Tectonics 2024

A new explanation for the Neoproterozoic Snowball Earth episodes

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The Cryogenian Period that lasted from 860 to 635 million years ago is aptly named, for it encompassed two maybe three episodes of glaciation. Each left a mark on every modern continent and extended from the poles to the Equator. In some way, this series of long, frigid catastrophes seems to have been instrumental in a decisive change in Earth's biology that emerged as fossils during the following Ediacaran Period (635 to 541 Ma). That saw the sudden appearance of multicelled organisms whose macrofossil remains – enigmatic bag-like, quilted and ribbed animals – are found in sedimentary rocks in Australia, eastern Canada and NW Europe. Their type locality is in the Ediacara Hills of South Australia, and there can be little doubt that they were the ultimate ancestors of all succeeding animal phyla. Indeed one of them *Helminthoidichnites,* a stubby worm-like animal, is a candidate for the first bilaterian animal and thus our own ultimate ancestor. Using the index for Palaeobiology or the *Search Earth-logs* pane you can discover more about them in 12 posts from 2006 to 2023. The issue here concerns the question: Why did Snowball Earth conditions develop? Again, refresh your knowledge of them, if you wish, using the index for Palaeoclimatology or *Search Earth-logs*. From 2000 onwards you will find 18 posts: the most for any specific topic covered by Earth-logs. The most recent are Kicking-off planetary Snowball conditions (August 2020) and Signs of Milankovich Effect during Snowball Earth episodes (July 2021): see also: Chapter 17 in *Stepping Stones*.

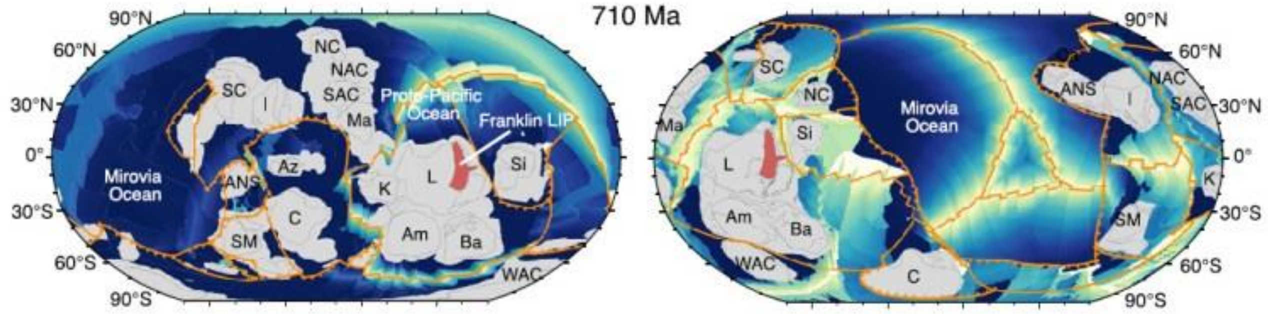
One reason why Snowball Earths are so enigmatic is that CO_2 concentrations in the Neoproterozoic atmospheric were far higher than they are at present. In fact since the Hadean Earth has largely been prevented from being perpetually frozen over by a powerful atmospheric greenhouse effect. Four Ga ago solar heating was about 70 % less intense than today, because of the 'Faint Young Sun' paradox. There was a long episode of glaciation (from 2.5 to 2.2 Ga) at the start of the Palaeoproterozoic Era during which the Great Oxygenation Event (GOE) occurred once photosynthesis by oxygenic bacteria became far more common than those that produced methane. This resulted in wholesale oxidation to carbon dioxide of atmospheric methane whose loss drove down the early greenhouse effect – perhaps a narrow escape from the fate of Venus. There followed the 'boring billion years' of the Mesoproterozoic during which tectonic processes seem to have been less active. in that geologically tedious episode important proxies (carbon and sulfur isotopes) that relate to the surface part of the Earth System 'flat-lined'. The plethora of research centred on the Cryogenian glacial events seems to have stemmed from the by-then greater complexity of the Precambrian Earth System.

Since the GOE the main drivers of Earth's climate have been the emission of CO_2 and SO_2 by volcanism, the sedimentary burial of carbonates and organic carbon in the deep oceans, and weathering. Volcanism in the context of climate is a two-edged sword: CO_2 emission results in greenhouse warming, and SO_2 that enters the stratosphere helps reflect solar radiation away leading to cooling. Silicate minerals in rocks are attacked by hydrogen ions (H^+) produced by the solution of

CO_2 in rain water to form a weak acid (H_2CO_3: carbonic acid). A very simple example of such chemical weathering is the breakdown of calcium silicate:

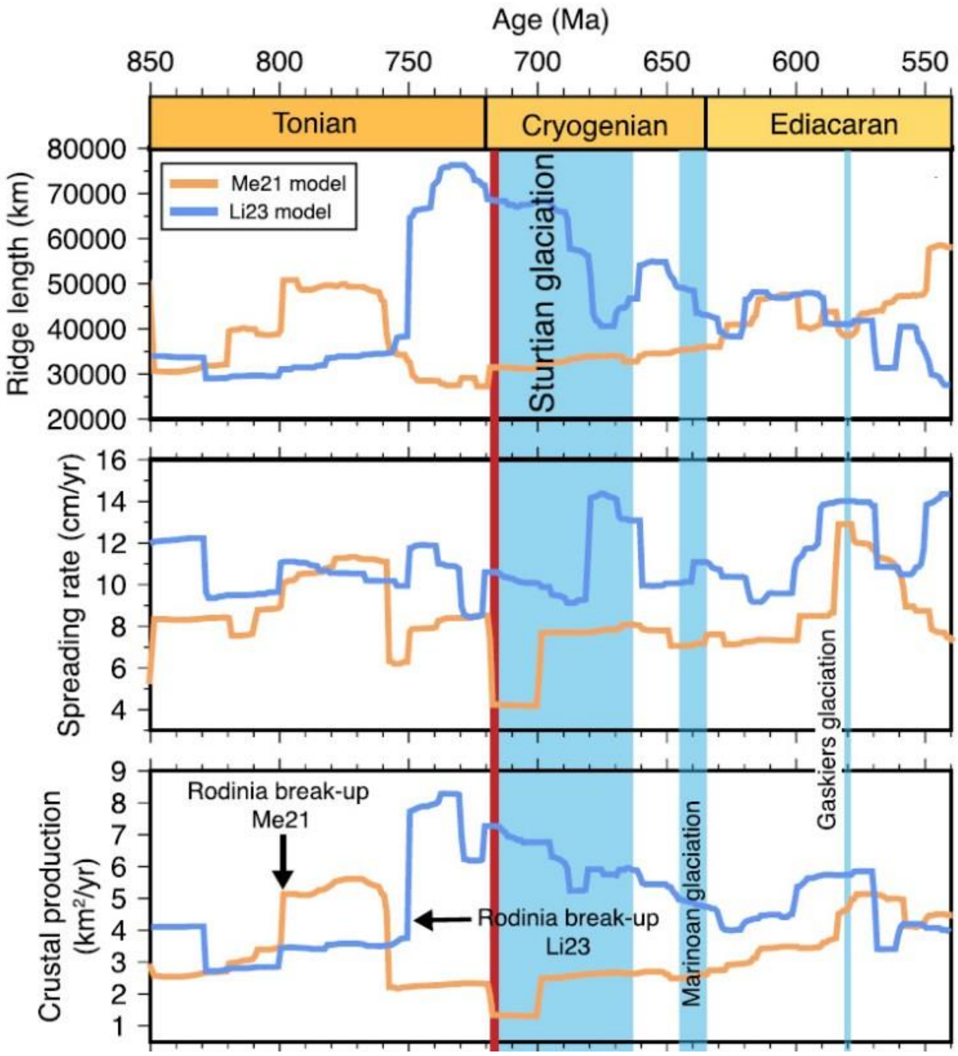
$$CaSiO_3 + 2CO_2 + 3H_2O = Ca^{2+} + 2HCO_3^- + H_4SiO_4$$

The reaction results in calcium and bicarbonate ions being dissolved in water, eventually to enter the oceans where they are recombined in the shells of planktonic organisms as calcium carbonate. On death, their shells sink and end up in ocean-floor sediments along with unoxidised organic carbon compounds. The net result of this part of the carbon cycle is reduction in atmospheric CO_2 and a decreased greenhouse effect: increased silicate weathering cools down the climate. Overall, internal processes – particularly volcanism – and surface processes – weathering and carbonate burial – interact. During the 'boring billion' they seem to have been in balance. The two processes lie at the core of attempts to model global climate behaviour in the past, along with what is known about developments in plate tectonics – continental break-up, seafloor spreading and orogenies – and large igneous events resulting from mantle plumes. A group of geoscientists from the Universities of Sydney and Adelaide, Australia have evaluated the tectonic factors that may have contributed to the first and longest Snowball Earth of the Neoproterozoic: the Sturtian glaciation (717 to 661 Ma) (Dutkiewicz, A. *et al*. 2024. Duration of Sturtian "Snowball Earth" glaciation linked to exceptionally low mid-ocean ridge outgassing. *Geology*, v. **52**, online early publication; DOI: 10.1130/G51669.1).



Palaeogeographic reconstructions (Robinson projection) during the early part of the Sturtian global glaciation: LEFT based on geological data from Neoproterozoic terrains on modern continents; RIGHT based on palaeomagnetic pole positions from those terrains. Acronyms refer to each terrains, e.g. Am is Amazonia, WAC is the West African Craton. Orange lines are ocean ridges, those with teeth are subduction zone. (Credit: Dutkiewicz et al., parts of Fig. 1)

Shortly before the Sturtian began there was a major flood volcanism event, forming the Franklin large igneous province, remains of which are in Arctic Canada. The Franklin LIP is a subject of interest for triggering the Sturtian, by way of a 'volcanic winter' effect from SO_2 emissions or as a sink for CO_2 through its weathering. But both can be ruled out as no subsequent LIP is associated with global cooling and the later, equally intense Marinoan global glaciation (655 to 632 Ma) was bereft of a preceding LIP. Moreover, a world of growing frigidity probably could not sustain the degree of chemical weathering to launch a massive depletion in atmospheric CO2. In search of an alternative, Adriana Dutkiewicz and colleagues turned to the plate movements of the early Neoproterozoic. Since 2020 there have been two notable developments in modelling global tectonics of that time, which was dominated by the evolution of the Rodinia supercontinent. One is based largely on geological data from the surviving remnants of Rodinia (download animation), the other uses palaeomagnetic pole positions to fix their relative positions: the results are very different (download animation).



Variations in ocean ridge lengths, spreading rates and oceanic crust production during the Neoproterozoic estimated from the geological (orange) and palaeomagnetic (blue) models. Credit: Dutkiewicz et al., parts of Fig. 2)

The geology-based model has Rodinia beginning to break up around 800 Ma ago with a lengthening of global constructive plate margins during disassembly. The resulting continental drift involved an increase in the rate of oceanic crust formation from 3.5 to 5.0 km^2 yr^{-1}. Around 760 Ma new crust production more than halved and continued at a much slowed rate throughout the Cryogenian and the early part of the Ediacaran Period. The palaeomagnetic model delays breakup of the Rodinia supercontinent until 750 Ma, and instead of the rate of crust production declining through the Cryogenian it more than doubles and remains higher than in the geological model until the late Ediacaran. The production of new oceanic crust is likely to govern the rate at which CO_2 is out-gassed from the mantle to the atmosphere. The geology-based model suggests that from 750 to 580 Ma annual CO_2 additions could have been significantly below what occurred during the Pleistocene ice ages since 2.5 Ma ago. Taking into account the lower solar heat emission, such a drop is a plausible explanation for the recurrent Snowball Earths of the Neoproterozoic. On the other hand, the model based on palaeomagnetic data suggests significant warming during the Cryogenian contrary to a mass of geological evidence for the opposite.

A prolonged decrease in tectonic activity thus seems to be a plausible trigger for global glaciation. Moreover, reconstruction of Precambrian global tectonics using available palaeomagnetic data seems to be flawed, perhaps fatally. One may ask, given the trends in tectonic data: How did the Earth repeatedly emerge from Snowball episodes? The authors suggest that the slowing or shut-down of silicate weathering during glaciations allowed atmospheric CO_2 to gradually build up as a result of on-land volcanism associated with subduction zones that are a quintessential part of any tectonic scenario.

This kind of explanation for recovery of a planet and its biosphere locked in glaciation is in fact not new. From the outset of the Snowball Earth hypothesis much the same escape mechanisms were speculated and endlessly discussed. Adriana Dutkiewicz and colleagues have fleshed out such ideas quite nicely, stressing a central role for tectonics. But the glaring disparities between the two models show that geoscientists remain 'not quite there'. For one thing, carbon isotope data from the Cryogenian and Ediacaran Periods went haywire: living processes almost certainly played a major role in the Neoproterozoic climatic dialectic.

Drip tectonics beneath Türkiye

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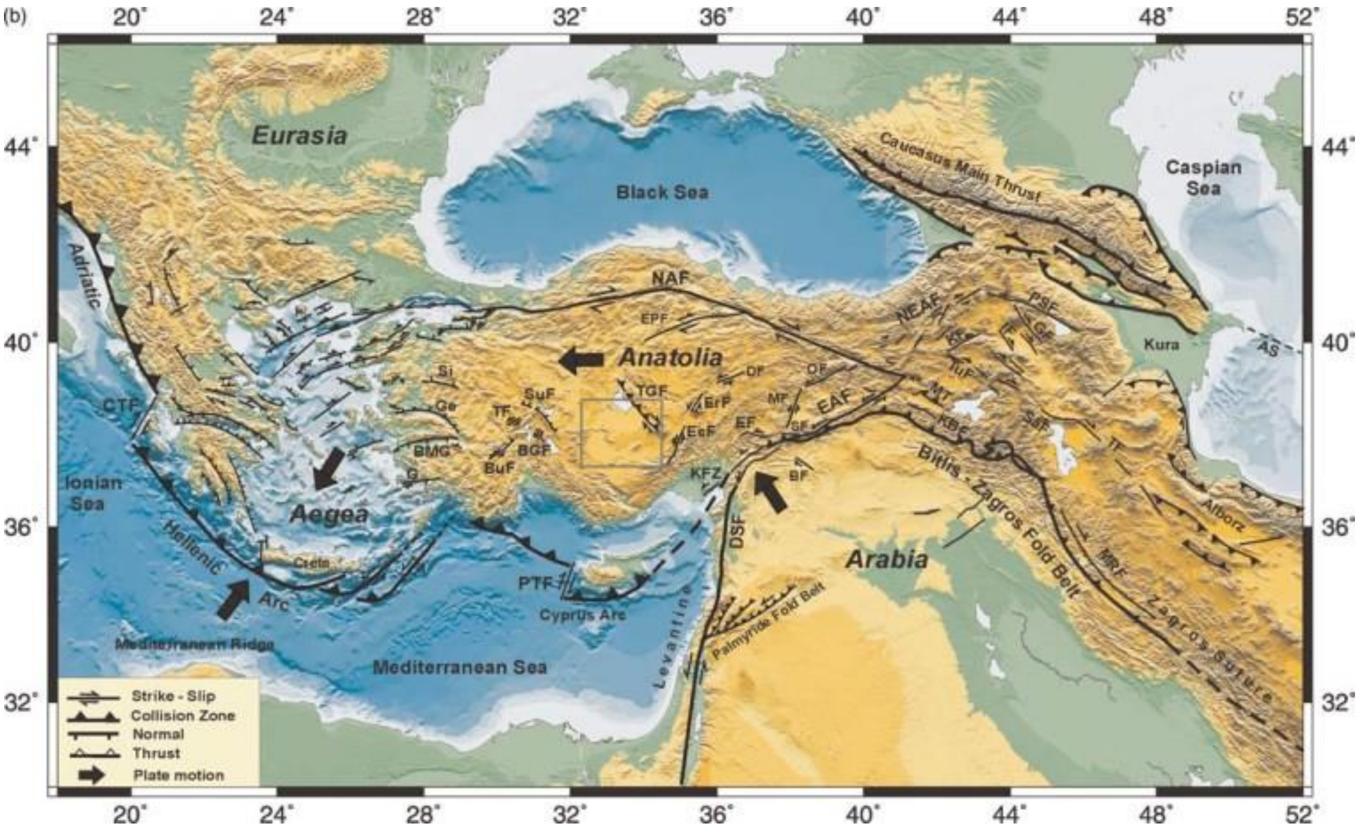
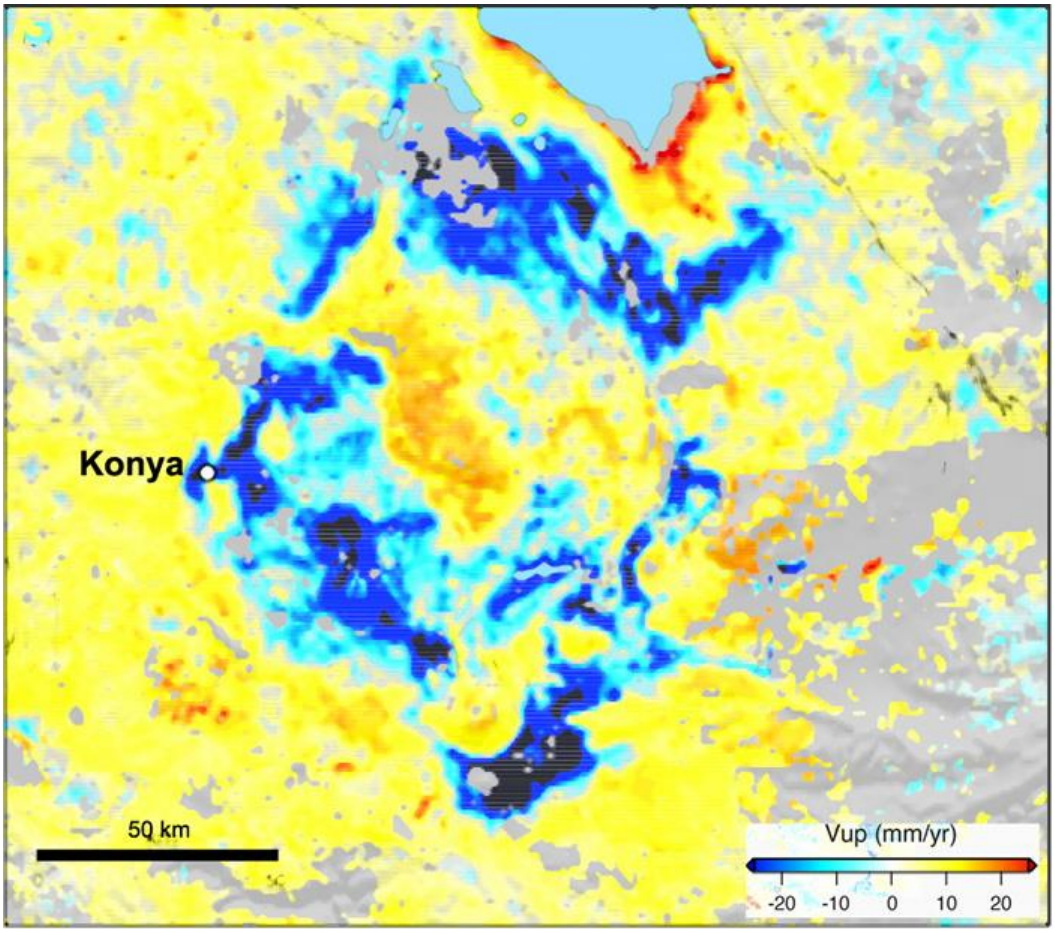


Tectonics and geomorphology of Turkey showing the main fault systems. The Konya basin is enclosed by the grey rectangle at centre. (Credit: Taymaz et al. Geological Society of London, Special Publication 291, p1-16, Fig 1)

The 1.5-2.0 km high Central Anatolian plateau in Türkiye has been rising since ~11 Ma ago: an uplift of about 1 km in the last 8 Ma. However, part of the southern Plateau shows signs of rapidly subsidence that has created the Konya Basin, marked by young lake sediments. Interferometric radar (InSAR) data from the European Space Agency's Sentinel-1 satellite, which detects active movement of the Earth's surface, reveal a crude, doughnut-shaped area of the surface that is subsiding at up to 50 mm per year. This ring of subsidence surrounds a core of active uplift that is about 50 km across (see the first figure). Expressed crudely, active subsidence suggests an excess of mass beneath the affected area, whereas uplift implies a mass deficit; in both cases within the lithosphere. So, when the InSAR data were published in 2020, it became clear that the lithosphere beneath Anatolia is doing something very strange.

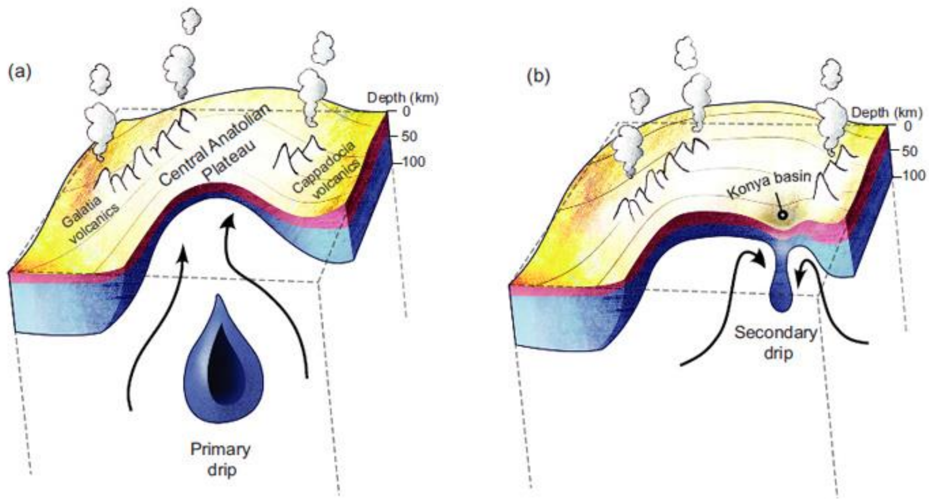


Vertical velocities affecting the surface in the Konya Basin derived from InSAR data, velocities colour-coded cyan to blue show subsidence, yellow to red suggesting that the surface is rising. (Credit: Andersen et al., Fig 1c)

Canadian and Turkish geophysicists set out to find a tectonic reason for such aberrant behaviour (Andersen, A.J. *et* al. 2024. Multistage lithospheric drips control active basin formation within an uplifting orogenic plateau. *Nature Communications*, v. **15**, Article 7899; DOI: 10.1038/s41467-024-52126-7). They wondered if a process known as 'drip tectonics', first mooted as an explanation of anomalous features in some mountain belts in 2004 (see: Mantle dripping off mountain roots, October 2004; and A drop off the old block? May 2008) might be applicable to the Anatolian Plateau. The essence of this process is similar to the slab-pull force at the heart of subduction. Burial and cooling of basaltic material in oceanic lithosphere being driven beneath another tectonic plate converts its igneous mineralogy to the metamorphic rock eclogite, whose density exceeds that of mantle rocks. Gravity then acts to pull the changed material downwards. However, Anatolia shows little sign of subduction. But the mantle beneath shows seismic speed anomalies that hint at anomalously dense material.

Seismic tomography shows that in a large volume 100 to 200 km beneath the central part of the Plateau S-waves travel faster than in the surrounding mantle. The higher speed suggests a body that is denser and more rigid than its surroundings. This could be a sinking, detached block of 'eclogitised' lithosphere whose disconnection from the remaining continental lithosphere has been causing the uplift of the Plateau that began in the Late Miocene. A smaller high-speed anomaly lies directly under the Konya Basin, but at a shallower depth (50 to 80 km) just beneath the lithosphere-asthenosphere boundary. The authors suggest that this is another piece of the lower lithosphere that is beginning to sink and become a 'drip'. Still mechanically attached to the lithosphere the sinking dense block is dragging the surface down.

Andersen *et al*. instead of relying on computer modelling created a laboratory analogue. This consisted of a tank full of a fluid polymer whose viscosity is a thousand times that of maple syrup that represents the Earth's deep mantle beneath. They mimicked an overlying plate by a layer of the same material with additional clay to render it more viscous – the model's lithospheric mantle – with a 'crust' made of a sand of ceramic and silica spherules. A dense seed inserted into the model lithospheric mantle began to sink, dragging that material downwards in a 'drip'. After that 'drip' had reached the bottom of the tank hours later, it became clear that another, smaller drip materialised along the track of the first and also began to sink. Monitoring of the surface of the 'crust' revealed that the initial drip did result in a basin. But the further down the drip fell the basin gradually became shallower: there was surface uplift. Once the initial drip had 'bottomed-out' the basin began to deepen again as the secondary drip formed and slowly moved downwards. The model seems to match the authors' interpretation of the geophysics beneath the Anatolian Plateau. One drip created the potential for a lesser one, a bit like in inversion of the well-known slo-mo videos of a drop of milk falling into a glass of milk, when following the drop's entry a smaller drop rebounds from the milky surface.



Cartoons of drip tectonics beneath the Anatolian Plateau. (a) Lower lithosphere detached from beneath Anatolia in the Late Miocene (10 to 8 Ma) descends into the mantle as it is 'eclogitised'; (b) a smaller block beneath the Konya Basin beginning to 'drip', but still attached to the lithosphere. (Credit: Andersen et al., Fig 4)

In Anatolia the last 10 Ma has not been just ups and downs of the surface corresponding to drip tectonics. That was accompanied by volcanism, which can be explained by upwelling of mantle material displaced by lithospheric drips. When mantle rises and the pressure drops partial melting can occur, provided the mantle material rises faster than it can lose heat: adiabatic melting.

How India accelerated towards Eurasia at the end of the Cretaceous

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About 70 Ma ago the magnetic striping of the Indian Ocean floor suggests that the Indian subcontinent was then moving towards the huge, almost stationary Eurasian continent at about 8 cm per year. Over the next 5 Ma this convergence rate underwent a tectonically startling acceleration to reach 18 cm yr^{-1} by around the time of the Cretaceous-Palaeogene boundary (65 Ma): more than doubling the approach rate. Thereafter it slowed, eventually to a few centimetres per year once collision and building of the Himalayan mountain belt were more or less complete about 30 Ma ago. This cannot easily be explained by a speeding up of the sea-floor spreading rate at an Indian Ocean ridge to the south, 18 cm yr^{-1} being as fast as tectonic forces can manage at present. At that time ocean floor to the north of India was being subducted beneath Eurasia, and basaltic volcanism was flooding what is now the Deccan Plateau on western India. A couple of suggestions have been made: two northward subduction zones may have developed or the mantle plume feeding the Deccan flood basalts may have driven the tectonic acceleration. A third possibility is that the subduction was somehow lubricated. That approach has recently been considered by geoscientists from China and Singapore (Zhou, H. *et al*. 2024. India–Eurasia convergence speed-up by passive-margin sediment subduction. *Nature*, v. **635**, p. 114-120; DOI: 10.1038/s41586-024-08069-6).

Hao Zhou and colleagues studied the isotopic and trace-element geochemistry of volcanic and plutonic igneous complexes to the north of the Himalaya. They were emplaced in arc environments in three stages: from 98 to 89; 65 to 60; and 57 to 50 Ma. In this tectonic setting fluids rise from the subducted slab to induce the mantle part of the overriding lithosphere to partially melt. That yields magmas which penetrate the crust above. The first and last magmatic events produced similar isotopic and trace-element 'signatures', which suggest fluids rose from subducted ocean lithosphere. But those in the latest Cretaceous to earliest Palaeocene are markedly different. Instead of showing signs of their magmas being entirely mantle derived like the earlier and later groups, the 65 to 60 Ma rocks exhibit clear evidence of partial melting having incorporated materials that had originated in older continental crust. The authors suggest that this crustal contamination stemmed from sediments that had been deposited at the northern margin of the Indian subcontinent during the Mesozoic. These sediments had formed by weathering of the ancient rocks that underpin India, transport of the debris by rivers and deposition on the seafloor as water-saturated sands, silts and clays. Once those sediments were subducted beneath what is now Tibet they would yield fluids with a geochemical 'fingerprint' inherited from old continental crust. Moreover, far more fluids than subducted oceanic crust could ever release would rise into the overriding lithosphere than.

The fluids rising from a subducted wedge of sediments may have reduced friction between the overriding Eurasian lithosphere and the subducted slab derived from the Indian tectonic plate. That scenario would not only have lubricated subduction, but allowed compressive forces in the overriding lithosphere to relax. Both would have allowed convergence of the two plates to move significantly faster as the sediments were progressively consumed. Once completed, convergence would have slowed without such 'lubrication'.Earlier continent-continent collision zones, such as those that united Pangaea and older supercontinents may well have involved such tectonic surges. And the same kind of process may eventually speed up the reassembly of the latest distribution of continents.

Watch an animation of the India-Eurasia convergence (just over 3 minutes long)compiled by Christopher Scotese of Northwestern University in Evanston, Illinois, USA, which is a component of his Paleomap Project. It starts by following India from its current position to its origin in the break-up of Gondwanaland ~100 Ma ago. The last half reverses the motions to show India's slow collision with Eurasia.