
The only answer to the question posed by this item's title is 'There probably wasn't a single supercontinent at the end of the Archaean, but maybe two megacontinents or 'supercratons'. Lumps of continental lithosphere would move and – given time – collide once more than one lump existed, however the Earth's tectonics operated …

Climate and tectonics since 250 Ma (June 2021)

A central feature of the Earth's climate system is the way that carbon bound in two gases – carbon dioxide (CO_2) and methane (CH_4) – controls the amount of incoming solar energy that is retained by the atmosphere. Indeed, without one or the other our home world would have been locked in frigidity since shortly after its formation: a sterile, ice-covered planet. The 'greenhouse effect' has been ever-present because the material from which the Earth accreted contained carbon as well as every other chemical element from hydrogen to uranium. Naturally reactive, it readily combines with hydrogen and oxygen to form methane and carbon dioxide, which would have escaped the inner Earth as gases to enter the earliest atmosphere as a 'comfort blanket', along with water vapour, another greenhouse gas. Their combined effects have remained crudely balanced so that neither inescapable frigidity nor surface temperatures high enough to boil-off the oceans have ever occurred in the last 4.5 billion years. Earth has remained like the wee bear's porridge in the Goldilocks story! Even so, global climate has fluctuated again and again from that akin to a steamy greenhouse, through long periods of moderation to extensive glacial conditions, including three that extended from pole-to-pole – 'Snowball' Earths – during in the Precambrian. During the Phanerozoic the Earth has entered three long periods of generally low global temperatures, in the Ordovician, the Carboniferous and during the last 2.5 Ma that allowed polar ice caps and sea-ice to extend a third of the way to the Equator. These were forced back and forth repeatedly by cyclical influences apparently triggered by astronomically controlled changes to Earth's orbital and rotational parameters – the Milankovich Effect. Anthropogenic emissions of greenhouse gases in vast and increasing amounts now threaten to disrupt natural climate variation, effectively overthrowing the gravitational influences of distant giant planets that have controlled climate changes that shaped our own evolution since the genus *Homo* first emerged.

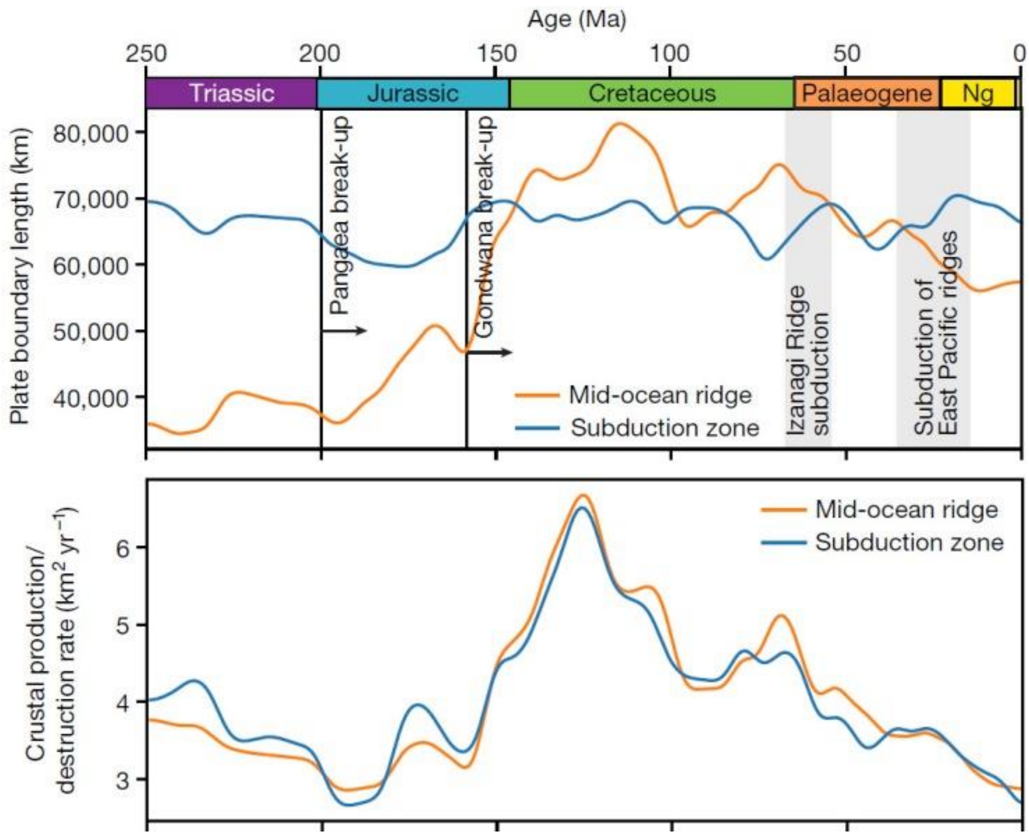
Bubbles of air trapped in cores through the ice sheets of Antarctica and Greenland record decreased volumes of land ice as CO_2 content increased and the opposite during glacial episodes. Somehow in step with the astronomical forcing the Earth released greenhouse gas to warm the climate and drew it down to bring on cooling. Since all life forms are built from carbon-rich compounds and some extract it from the environment to build carbonate hard parts, climate and life on land and in the oceans are interlinked. In fact life and death are involved, because once dead organisms and their hard parts are buried before being oxidised in sediments on land, as in peat and ultimately coal, and on the ocean floors as limestones or carbonaceous mudstones, atmospheric carbon is sequestered. Exposed to acid water containing dissolved CO_2 from the atmosphere or to oxygen, respectively, the two forms of carbon in solid form are released as greenhouse gas once more. Both take place when sedimentary deposits are exhumed as a result of erosion and tectonics. Another factor is the abundance of available nutrients, themselves released and distributed by erosion and agents of transportation. At present surface waters of the most distant parts of the oceans contains plenty of such nutrients, except for a vital one, dissolved iron. So they are wet 'deserts'. It seems that during the much dustier times of glacial episodes iron in fine form reached far out into the world's oceans so that phytoplankton at the base of the food chain 'bloomed 'and so did planktonic animals. Dead organisms 'rained' to the ocean floor so drawing down CO_2 from the atmosphere and decreasing the greenhouse effect. The surface parts of the carbon and rock cycles are extremely complex and climatologists have yet to come to grips with modelling its future climates convincingly. Yet the carbon cycle and much deeper parts of the rock cycle are interwoven too.

Carbon in sedimentary rock can be heated by burial, and some can be subducted to great depths at destructive plate margins together. The same applies to in ocean-floor basalts that have been permeated by circulating sea water through hydrothermal circulation to form carbonates in the altered volcanic rock. In both cases carbon stored for hundreds of million years can be released by metamorphism in orogenic belts at zones of continental collision and deep below island arcs. Carbon from mantle depths that has never 'seen the light of day' is also added to the atmosphere when magmas form below oceanic constructive margins, hot spots and subduction zones, and where magmas flood the continental surface. Consequently, plate tectonics and deep mantle convection have surely played a long-term role in the evolution of our planet's climate system. Geoscientists based in Australia and the UK have used geochemical data to reconstruct the stores of carbon in oceanic plates and thermodynamic modelling to track what may have happened to it and the climate through the last 250 Ma (Müller, R.D. *et al*. 2022. [Evolution of Earth's tectonic carbon conveyor belt](). *Nature*, v. **605**, p. 629-639; DOI: 10.1038/s41586-022-04420-x). Their review is an important step in understanding what underpins climate on a geological time scale, onto which much shorter-term surface influences are superimposed.



The amount of carbon being outgassed as CO2 each year along plate boundaries in the early Jurassic (185 Ma) shown in dark purple (low) to yellow (high). Also shown in shades of blue is the accumulation of carbon stored in each square metre of the ocean plates. Plate motions are shown as grey arrows (credit: Müller, R.D. et al. Clip from video in Supplementary Information)

At mid-ocean ridges basaltic magma wells up from mantle depths and loses much of its content of dissolved CO_2. The annual outgassing at ridges, which depends on the global rate of plate formation, has varied from 13 to 30 million tonnes of carbon (MtC yr^{-1}) since the start of the Mesozoic Era 250 Ma ago. Similarly, there is greenhouse-gas escape from volcanic arcs above subduction zones, estimated to have ranged from 0 to 18 MtC yr^{-1}. As an oceanic plate moves away from its source various processes sequester CO_2 into the oceanic crust and upper mantle through accumulation of deep-sea sediments and hydrothermal alteration of basaltic crust and peridotite mantle (ranging from 30 to 311 MtC yr^{-1}). Of this influx of carbon into oceanic plates between 36 to 103 MtC yr^{-1} has gone down subduction zones in descending slabs. Between 0 to 49 MtC yr^{-1} of that has been outgassed by arc volcanic activity or absorbed into the overriding plate. The rest continues down into the deep mantle, perhaps to form diamonds. Overall, when the rate at which oceanic plates grow is rapid and plate motion speeds up, outgassing should be high. When plate growth slows, so does the rate of CO_2 release. Variations in plate growth can be estimated from the magnetic reversal stripes above the ocean floors. The authors have released an animation of the break-up of Pangaea (well worth watching at full screen – you can skip the ad at the start), with the rate of carbon emission at ridges and volcanic arcs being colour-coded. Also shown is the storage of carbon within oceanic plats plates as time passes.



Length of mid-ocean ridges (orange) and subduction zones (blue) through the last 250 Ma (top). The areas of oceanic crust produced at ridges and consumed by subduction (bottom) (credit: Müller, R.D. et al., Figs 1a, 1c)

Before Pangaea began to break up at the end of the Triassic (200 Ma) the total length of mid-ocean ridges was at a minimum of about 40 thousand km. Through the Jurassic it never exceeded 50,000 km, but rose to a maximum of 80,000 km during the Cretaceous then declined slowly to the current length of 60,000 km. Throughout the last 250 Ma the length of subduction zones stayed roughly the same at about 65 thousand km – not always in the same places – although the overall rate of subduction changed in line with the rate of oceanic plate growth (the volume that is added must be balanced roughly by the amount that returns to the mantle). Between the end of the Jurassic and the mid-Cretaceous crustal production and destruction doubled, shown by the bottom plot in the figure above. The very fast movement of plates and an increase in the global length of ridges during Jurassic to mid-Cretaceous times led to a dramatic increase in CO_2 outgassing from ridges so that its content in the atmosphere rose as high as 1200 ppm – more than four times that before the Industrial Revolution. That level resulted in global 'hothouse' conditions during the Cretaceous. Another factor behind the Cretaceous climate was a decrease in the global complement of mountains. That led to decreases in erosion and the weathering of silicates by acid rain, thus reducing natural sequestration of carbon.

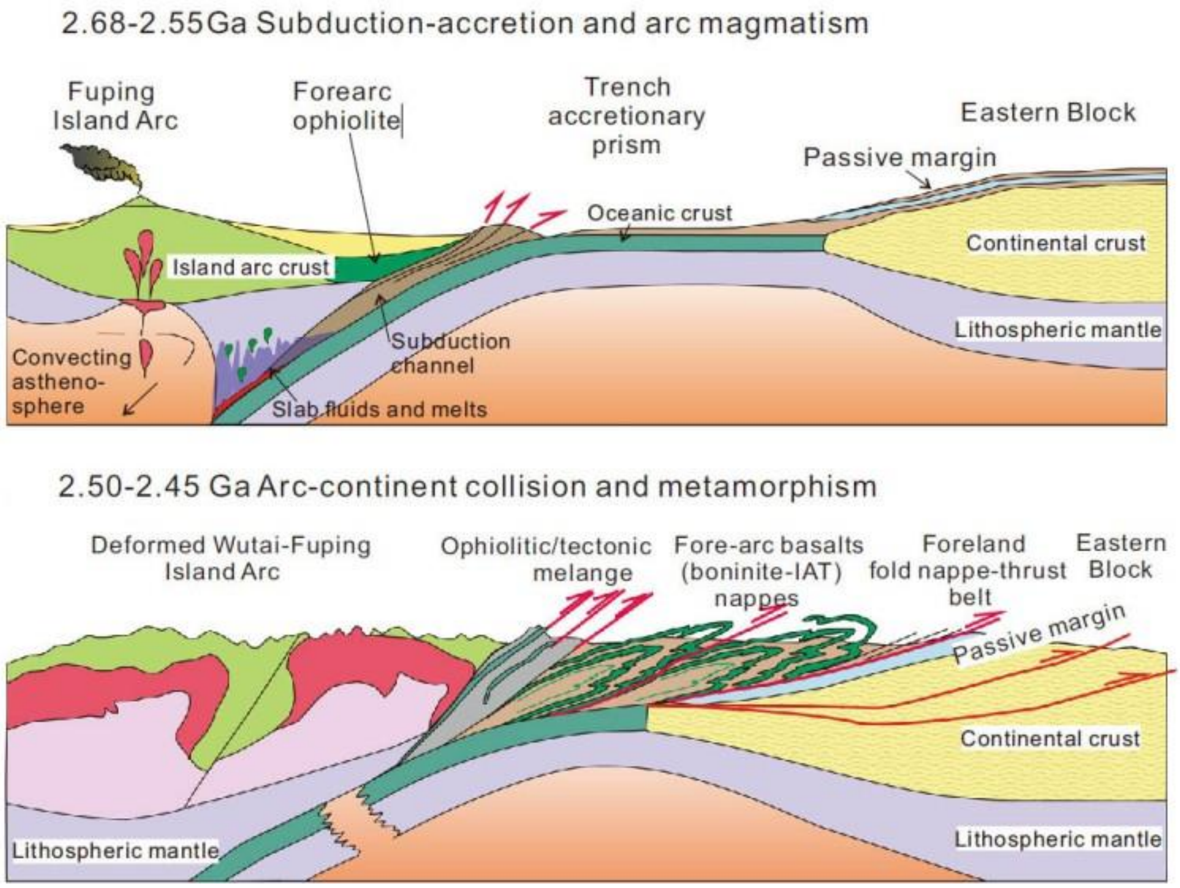
During the Cenozoic (after 65 Ma) declining ridge outgassing was actually outpaced by that associated with subduction, according to the modelling. That is strange, for by around 35 Ma glaciation had begun on Antarctica as the Earth was cooling, which implies a major, unexpected sink for excess CO_2. The most likely way this might have arisen is through increased erosion and silicate weathering on the exposed continents that consumed CO_2 faster than tectonics was releasing the gas. The length of continental arcs shows no sign of a major increase during the Cenozoic, which might have accelerated that kind of sequestration, but a variety of proxies for signs of weathering definitely suggests that there was an upsurge. Also there was increased storage of carbon on the deep ocean floor, shown by the video. Increased calcium released by weathering to enter ocean water in solution would allow more planktonic organisms to secrete calcite ($CaCO_3$) skeletons that would then fall to the ocean floor when they died.

There may be more to be discovered in this hugely complex interplay between tectonics and climate. For instance, when the bottom waters of the oceans are oxygenated by deep currents of cold dense seawater sinking from polar regions, carbon in tissues of sunken dead organism is oxidised to release CO_2. If bottom waters are anoxic, this organic carbon is preserved in sediments. The authors mention this as something to be considered in their future work on the 'tectonic carbon conveyor belt'.

Nappe tectonics at the end of the Archaean (November 2021)

The beginning of modern-style plate tectonics is still debated in the absence of definite evidence. Because Earth's mantle generates heat through radioactive decay and still contains heat left over from planetary accretion and core formation it must always have maintained some kind of heat transfer through some kind of circulatory motion involving the mantle and lithosphere. That must always too have involved partial melting and chemical differentiation that created materials whose density was lower than that of the mantle; i.e. continental crust. Since continental materials date back to more than 4 billion years ago and some may have been generated earlier in the Hadean, only to be largely resorbed, a generalised circulation and chemical differentiation have been Earth's main characteristics from the start. One view is that early circulation was a form of vertical tectonics without subduction via a sort of 'dripping' or delamination of particularly dense crustal materials back into the mantle. A sophisticated model of how the hotter early Earth worked in this way has been called 'lid tectonics', from which plate tectonics evolved as the Earth cooled and developed a thicker, more rigid lithosphere. Such an outer layer would then be capable of self-generating the slab pull that largely drives *lateral* motions of lithospheric plates. That process occurs once a slab of oceanic lithosphere becomes cool and dense enough to be subducted (see: How does subduction start?; August 2018).

The most convincing evidence for early plate tectonics would therefore be tangible signs of both subduction and large horizontal movements of lithospheric plates: common enough in the Neoproterozoic and Phanerozoic records, but not glaringly obvious in the earlier Archaean Eon. These unequivocal hallmarks have now emerged from studies of Archaean rocks in the Precambrian basement that underpins northern China and North Korea. The North China Craton has two main Archaean components: an Eastern Block of gneisses dated between 3.8 and 3.0 Ga and a Western Block of younger (2.6 to 2.5 Ga) gneisses, metavolcanics and metasediments. They are separated by a zone of high deformation. A key area for understanding the nature of the deformed Central Orogenic Belt is the Zanhuan Complex near the city of Kingtai (Zhong, YL. *et al.* 2021. [Alpine-style nappes thrust over ancient North China continental margin demonstrate large Archean horizontal plate motions](). *Nature Communications*, v. **12,** article6172, DOI: 10.1038/s41467-021-26474-7).



Schematic west to east cross sections through the Zanhuan Complex of northern China, showing early and final development of the Central Orogenic Belt in the North China Block . (Credit: Zhong, YL. et al.;Figs 10b and c)

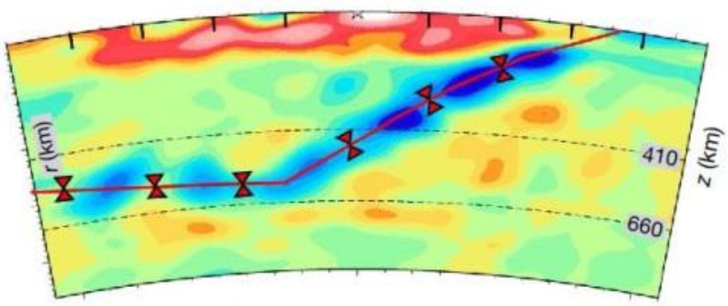
This small, complex area reveals that the older Eastern Block is unconformably overlain by Neoarchaean sediments, above which has been thrust a stacked series of nappes similar in size and form to those of the much younger Alpine orogenic belt of southern Europe. Though highly complex, the rocks involved having been folded and stretched by ductile processes, they are still recognisable as having originally been at the surface. Metavolcanics in the nappes can be assigned from their geochemistry to a late-Archaean fore-arc, through comparison with that of modern igneous rocks formed at such a setting in the Western Pacific. Thrust over the nappe complex is a jumble or mélange of highly deformed metasediments containing blocks of metabasalts and occasional ultramafic igneous rocks that geochemically resemble oceanic crust formed at a mid-ocean ridge. Some of them contain high-pressure minerals formed at depth in the mantle, indicating that they had once been subducted. The whole complex is cut by undeformed dykes of granitic composition dated at 2.5 Ga, confirming that the older rocks and the structures within them are Archaean in age. Thrust over the melange and tectonically underlying nappe complex are less-deformed volcanic rocks and granitic intrusions that closely resemble what is generally found in modern island arcs.

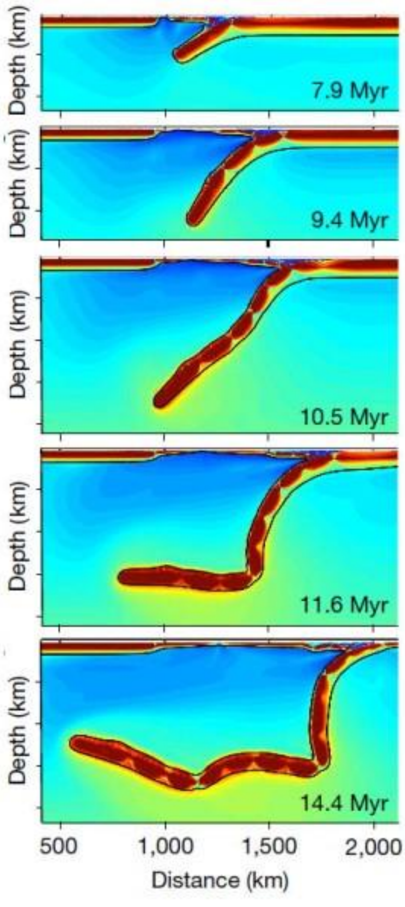
Orogenic belts bear witness to enormous crustal shortening caused by horizontal compressive forces. Assuming the average rate of modern subduction (2 cm yr^{-1}) the 178 Ma history of the Zanhuan Complex implies more than 3,500 km of lateral transport. 2.5 billion years ago, higher radioactive heat production in the mantle would have made tectonic overturning considerably faster The unconformity at the base of the complex suggests that it was driven over the equivalent of a modern passive, continental margin. So the complex provides direct evidence of horizontal plate tectonics and associated subduction during the latter stages of the Archaean that ranks in scale with that of many Phanerozoic orogenic belts, such as that of the European Alps. The Zanhuan Complex is a result of arc accretion that played a major role in many later orogens. The North China craton itself is reminiscent of continent-continent collision, as required in the formation of supercontinents.

New ideas on how subduction works (November 2021)

Nowadays, plate tectonics is thought mainly to be driven by the sinking of old, relatively cold and dense oceanic lithosphere at subduction zones: slab-pull force dominates the current behaviour of the outermost Earth. At the eastern edge of Eurasia subduction beneath Japan has yet to consume Pacific Ocean lithosphere younger than 180 Ma (Middle Jurassic). The Pacific Plate extends eastwards from there for over 7000 km to its source at the East Pacific Rise. That spreading axis disappeared quite recently beneath the North American Plate between Baha California and northern California. It has been subducted. Since, to a first approximation, sea-floor spreading is at the same pace either side of mid-ocean constructive plate margins, subduction at the western edge of the North America has consumed at least 7000 km of old ocean lithosphere. Slab-pull force there has been sustained for probably more than 250 Ma. As a result several former island arcs have been plastered onto the leading edge of the North American Plate to create the geological complexity of its western states. If at any time the weight of the subducting slab had caused it leading edge literally to snap and fall independently wouldn't that have decreased slab-pull force or shut it off, and spreading at the East Pacific Rise, altogether? No, says active spreading of the vast expanse of the West Pacific plate

That dichotomy once encouraged scientists of the plate-tectonic era to assume that a subducted slab remains as strong as rigid plates at the surface. They believed that subduction merely bends a plate so that it can slide into the mantle. The use of seismic waves (seismic tomography) to peer into the mantle has revealed a far more complex situation. Beneath North America traces of subducted slabs are highly deformed and must have lost their rigidity, yet they still maintain slab-pull force. Three geoscientists from the Swiss Federal Institute of Technology Zurich, Switzerland, and the University of Texas at Austin, USA (Gerya T. V., Becovici, D. & Becker, T.W. 2021. Dynamic slab segmentation due to brittle–ductile damage in the outer rise. *Nature*, v. **599**, p 245-250; DOI: 10.1038/s41586-021-03937-x) used computer-generated models of how various forces and temperature conditions at small and large scales bear on the behaviour of slabs being subducted. Where a plate bends into a subduction zone its rigidity results in cracking and faulting of its no convex upper surface, while the base is compressed. Seismic anomalies in the descending slab reflect the formation of pulled-apart segments, similar to those in a bar of chocolate (for a possible example from an exhumed subduction zone see: A drop off the old block? May 2008). Thermo-mechanical modelling suggests that the slab becomes distinctly weakened through brittle damage and by reduction in grain size because of ductile deformation, yet each segment maintains a high viscosity relative to the surrounding mantle rocks. Under present conditions and those extrapolated back into the Proterozoic, where the slab is thinned between segments it remains sufficiently viscous to avoid segments detaching to sink independently of one another. Such *delamination* would reduce slab-pull force. Another process operates in the surrounding mantle. The occurrence of earthquakes in a subducted slab down to a depth of about 660 km – the level of a major discontinuity in the mantle where pressure induces a change in its mineralogy and density – confirms that a modern slab maintains some rigidity and deforms in a brittle fashion. But at this depth it cannot continue to descend steeply and travels horizontally along the discontinuity, pushed by the more shallow subduction. It can now become buckled as the mantle resists its lateral motion.





Left: the subduction zone beneath Japan defined by seismic tomography (yellow to red = lower seismic wave speeds – more ductile; yellow to blue = higher speeds – more rigid). Right: modelled evolution of viscosity in a similar subduction zone under modern conditions showing slab segmentation (blue to brown = increasing viscosity). (Credit: Gerya et al., Figs 4c & 1a-e)

Rather than trying to mimic the chaos beneath North America the authors compared their results with seismic tomography of the younger system of westward subduction beneath Japan. This allowed them to 'calibrate' their modelling against actual deep structure well-defined by seismic tomography. The tectonic jumble beneath North America probably resulted from a much longer history of eastwards subduction. The complexity there may be explained by successive foundering of deformed slabs into the deeper mantle looking a bit like a sheet of still viscous pie pastry dropped on its edge. This happened, perhaps, as island arcs that had formed in the eastern Pacific sporadically accreted to the continent as the intervening oceanic lithosphere was subducted.

There is ample evidence that modern-style subduction was widespread back as far as the Palaeoproterozoic. But in the Archaean the evidence is fitful: some hints of subduction, but plenty of contrary evidence. Gerya and co-workers suggest that higher heat production from radioactive decay mantle earlier in Earth's history would have reduced plate strength and mantle resistance to slab penetration. Subduction may have occurred but was interrupted repeatedly by foundering/delamination of individual detached segments at much shallower depths. That implies weaker as well as intermittent slab pull or, even further back, its complete absence, so that planetary recycling would then have required other mechanisms, such as 'drip tectonics'.

See also: Crushed resistance: Tectonic plate sinking into a subduction zone and Fate of sinking tectonic plates is revealed, *Science Daily*, 11 November 2021