Tectonics

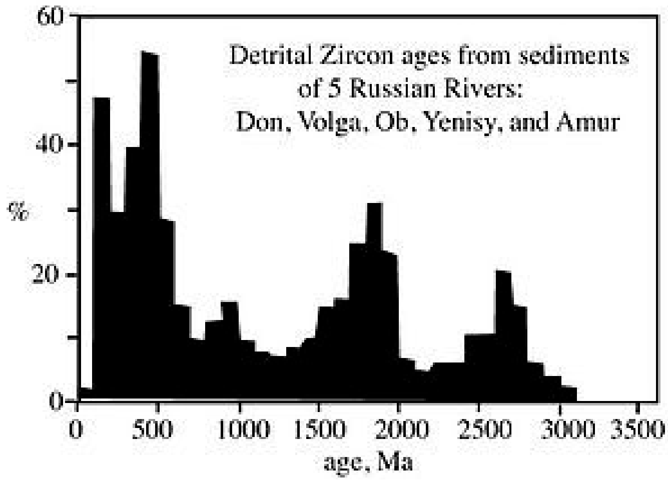
Charting the growth of continental crust (*March 2012*)

When continents first appeared; the pace at which they grew; the tectonic and magmatic processes responsible for continental crust, and whether or not crustal material is consumed by the mantle to any great extent have been tough issues for geologists and geochemists to ponder on for the last four decades. Clearly, continental material was rare if not absent in the earliest days of the solid Earth, otherwise Hadean crust should have been found by now. Despite the hints at some differentiated, high silica rocks that may have hosted >4 billion-year old zircon crystals from much younger sediments, the oldest tangible crust – the Acasta Gneiss of northern Canada – just breaks the 4 Ga barrier: half a billion years short of the known age of the Earth (see *At last, 4.0 Ga barrier broken* November 2008). Radiometric ages for crustal rocks steadily accumulated following what was in the early 1970s the astonishing discovery by Stephen Moorbath and colleagues at Oxford University and the Geological Survey of Greenland of a 3.8 billion year age for gneisses from West Greenland. For a while it seemed as if there had been great pulses that formed new crust, such as one between 2.8 and 2.5 Ga (the Neoarchaean) separated by quieter episodes. Yet dividing genuinely new material coming from the mantle from older crust that later thermal and tectonic events had reworked and remelted required – and still does – lengthy and expensive radiometric analysis of rock samples with different original complements of radioactive isotopes.

Archaean gneisses from West Greenland

One approach to dating has been to separate tiny grains of zircon from igneous and metamorphic rocks and date them using the U-Pb method as a route to the age at which the rock formed, but that too was slow and costly. Yet zircons, being among the most intransigent of Earth materials, end up in younger sedimentary rocks after their parents have been weathered and eroded. It was an investigation of what earlier history a sediment's zircons might yield that lead to the discovery of grains almost as old as the Earth itself (see *Mistaken conclusions from earths oldest materials* Planetary science December

2011; and [Zircon and the quest for life's origin] Palaeobiology May 2005). That approach is beginning to pay dividends as regards resolving crustal history as a whole. Almost 7000 detrital zircon grains separated from sediments have been precisely dated using lead and hafnium isotopes. Using the age distribution alone suggests that the bulk of continental crust formed in the Precambrian, between 3 and 1 Ga ago, at a faster rate than it formed during the Phanerozoic. However, that assumes that a zircon's radiometric age signifies the time of separation from the mantle of the magmas from which the grain crystallised. Yet other dating methods have shown that zircon-bearing magmas also form when old crust is remelted, and so it is important to find a means of distinguishing zircons from entirely new blocks of crust and those which result from crustal reworking. It turns out that zircons from mantle-derived crust have different oxygen isotope compositions from those which crystallised from remelted crust.



An example of ages of detrital zircons from sediments, in this case from five Russian rivers

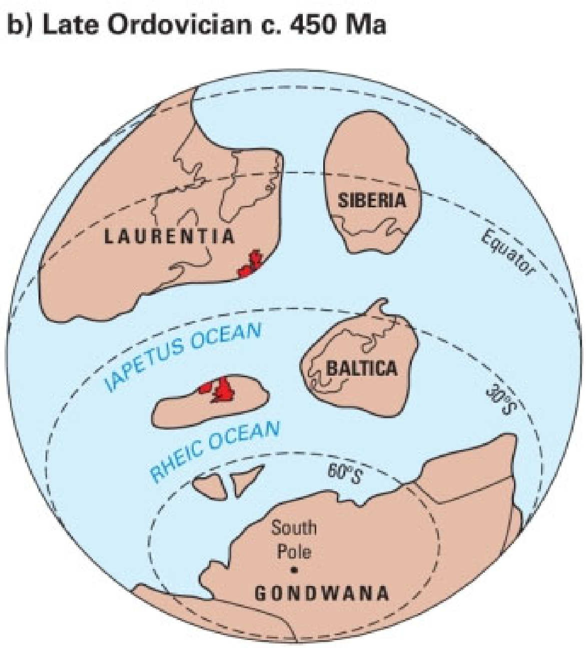
Bruno Dhuime and colleagues from St.Andrew's and Bristol universities in the UK measures hafnium model ages and $\delta^{18}O$ values in a sample of almost 1400 detrital zircons collected across the world from sediments of different ages (Dhuime, B. *et al*. 2012. A change in the geodynamics of continental growth 3 billion years ago. *Science*, v. **335**, p. 1334-1336; DOI: 10.1126/science.1216066). Plotting $\delta^{18}O$ against Hf model age reveals two things: there are more zircons from reworked crust than from mantle-derived materials; plotting the proportion of new crust ages to those of reworked crust form 100 Ma intervals through geological time reveals dramatic changes in the relative amounts of 'mantle-new' crust being produced. Before 3 Ga about three quarters of all continental crust emerged directly from the mantle. Instead of the period from 3 to 1 Ga being one of massive growth in the volume of the crust, apparently the production rate of new crust fell to about a fifth of all crust in each 100 Ma time span by around 2 Ga and then rose to reach almost 100% in the Mesozoic and Cenozoic. This suggests that the late Archaean and most of the Proterozoic were characterised by repeated reworking of earlier crust, perhaps associated with the repeated formation and break-up of supercontinents by collision orogeny and then tectonic break up and continental drift.

Dhuine and colleagues then use the record of varying new crust proportions to 'correct' the much larger database of detrital zircon ages. What emerges is a well-defined pattern in the rate of crustal growth through time. In the Hadean and early Archaean the net growth of the continents was 3.0 $km^3\ yr^{-1}$, whereas throughout later time this suddenly fell to and remained at 0.8 $km^3 yr^{-1}$. Their explanation is that the Earth only came to be dominated by plate tectonic processes mainly driven by slab-pull at subduction zones after 3 Ga. Subduction not only produces mantle-derived magmas but inevitably allows continents to drift and collide, thereby leading to massive deformation and thermal reworking of older crust in orogenic belts and an apparent peak in zircon ages. The greater rate of new crust generation before 3 Ga may therefore have been due to other tectonic processes than the familiar dominance of subduction. Yet, since there is convincing evidence for subduction in a few ancient crustal blocks, such as west Greenland and around Hudson's Bay in NE Canada, plate tectonics must have existed but was overwhelmed perhaps by processes more directly linked to mantle plumes.

More on continental growth can be found here

Related articles: Earth's first continents oozed from its crust (msnbc.msn.com); A new theory on the formation of the oldest continents (eurekalert.org)

When Iapetus opened (*June 2012*)



Iapetus Ocean between Baltica, Laurentia and Avalonia palaeocontinents (Credit: BGS)

The first sign that there was something odd about the Lower Palaeozoic in NW Europe and North America stemmed from gross mismatches between fossil assemblages only a few tens of kilometers apart across the regional strike of sedimentary rocks older than the Upper Silurian. It didn't show up in the Devonian and Carboniferous, and nothing like it reappeared until well into the Jurassic. Until the 1960s the separation of these faunal provinces was ascribed to something akin to the Wallace Line that currently separates the flora and fauna of Oceania, Australia and the eastern islands of Indonesia from those of western Indonesia and Asia: a barrier to migration presented by the deep-water but narrow channel between Bali and Lombok in the Indonesian archipelago. The ancient biological boundary roughly coincides with the long-described Caledonian and Acadian Orogens of NW Europe and eastern North America respectively. With the discovery of plate tectonics another explanation arose: that formerly the opposite sides of the once contiguous orogens had been separated by thousands of kilometers across a former ocean. This was named in 1966 by John Tuzo Wilson after Iapetus , one of the mythical Greek titans who fathered Atlas – the eponym of the Atlantic Ocean. So, in the tectonic canon, the Caledonian-Acadian mountain belt marks the closure through subduction of its former oceanic lithosphere which brought the distinct faunal provinces together across a line known as the Iapetus Suture. Many lines of evidence time-stamp this continental collision to the end of the Silurian Period.

The Iapetus Suture, marked by the Niarbyl Fault on the Isle of Man. (Credit: G.J Kingsley)

When the Iapetus Ocean began to open is not so easy to pin-point, save that it predated the Cambrian Period. The most likely possibility is that it marked the line of separation between fragments of the 1 billion-year old Rodinia supercontinent, which started to break up in the early Neoproterozoic. That was a protracted event, palaeomagnetic, radiometric and stratigraphic data loosely constraining extension between the former two sides of Iapetus to between 620 and 570 Ma. Around Quebec City, Canada are a number of large faults in the St Lawrence rift system that bound a zone of deep water sediments and volcanic rocks that yielded this broad age range. Yet the faults are associated with glassy rocks formed by frictional melting during brittle fracturing. These pseudotachylites can be dated, and have now helped resolve the 'fuzziness' of Iapetus's formation (O'Brien, T.M. & van der Pluijm, B.A. 2012. Timing of Iapetus Ocean rifting from Ar geochronology of pseudotachylites in the St Lawrence rift system of southern Quebec. *Geology*, v. **40**, p. 443-446; DOI: 10.1130/G32691.1). The two co-workers from the University of Michigan show that the rifting occurred between 613 and 614 Ma, coinciding with a brief period of mafic dyke emplacement in Newfoundland and Labrador. Since the Iapetus Suture occurs not far away from the St Lawrence rift system in eastern Canada the area has now become the best constrained example of what soon became known in the early days of plate tectonics as a Wilson Cycle, representing rift, drift and collision. John Tuzo Wilson (1908-1993), a Canadian descended from French and Scottish settlers, and a pioneer of the modern phase of geology, would be pleased it had finally homed in on terrain he knew well.

Brittle-ductile deformation in subduction zones (*August 2012*)

The ultra-dense form of basalt, eclogite made from mainly garnet and a strange high-pressure, low-temperature pyroxene (omphacite) that forms from plagioclase and some of the basalt's ferromagnesian minerals, is possibly the most important rock there is. Without the basalt to eclogite transition that takes place when ocean-floor is subducted the density of the lithosphere would be insufficient to pull more ocean floor to destruction and maintain the planetary circulation otherwise known as plate tectonics. Since the transition involves the formation of anhydrous eclogite from old, cold and wet basalt water is driven upwards into the mantle wedge that lies over subduction zones. The encourages partial melting which creates andesite magmas and island arcs, the ultimate source of the Earth's continental crust.

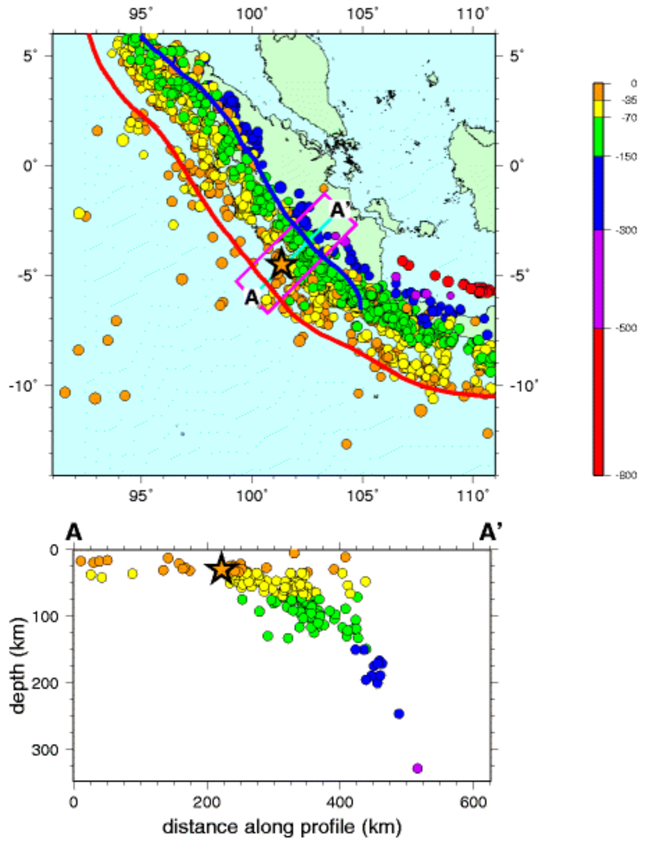
Eclogite: red-brown garnet, green omphacite and white quartz. (Credit: Kevin Walsh). Eclogite breccia from the Western Alps (Credit: Angiboust *et al*. 2012; Fig. 2a)

Despite being cold and rigid, subducted oceanic lithosphere somehow manages to be moved *en masse*, showing its track by earthquakes down to almost 700 km below the Earth's surface. A major ophiolite in the Western Alps on the Franco-Italian border escaped complete loss to the mantle by rebounding upwards after being subducted and metamorphosed under high-P, Low-T condition when the Alps began to form. So the basaltic crustal unit is eclogite and that preserves a petrographic record of what actually happened as it descended (Angiboust, S. *et al*. 2012. Eclogite breccia in a subducted ophiolite: A record of intermediate depth earthquakes? *Geology*, v. **40**, p. 707-710; DOI: 10.1130/G32925.1). The French geologists found breccias consisting of gabbroic eclogite blocks set in a matrix of serpentinite and talc. The blocks themselves are breccias too, with clasts of eclogite mylonite set in fine-grained lawsonite-bearing eclogite. The relationships in the breccias point to possibly earthquake-related processes, grinding and fracturing basalt as it was metamorphosed: an essentially brittle process, yet the shearing that forms mylonites does seem reminiscent of ductile deformation too.

The deformation seems to have been at the middle level of oceanic crust where oceanic basalt lavas formed above cumulate gabbro, their plutonic equivalents. Yet much deformation was also at the gabbro-serpentinite or crust-mantle boundary, where water loss from serpentine may have helped lubricate some of the processes. Clearly the Monviso ophiolite will soon become a place to visit for geophysicists as well as metamorphic petrologists.

Unusual behaviour at a plate boundary (*September 2012*)

Few people will fail to remember the Indian Ocean tsunamis of 26 December 2004 because of their quarter-million death toll. The earthquake responsible for them resulted from thrusting movements on the subduction zone where part of the India-Australia plate descends beneath Sumatra. Since 2004 there have been some equally large but far less devastating events and many lesser earthquakes in the same region. Some have been on the massive Wadati-Benioff zone but many, including two with magnitudes >8 in April 2012, have occurred well off the known plate boundary. Oddly, those two had strike-slip motions and were the largest such events since seismic records have been kept. Such motions where masses of lithosphere move past one another laterally can be devastating on land, yet those offshore rarely cause tsunamis, for a simple reason: they neither lift nor drop parts of the ocean floor. So, to the world at large, both events went unreported.



Historical seismicity across the Sunda trench, colour-coded for depth (Credit: USGS)

To geophysicists, however, they were revealing oddities, for there is no bathymetric sign of an active sea-floor strike-slip fault. But there is a series of linear gravity anomalies running roughly N-S thought to represent transform faults that shut down about 45 Ma ago (Delescluse, M. *et al*. 2012. April 2012 intra-oceanic seismicity off Sumatra boosted by the Banda-Aceh megathrust. *Nature*, v. **490**, p. 240-244; DOI :10.1038/nature11520). Examining the post-December 2004 seismic record of the area the authors noted a flurry of lesser events, mostly in the vicinity of the long dead fracture zones. Their analysis leads them to suggest not only that the Banda-Aceh earthquake and others along the Sumatran subduction zone reactivated the old strike-slip faults but that differences in the motion of the India-Australia plate continually stress the lithosphere. Indian continental crust is resisting subduction beneath the Himalaya thereby slowing plate movement in its wake. Ocean lithosphere north of Australia slides more easily down the subduction zone, so its northward motion is substantially faster, creating a torque in the region affected by the strike-slip motions. Ultimately, it is thought, this will split the plate into separate Indian and Australian plates.

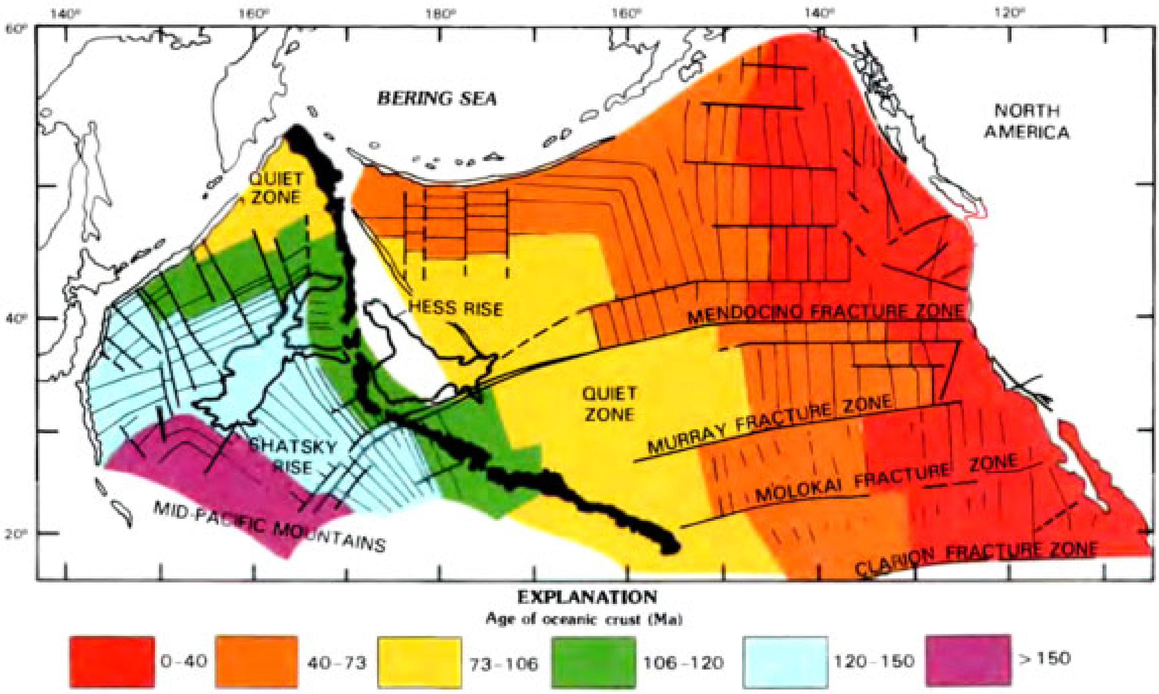
Another surprising outcome of this complex seismic linkage in the far-east of the Indian Ocean is that the April strike-slip earthquake set the Earth ringing. For six days afterwards there was a five-fold increase in events of magnitudes greater than 5.5 more than 1500 km away, including some of around magnitude 7.0 (Polliitz, F.F. *et al*. 2012. The 11 April 2012 east Indian Ocean earthquake triggered large aftershocks worldwide. *Nature*, v. 490, p. 250-253; DOI: 10.1038/nature11504). Although distant minor shocks often follow large earthquakes, this is the first time that a swarm of magnitude 5.5 and greater has been noticed.

Related articles: Shen, H. 2012. Unusual Indian Ocean Earthquakes Hint at Tectonic Breakup. *Nature* ; DOI: 10.1038/nature.2012.11487; Royer, J.-Y. 2012. When an oceanic tectonic plate cracks. *Nature*, v. **490**, p. 183-185; DOI: 10.1038/490183a.

The shuffling poles (*October 2012*)

The mechanical disconnection of the lithosphere from the Earth's deep mantle by a more ductile zone in the upper mantle – the asthenosphere – suggests that the lithosphere might move independently. If that were the case then points on the surface would shift relative to the axis of rotation and the magnetic poles, irrespective of plate tectonics. So it makes sense to speak of absolute and relative motions of tectonic plates. The second relates to plates' motions relative to each other and to the ancient position of the magnetic poles, assumed to be reasonably close to that of the past pole of rotation, yet measurable from the direction of palaeomagnetism retained in rocks on this or that tectonic plate.

Plotting palaeomagnetic pole positions through time for each tectonic plate gives the impression that the poles have wandered. Such apparent polar wandering has long been a key element in judging ancient plate motions. Absolute plate motion judges the direction and speed of plates relative to supposedly fixed mantle plumes beneath volcanic hot spots, the classic case being Hawaii, over which the Pacific Plate has moved to leave a chain of extinct volcanoes that become progressively older to the west. But it turns out that between about 80 to 50 Ma there are some gross misfits using the hot-spot frame of reference. An example is the 60° bend of the Hawaiian chain to become the Emperor seamount chain that some have ascribed to hot spots shifting (see *[The great bend on the Pacific Ocean floor](#)* Tectonics May 2009).



Age of Pacific Ocean floor, showing the Hawaii-Emperor seamount chain in black

Ideas have shifted dramatically since it became clear that hot spots can shift, and there has been an attempt to estimate their actual motions (Doubrovine, P.V. *et al*. 2012. Absolute plate motions in a reference frame defined by moving hot spots in the Pacific, Atlantic, and Indian oceans. *Journal of Geophysics Research: Solid Earth*, v. **117**, B09101; DOI: 10.1029/2011JB009072). It is early days for the revised view of absolute motion of the lithosphere and estimates go back only 120 Ma. However, one outcome has been a realistic examination of whether the positions of the poles have shifted through time; a possibility that is hidden in apparent polar wander paths. Since the mid-Cretaceous it seems that a slow and hesitant, but significant polar shuffle has taken place, varying between 0.1 and 1.0° Ma^{-1}, starting in one direction and then the movement retraced its steps to achieve the current proximity of magnetic poles to the poles of rotation.

Related articles: No absolutes: How shifting plates completely remake the Earth (arstechnica.com)