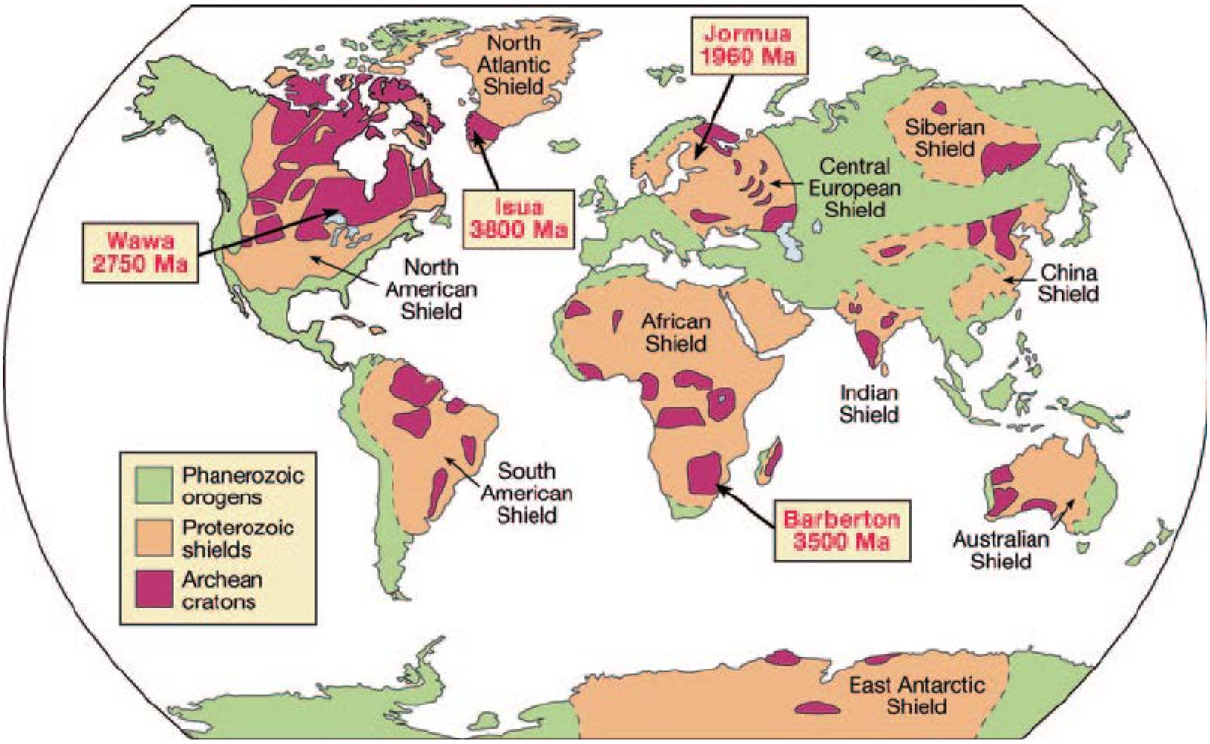
Tectonics

So, when *did* plate tectonics start up? (*February 2016*)

Tiny, 4.4 billion year old zircon grains extracted from much younger sandstones in Western Australia are the oldest known relics of the Earth system. But they don't say much about early tectonic processes. For that, substantial exposures of rock are needed, of which the undisputedly oldest are the Acasta gneisses 300 km north of Yellowknife in Canada's North West Territories, which have an age of slightly more than 4 Ga. The 'world's oldest rock' has been something of a grail for geologists and isotope geochemists who have combed the ancient Archaean cratons for 5 decades. But since the discovery of metasediments with an age of 3.8 Ga in West Greenland during the 1970s they haven't made much headway into the huge time gap between Earth's accretion at 4.54 Ga and the oldest known rocks (the Hadean Eon).



Archaean cratons (red), continental shields (orange). (Credit: Yildirim Dilek)

There have been more vibrant research themes about the Archaean Earth system, specifically the issue of when our planet settled into its modern plate tectonic phase. A sprinkling of work on reconstructing the deep structural framework of Archaean relics has convinced some that opposed motion of rigid, brittle plates was responsible for their geological architecture, whereas others have claimed signs of a more plastic and chaotic kind of deformation of the outer Earth. More effort has been devoted to using the geochemistry of all the dominant rocks found in the ancient cratons, seeking similarities with and differences from those of more recent vintage. There can be little doubt that the earliest processes did form crust whose density prevented or delayed it from being absorbed into the mantle. Even the 4.4 Ga zircons probably crystallized from magma that was felsic in composition. Once trapped by buoyancy at the surface and subsequently wrapped around by similarly low density materials continental crust formed as a more or less permanent rider on the Earth's deeper dynamics. But did it all form by the same kinds of process that we know to be operating today?

Plate tectonics involves the perpetual creation of rigid slabs of basalt-capped oceanic lithosphere at oceanic rift systems and their motions and interactions, including those with continental crust. Ocean floor cools as it ages and becomes hydrated by seawater that enters it. The bulk of it is destined eventually to oppose, head-to-head, the motions of other such plates and to deform in some way. The main driving force for global tectonics begins when an old, cold plate does deform, breaks, bends and drives downwards. Increasing pressure on its cold, wet basaltic top transforms it into a denser form: from a wet basaltic mineralogy (feldspar+pyroxene+amphibole) to one consisting of anhydrous pyroxene and garnet (eclogite) from which watery fluid is expelled upwards. Eclogite's density exceeds that of mantle peridotite and compels the whole slab of oceanic lithosphere to sink or subduct into the mantle, dragging the younger parts with it. This gravity-induced 'slab pull' sustains the sum total of all tectonic motion. The water rising from it induces the wedge of upper mantle above to melt partially, the resulting magma evolves to produce new felsic crust in island arcs whose destiny is to be plastered on to and enlarge older continental masses.

Relics of eclogites and other high-pressure, low-temperature versions of hydrated basalts incorporated into continents bear direct and unchallengeable witness to plate tectonics having operated back to about 800 Ma ago. Before that, evidence for plate tectonics is circumstantial and in need of special pleading. Adversarial to-ing and fro-ing seems to be perpetual, between geoscientists who see no reason to doubt that Earth has always behaved in this general fashion and others who see room for very different scenarios in the distant past. The non-Huttonian tendency suggests an early, more ductile phase when greater radioactive heat production in the mantle produced oceanic crust so fast that when it interacted with other slabs it was hot enough to resist metamorphic densification wherever it was forced down. Faster production of magma by the mantle without slab-pull could have produced a variety of 'recycling' turnover mechanisms that were not plate-tectonic.

One thing that geochemists have discovered is that the composition of Archaean continental crust is very different from that produced in later times. In 1985 Ross Taylor and Scott McLennan, then of the Australian National University, hit on the idea of using shales of different ages as proxies for the preceding continental crust from which they had been derived by long erosion (Taylor, S.R. & McLennan, S.M. 1985. *The continental crust, its composition and evolution : an examination of the geochemical record preserved in sedimentary rocks*. Blackwell; Oxford; ISBN: 0632011483). Archaean and younger shales differed in such a way that suggests that after 2.5 Ga (the end of the Archaean) vast amounts of feldspar were extracted from the continent-forming magmas. This left the later Precambrian and Phanerozoic upper crust depleted in the rare-earth element europium, which ended up in a mafic, feldspar-rich lower crust. On the other hand, no such mass fractionation had left that signature before 2.5 Ga. Along with two colleagues, another ANU geochemist, now at the University of Maryland, Roberta Rudnick has subsequently carried this approach further, culminating in a recent paper (Tang, M., Chen, K & Rudnick, R.L. 2016. Archean upper crust transition from mafic to felsic marks the onset of plate tectonics. *Science*, v. **351**, p. 372-375; DOI: 10.1126/science.aad5513). This uses nickel, chromium and zinc concentrations in ancient igneous and sedimentary rocks to track the contribution of magnesium (the 'ma' in 'mafic') to the early continents. The authors found that between 3.0 to 2.5 Ga continental additions shifted from a dominant, more mafic composition to one similar to that of later times by the end of the Archaean. Moreover, this accompanied a fivefold increase in the pace of continental growth. Such a spurt has long been suspected and widely suggested to mark to start of true plate tectonics: but an hypothesis bereft of evidence.

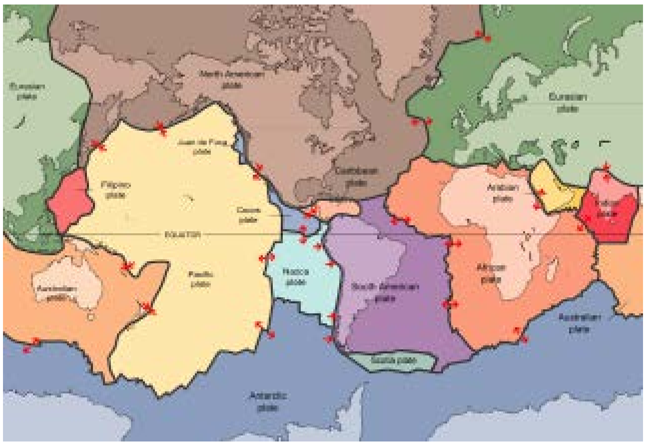
A better clue, in my opinion, came 30 years ago from a study of the geochemistry of actual crustal rocks that formed before and after 2.5 Ga (Martin, H. 1986. Effect of steeper Archean geothermal gradient on geochemistry of subduction-zone magmas. *Geology*, v. **14**, p. 753-756; DOI: 10.1130/0091-7613(1986)14<753:EOSAGG>2.0.CO;2). Martin showed that plutonic Archaean and post-Archaean felsic rocks of the continental crust lie in distinctly different fields on plots of their rare-earth element (REE) abundances. Archaean felsic plutonic rocks show a distinct trend of enrichment in light REE relative to heavy REE as measures of the degree of partial melting decreases, whereas the younger crustal rocks show almost constant, low values of heavy REE/light REE whatever the degree of melting. The conclusion he reached was that while in the post Archaean the source was consistent with modern subduction processes – i.e. partial melting of hydrated peridotite in the mantle wedge above subduction zones – but during the Archaean the source was hydrated, garnet-bearing amphibolite of basaltic composition, in the descending slab of subducted oceanic crust. Together with Taylor and McLennan's lack of evidence for any fractional crystallization in Archaean continental growth, in contrast to that implicated in Post-Archaean times.

The geochemistry forces geologists to accept that a fundamental change took place in the generation and speed of continental growth at the end of the Archaean, marking a shift from a dominance of melting of oceanic, mafic crust to one where the upper mantle was the main source of felsic, low-density magmas. Yet, no matter how much we might speculate on indirect evidence, whether or not subduction, slab-pull and therefore plate tectonics dominated the Archaean remains an open question.

More on continental growth and plate tectonics

And now, here is the plate tectonic forecast (*July 2016*)

As computing power and speed have grown, ever more sophisticated models of dynamic phenomena have emerged, particularly those that focus on meteorology and climatology. Weather and climate models apply to the thin spherical shell that constitutes Earth's atmosphere. They consider incoming solar radiation and longer wavelength thermal radiation emitted by the surface sources and sinks of available power, linked to the convective circulation of energy and matter, most importantly water as gas, aerosols, liquid and ice in atmosphere and oceans. Such general circulation models depend on immensely complex equations that relate to the motions of viscous media on a rotating sphere, modulated by other aspects of the outermost Earth: the absorptive and reflective properties of the materials from which it is composed – air, rocks, soils, vegetation, water in liquid, solid and gaseous forms; different means whereby energy is shifted – speeds of currents and wind, adiabatic heating and cooling, latent heat, specific heat capacity of materials and more still. The models also have to take into account the complex forms taken by circulation on account of Coriolis' Effect, density variations in air and oceans, and the topography of land and ocean floor. The phrase, '*and much more besides*' isn't really adequate for such an enormous turmoil, for the whole caboodle has chaotic tendencies in time as well as 3-D space. The fact that such modelling does enable weather forecasting that we can believe, together with meaningful forward and backward 'snapshots' of overall climate, depends on increasing amounts of empirical data about what is happening, where and when. Models of this kind are also increasingly able to address issues of why such and such outcomes occur, an important example being the teleconnections between major weather events around the globe and phenomena, such as the El Nino-Southern Oscillation – the periodic fluctuation of ocean movements, winds and sea-surface temperatures over the tropical eastern Pacific Ocean.



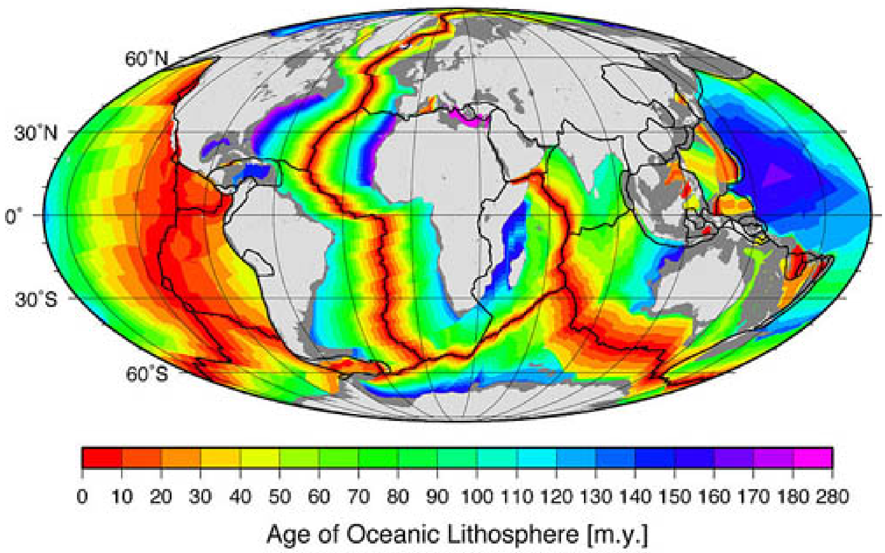
The Earth's 15 largest tectonic plates. (credit: Wikipedia)

The Earth's lithosphere and deeper mantle in essence present much the same challenge to modellers. Silicate materials circulate convectively in a thick spherical shell so that radiogenic heat and some from core formation can escape to keep the planet in thermal balance. There are differences from climate modelling, the obvious ones being sheer scale and a vastly more sluggish pace, but most important are the interactions between materials with very different viscosities: the ability of the deep mantle to move by plastic deformation while the lithosphere behaves as rigid, brittle plates. For geophysicists interested in modelling there are other differences: information that bears on the system is orders of magnitude less; its precision is much poorer; and all of it is based on measurement of proxies. For instance, information on mantle temperature comes from variations in seismic wave speed given by analysis of arrival times at surface observatories of different kinds of wave emitted by individual earthquakes. That is, from seismic tomography, itself a product of immensely complex computation. The temptation of computing power and the basic equations of fluid dynamics, however, has proved hard to resist and the first results of a general circulation model for the solid Earth have emerged (Mallard, C. *et al*. 2016. Subduction controls the distribution and fragmentation of Earth's tectonic plates. *Nature*, v. **535**, p. 140-143; DOI: 10.1038/nature17992).

As the title suggests, the authors' main objective was understanding what controls the variety of lithospheric tectonic plates, particularly how strain becomes localised at plate boundaries. They used a circulation model for an idealised planet and examined several levels of a plastic limit at which the rigidity of the lithosphere drops to localise strain. At low levels the lithosphere develops many plate boundaries, and as the plastic limit increases so the lithosphere ends up with increasingly fewer plates and eventually a rigid 'lid'. The modelling also identified divergent and convergent margins, i.e. mid-ocean ridges and subduction zones. The splitting in two of a single plate must form two triple junctions, whose type is defined by the kinds of plate boundary that meet: ridges; subduction zones; transform faults. Both the Earth and the models show significantly more triple junctions associated with subduction than with extension, despite the fact that ridges extend further than do subduction zones. And these trench-associated triple junctions are mainly those dividing smaller plates. This suggests that it is subduction that focuses fragmentation of the lithosphere, and the degree of fragmentation is controlled by the lithosphere's strength. There is probably a feedback between mantle convection and lithosphere strength, suggesting that an earlier, hotter Earth had more plates but operated with fewer, larger plates as it cooled to the present. But that idea is not new at all, although the modelling gives support to what was once mere conjecture.

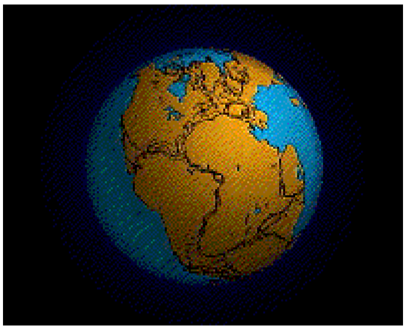
Ancient oceanic lithosphere beneath the eastern Mediterranean (*August 2016*)

The extensive active subduction zones around the Pacific ocean are responsible for a dearth of oceanic lithosphere older than about 200 Ma that still remains where it formed. Trying to get an idea of pre-Mesozoic ocean-floor processes depends almost entirely on fragmented ophiolites thrust or obducted onto continent at destructive plate margins. Yet the characteristically striped magnetic signature above *in situ* oceanic lithosphere offers a good chance of spotting any old oceanic areas, provided the stripes are not imperceptible because of thick sediment cover. One of the most intriguing areas of ocean floor is that beneath the eastern Mediterranean Sea in the 3 km deep Herodotus Basin, which has long been thought to preserve a relic of old ocean floor. Roi Granot of Ben-Gurion University of the Negev, Israel has analysed magnetic data gathered along 7 000 km of survey lines and indeed there are vague traces of stripy geomagnetic variation that has a long wavelength, to be precise there are two bands of . Mathematical analysis of the magnetic profiles suggest that they have a source about 13 to 17 km beneath the seabed: probably crystalline crust beneath thick Mesozoic sediments (Granot, R. 2016. Palaeozoic oceanic crust preserved beneath the eastern Mediterranean. *Nature Geoscience*, doi:10.1038/ngeo2784).



Ages of oceanic lithosphere (Credit: NOAA)

The shape of the anomalies cannot be matched with those of younger magnetic stripes, but can be modelled to fit with a sequence of normal-reverse-normal magnetic polarity preserved in continental sequences of early Carboniferous age, about 340 Ma ago. At that age, the lithosphere would by now be old, cold and dense enough to subside to the observed depth, but the fact that it escaped subduction during amalgamation of Pangaea in the Upper Palaeozoic or when Africa collided with Eurasia in the early Cenozoic is a puzzle. Granot reckons that it most likely formed in Pangaea's great eastern ocean embayment, known as Palaeotethys. An interesting view, but one that does not seem likely to lead any further, simply because of the great depth to which the oceanic material is buried. The deepest yet to be achieved is only 12 km in the onshore Kola Superdeep Borehole in Russia. So the changes of getting samples are slim, even if the overlying sedimentary pile proves to have hydrocarbon potential.



Pangea break-up animation (Credit: USGS)

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