

A story of lithospheric plates

Earth's early plate tectonics might have closely resembled those of today

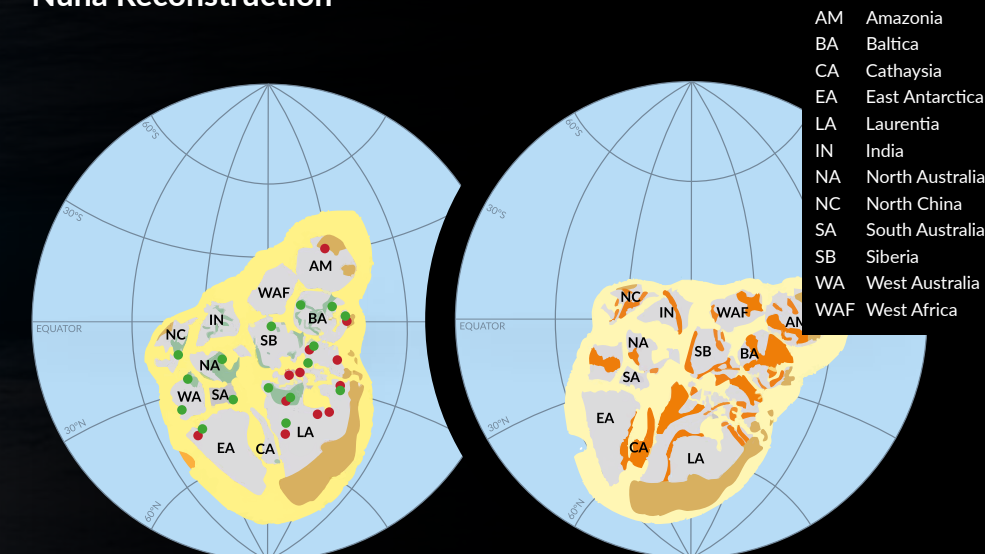
The Earth's landscape evolves through a combination of internal and external factors driven by our planet's internal geodynamics. Continents and oceans have been formed and destroyed by plate tectonics, a long-term, well-established framework of moving rigid plates made of oceanic and continental lithosphere.

The main driving force of this system is currently the slab pull—a force exerted on the plate as the older and colder subducting portion sinks into the asthenosphere at convergent boundaries. It is still uncertain when and how the onset of plate tectonics, mainly driven by the slab pull, occurred. Opposing models arise from the poorly preserved rock record as we go back into the Precambrian (before the appearance of hard skeletons, before ca. 540 million years). Some studies suggest that early Earth was too hot to initiate cold plate subduction (Brown, Johnson and Gardiner, 2020; Chowdhury, Chakraborty and Gerya, 2021; van Hunen and van den Berg, 2008), while others suggest the presence of subduction and plate tectonics as early as 4.0 billion years ago (e.g. Korenaga, 2013). Regardless, most of the evidence collected over decades seems to indicate that something significant happened during the Archean, most notably towards the end.

The 'early Earth'

The Archean extends from about 4.0 to 2.5 billion years ago, and although limited, there is a good representation of rocks covering this period. Some constraints suggest the mantle potential temperatures were 150 °C hotter than present-day (Herzberg *et al.*, 2010). More recently, this has been challenged by using a revised rock dataset and testing other relevant melting parameters. Ganne and Feng (2017) propose lower ambient mantle temperatures, with an Archean ambient mantle that is only about 150°C hotter than today. These constraints are valuable because they are used to test the thermomechanical behaviour and stability of the tectonic plates, which are then fed into numerical simulations to test plate tectonic scenarios. While a very hot Archean Earth may not support plate tectonics like the modern Earth, if we had bimodal geothermal gradients during the

Nuna Reconstruction



Archean, it would be possible to sustain a plate tectonic world at the time.

The Archean rock record is mostly composed of tonalite, trondjemite and granodiorites (TTG) series, found in greenstone belts. These include variably metamorphosed volcanic, volcanoclastic and sedimentary sequences, along with minor granitoids. Two major lines of evidence for the operation of subduction arise from the geochemistry of TTG and from the secular transition from TTG to sanukitoids and K-rich granites (Laurent *et al.*, 2014; Martin and Moyen, 2002). TTG are derived from the melting of a mafic precursor rock. Martin and Moyen (2002) first described an evolution between the parental magmas of TTG from the early Archean to the late Archean, which could be best explained by deeper melting conditions of a mafic oceanic crust at subduction zones. At the end of the Archean, between 3.0 and 2.5 Ga, there is also a diachronic transition from these TTG suites to sanukitoids and K-rich granites that signal the hybridisation of the peridotite mantle. This has been interpreted as reflecting dehydration of a mafic slab and melting of the mantle above that slab (Laurent *et al.*, 2014), very similar to modern subduction zones. Such evidence suggests ambient mantle temperatures cooling by the end of the Archean.

While these findings suggest the presence of subduction zones, others have contested

them as equivocal evidence of modern-like plate tectonics (Nebel *et al.*, 2018). Indeed, numerical simulations and styles of tectonic deformation found in many Archean terranes indicate the existence of processes similar to subduction zones, named 'proto-subduction' (van Hunen and Moyen, 2012), 'subaccretion' (Bédard, 2018) or 'peel-back tectonics' (Chowdhury, Chakraborty and Gerya, 2021), where episodic subduction can take place, but it is neither flat nor long-lived, and therefore unlike modern plate tectonics.

Therefore, in the last years, many researchers have been hypothesising different types of plate geodynamics operating in the early Earth: 'platelet tectonics' (Ernst, 2017), 'squishy-lid tectonics' (Rozel *et al.*, 2017), 'lid tectonics' (Piper, 2018), 'drip tectonics' (Gerya, 2014; Nebel *et al.*, 2018), 'sluggish tectonics' (Brown, Johnson and Gardiner, 2020), 'transitional mobile-lid tectonics' (Cawood *et al.*, 2018; Chowdhury, Chakraborty and Gerya, 2021) and so on.

Because subduction in itself cannot be evidence of plate tectonics, a perhaps more useful approach is to look for other proxies that can be unequivocally linked to what is now considered as representing modern plate tectonics: strong lithosphere, linear orogenic belts, operation of dual, hot and cold geothermal gradients, and long-lived subduction (Brown, 2007; Cawood *et al.*, 2018; Gerya, 2014; Korenaga, 2006; Stern, 2018).

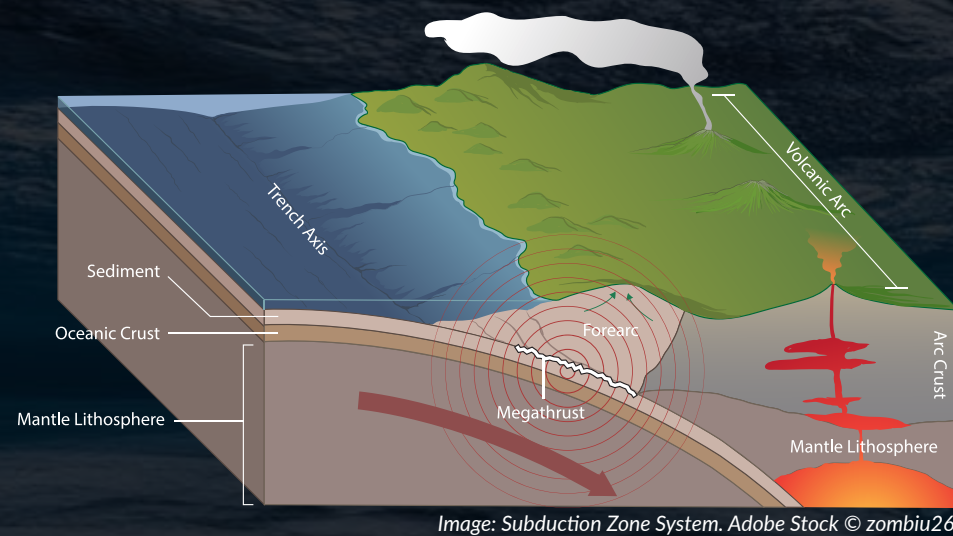


Image: Subduction Zone System. Adobe Stock © zombiu26

FINGER-PT aims to recover critical information about the mantle-crust thermal evolution, by assessing crustal geothermal gradients (T/P) derived from the metamorphic record, to investigate the presence of cold subduction in Earth's past and establish the prevailing tectonic regime earlier on."

The current known metamorphic rock record shows that the Earth's crust has evolved from dominant hotter gradients, producing high and intermediate temperature/pressure (T/P) rocks, to bimodal crustal gradients, producing pairs of high T/P (> 775 °C /GPa) and low T/P (< 375 °C /GPa) metamorphic belt (e.g. Brown and Johnson, 2019). A notable change within the metamorphic record is the appearance of low-temperature, high-pressure (LT-HP) rocks—blueschists—around 850–750 million years ago (Maruyama, Liou and Terabayashi, 1996; Yong *et al.*, 2013).

For many authors, blueschists are unambiguous proxies for modern subduction zones and of plate tectonics (Brown, Kirkland and Johnson, 2020; Cawood *et al.*, 2018; Stern, 2005) because they form under high pressure

(HP) and very cold geothermal gradients (150–350 °C/GPa). Other HP rocks, such as higher temperature eclogites, can be generated under higher geothermal gradients and geological settings without the need to invoke subduction zones (e.g. at the base of an overly thickened crust [Coleman *et al.*, 1965; Fischer and Gerya, 2016]).

There is increasing evidence for low T/P (LT eclogite facies) operating between 1800 and 2100 million years ago (François *et al.*, 2018; Ganne *et al.*, 2012; Weller *et al.*, 2021), suggesting that cold crustal gradients were occurring. However, such evidence is completely absent in the geological record from 1.0 to 1.7 billion years ago, during the Mesoproterozoic. At this time, several proxies, such as the absence of large orogenic gold deposits, glacial and iron deposits and an increase in anorogenic granites (Cawood and Hawkesworth, 2014), are envisaged as evidence of lithospheric stability during this 'Earth Middle Age', possibly representing a period of a single lid (Stern, 2020) or a slow-down tectonic regime (Cawood and Hawkesworth, 2014). So, was the Earth at a standstill?

While there are a few hypotheses for what the community believes happened during the Mesoproterozoic, the absence of blueschists or the scarcity of LT eclogite throughout most of the Proterozoic can be explained by other reasons other than the absence of cold subduction:

- a secular change of the average crustal mafic rock compositions that

prevented the growth of metamorphic index minerals that are indicative of blueschist or eclogite conditions before the Paleoproterozoic (as in Palin and White, 2016)

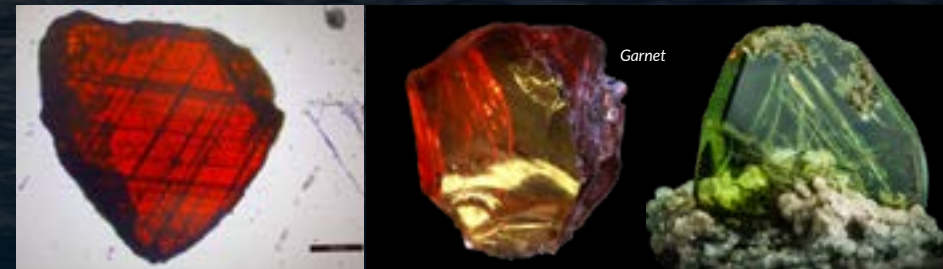
- a preservation bias affecting LT-HP metamorphic rocks. During Earth's long history, and due to the hydrated nature of its rock-forming minerals, blueschist may be re-equilibrated during exhumation, altered by fluid circulation and/or eroded more rapidly than other rocks. This would tend to bias the preserved geological record towards lower-pressure peaks. This is often the case even in relatively recent orogens (< 450 Ma), where limited LT-HP units are preserved.

What other alternatives do we have to study this conundrum?

In recent years, alternative methods for obtaining thermobarometric (T and P) conditions from single crystals have been developed, including the use of mineral inclusions, element-based thermometry and elastic barometry (e.g. Watson, Wark and Thomas, 2006; Enami, Nishiyama and Mouri, 2007; Hart *et al.*, 2016; Schönig *et al.*, 2018; Mazzucchelli *et al.*, 2019). These methods open new possibilities for studying the metamorphic record, not only based on metamorphic rocks but, more interestingly, on old eroded crustal rocks through the study of detrital grains found in sedimentary rocks.

The jigsaw puzzle using detrital single grains

To probe the metamorphic record using single, detrital grains, the ideal candidate must be a mineral that: (i) can grow in a wide range of rock compositions and (pressure temperature) P-T conditions, including those at low geothermal gradients (T/P); (ii) can survive chemical and mechanical weathering, withstanding sedimentary transport and diagenesis; (iii) is amenable for isotopic dating, in order to determine its age; and, ideally, (iv) is able to retain its chemical signature under low to moderate metamorphic overprinting conditions. Most pyroxenes,



Images: Rutile, Garnet and titanite.

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amphiboles and other major rock-forming minerals such as kyanite, which usually are reliable indicators of metamorphic conditions, are unstable during erosion, diagenesis and overprinting metamorphic processes (Morton and Hallsworth, 2007). Therefore, although very valuable for metamorphic studies, they are not ideal candidates as detrital minerals. In contrast, garnet, rutile and titanite fulfil these requirements and are, therefore, the ideal targets for such a task.

Fingerprinting cold plate tectonics using detrital minerals: a world of sand

The power of multiproxy approaches for the provenance analysis of detrital minerals is increasingly recognised (e.g. Gaschnig, 2019). Although garnet and rutile, and to a lesser extent titanite, are fairly robust to sedimentary processes (Morton and Hallsworth, 2007), the influence of fluvial system dynamics on the distribution of these minerals requires refinement. Also, the ability to derive provenance information specific to metamorphic grade from these detrital minerals, particularly as they are sampled further away from their source, is largely underexplored. This will be particularly relevant as low T/P belts that fingerprint cold plate tectonics are relatively limited compared to other exposed lithologies, even in modern mountain belts. The alpine belt is an ideal candidate to test these proxies and better understand dilution effects and other biases that affect our ability to trace metamorphic grades or conditions using these detrital minerals. Once these tools are sufficiently refined, they will be applied to older detrital components in sedimentary sequences found at key locations around the world

where the presence of Precambrian cold subduction can be tested.

FINGER-PT main objectives in the next five years

The project aims to apply existing thermobarometric tools and develop new tools to obtain P-T conditions from single grains. A multidisciplinary approach will be adopted due to the highly challenging nature of some of the new developments, including petrological experiments, while providing a robust assessment of their limitations. In addition, we aim to investigate the survival of eroded LT-HP terranes through multiproxy mineral analyses in modern sediments using an exposed subduction channel, where evidence for cold subduction is unambiguous. We also aim to trace LT-HP metamorphism in the geological record using Precambrian sedimentary rocks.

FINGER-PT aims to provide unambiguous evidence that cold subduction is present at least to the Proterozoic-Archean boundary, if not earlier, challenging models that advocate a much more recent transition to modern-style plate tectonics. In this way, FINGER-PT seeks to inspire a new generation of geodynamic and numerical models capable of justifying colder geothermal gradients earlier than previously accepted. This will have potential implications for other interdependent Earth systems, such as the hydrosphere, atmosphere and biosphere, especially as key events can be traced back to the Proterozoic, Earth's oxygenation events, the emergence of eukaryotes and multicellular life.

R References [click here](#)

PROJECT NAME

Fingerprinting cold subduction and plate tectonics using key minerals (FINGER-PT)

PROJECT SUMMARY

Whether plate tectonics began 850 million years ago or earlier is uncertain. FINGER-PT hypothesises that preservation bias obscures evidence of earlier modern-like tectonics. To test this, the project analyses detrital minerals in sedimentary rocks, employing experimental petrology, elastic barometry, and geochemistry to uncover when tectonic processes as we know them began.

PROJECT PARTNERS

This project benefits from the collaboration of Kenneth Koga at the Université Orléans (France), Emilie Bruand at Geo-Ocean, CNRS (France), Matteo Alvaro at the University of Pavia (Italy), José Feliciano at LNEG (Portugal), Pedro Dinis at the University of Coimbra (Portugal) and Eric Thiessen at the Memorial University of Newfoundland (Canada).

PROJECT LEAD PROFILE

Inês Pereira (PhD 2019; U.Portsmouth, UK) is a geologist and a research fellow at the U.Coimbra (2022) with FCT funding. Since 2024, she is also the head of the Geoscience Center. She is interested in applying petrogeochemical tools to unravel geodynamic processes, including how mountain belts form and collapse through time.

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