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Tectonic processes and the evolution of the continental crust

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Abstract: The Earth is the only known planet where plate tectonics operates. We review the features of Archean and early Proterozoic geology that constrain tectonic environments and inform discussions of the onset of plate tectonics. There is the question of scale and how the results of individual case studies are put into a wider global context. Global models may be difficult to test and we seek to integrate evidence for plate tectonics being active with ancient records of subduction. We explore evidence for when the continental crust became rigid enough to facilitate plate tectonics based on the occurrence of widespread dyke swarms and large sedimentary basins, relatively widespread granulite facies metamorphism and evidence for crustal thickening. We argue that it remains difficult to constrain tectonic settings from contemporaneous metamorphic events without spatial controls. Archean cratons stabilized at different times in different areas from 3.1 to 2.5 Ga, juvenile continental crust changed from mafic to more intermediate compositions, there was a reduction in crustal growth at *c.* 3 Ga and increasing evidence for the lateral movement of crustal fragments. These, together with the other changes at the end of the Archean, are taken to reflect the onset of plate tectonics as the dominant global regime.

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The continental crust is the archive of the evolution of the Earth, providing the surface we on which we live as well as a record of when life emerged and how it has evolved. It is the repository of most of the critical mineral resources that are currently in demand and so there is considerable interest in establishing when and how the continental crust formed, not least to understand the distribution of elements within it. The present day Earth is shaped by plate tectonics and is the only known planet in our solar system where plate tectonics is active. There is much discussion over when plate tectonics may have become the dominant tectonic regime on Earth and how that is best established. In the context of when and how the crust formed, the focus has been on the relative volumes of crust of different ages that are both preserved today and may have been present at different stages in Earth history, on the geochemistry of newly generated and bulk continental crust, on metamorphic regimes and on the tectonic processes involved in the production of continental crust.

The characteristics and definition of plate tectonics on the modern Earth are well established, but, going back in time, there is the question of how much things can change before the ‘plate tectonic’ label no longer fits. This is very difficult to resolve and it remains an underlying weakness, with questions like ‘when did plate tectonics start on Earth?’. Our approach is therefore to focus on what we regard as robust lines of evidence that tell us about processes and then to evaluate when signals unambiguously start to look like those produced by plate tectonics. We infer that plate tectonics involves a globally linked system of lateral motion of rigid surface plates, it is powered by subduction and evidence for subduction is often taken as evidence for plate tectonics. However, subduction has also been locally attributed to regional lateral movements in response to meteorite impacts and the emplacement of mega-plumes. The challenge is to establish when there was a global linked network of lateral motion of rigid blocks known as plates (cf. Cawood *et al.* 2018). One approach is to evaluate the consequences of plate tectonics, rather than to look for the oldest rocks that reflect subduction – for example, a marked increase in the rates at which continental crust is destroyed (reflecting the recycling of lithosphere via subduction), rather than the oldest blueschists. Another approach might be to look for evidence of the development of relatively rigid crust, strong enough, by implication, to act as plates in plate tectonics.

Relatively few rocks from early in Earth history are preserved. The oldest minerals are Hadean in age (e.g. Wilde *et al.* 2001), as are a few small outcrops of gneissic rocks (Stern and Bleeker 1998; Bowring and Williams 1999). More than half of the rocks exposed in the crust today are younger than 700 Ma and <7% are Archean in age (Fig. 1; Goodwin 1996). A number of crustal growth curves have been developed and these are discussed in more detail in the section on crustal evolution. Figure 1 contrasts the crustal growth curves of Guo and Korenaga (2023), Belousova *et al.* (2010), Dhuime *et al.* (2012) and Reimink *et al.* (2023) with the age distribution of rocks preserved at the present time (Goodwin 1996) and the age distribution of rocks with juvenile Nd isotope ratios (Condie and Aster 2010), indicating when the crust preserved at the present time was generated. The Goodwin (1996) curve might reflect ages older than that of the ‘true’ crust, but it remains difficult to evaluate the balance of relatively young and old material in the deeper crust – for example, in areas of magmatic underplating or continental collision (see later discussion). The Condie and Aster (2010) curve was constructed using igneous and detrital U/Pb zircon ages, whole-rock Nd and/or zircon Hf isotopic data, combined with the areal distributions of rocks of known ages estimated from geological maps. The Condie and Aster (2010) and Goodwin (1996) curves therefore refer to rocks preserved at the present time, whereas the Belousova *et al.* (2010), Dhuime *et al.* (2012), Guo and Korenaga (2023) and Reimink *et al.* (2023) crustal growth curves highlight that larger volumes of continental crust were present in the Archean than the volume of Archean rocks preserved today, with

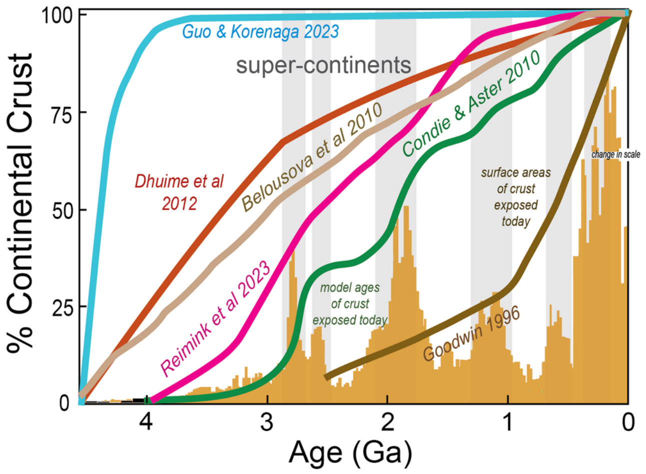

Fig. 1. Selected models for the evolution of the continental crust from Guo and Korenaga (2023), Dhuime *et al.* (2012), Belousova *et al.* (2010) and Reimink *et al.* (2023). These models are developed on the basis of elevated ^{142}Nd in Archean mantle-derived rocks (Guo and Korenaga 2023)), O and Hf isotope ratios in magmatic and detrital zircons (Dhuime *et al.* 2012; Belousova *et al.* 2010) and a major element index for identifying reworked crustal rocks (Reimink *et al.* 2023). Also plotted is the preserved age distribution of rocks with juvenile Nd isotope ratios (Condie and Aster 2010), the age distribution of surface rocks (Goodwin 1996) and the age distribution from 906 218 zircon analyses worldwide (from the compilation of Puetz *et al.* 2021).

differing implications for the amount of crust that has been destroyed by recycling into the mantle. The geological record is therefore incomplete, further implying that the record of the evolution of the continental crust is also biased, in that older rocks are under-represented in the present day crust relative to younger rocks.

The record of zircon crystallization ages is characterized by peaks and troughs (Fig. 1). The inference is that the relative proportions of zircons of different ages at least loosely reflect the relative volumes of felsic magmas. The discussion has been about the extent to which the zircon age record reflects a primary record of pulses of felsic magmatism or whether it has been biased by subsequent tectonic processes (Hawkesworth *et al.* 2009; Condie *et al.* 2011; Arndt 2023). We are uneasy about proposed causes of pulsed felsic magmatism that ascribe it to variations in the rate of crustal generation over the last three billion years and we prefer interpretations that associate the peaks of ages with collisional tectonics and the development of supercontinents. The rates at which crust is generated in the Andes, for example, is similar to the rates at which it is destroyed (e.g. Scholl and von Huene 2009) and so the preservation potential of rocks formed at convergent plate margins is much less than in collisional regimes. In our interpretation, the geological record is also biased by the higher preservation potential in collisional orogenic systems (Hawkesworth *et al.* 2009; Cawood *et al.* 2013).

This paper evaluates some of the most recent discussions, with an emphasis on data and models for the early Earth and when plate tectonics may have started on Earth. We consider some of the approaches used in recent discussions, which are briefly summarized in the following text. It is not our intention to provide a complete reference list and for that the reader is referred to Arndt (2023) and Salminen *et al.* (2021). Alternative interpretations on the timing of the initiation of plate tectonics are presented in the accompanying papers by Bédard (2024) and Harrison (2024).

- Regional geology. Some researchers have argued that there is no compelling reason in the preserved geological record to suggest that plate tectonics was not in operation for at least the last 4 Ga and that changes from more mafic to more felsic regimes can be accommodated in a plate tectonic model (Windley *et al.* 2021). Others have argued that the models invoked in a pre-plate tectonic world, such as stagnant lid and sagduction, are at best implausible (Korenaga 2021; Arndt 2023; Copley and Weller 2024).
- Oldest examples. A number of studies have highlighted the oldest known examples of igneous rocks with subduction-related geochemical signatures, and of blueschists, and argued that subduction and hence plate tectonics was active at those times (Polat *et al.* 2002). It may be that the oldest example provides a minimum age estimate of when analogous processes were in operation, at least regionally, but this may need to be linked to evidence for the processes being active. These might, for example, include a reduction in the crustal growth rate linked to increasing rates of destruction of the crust attributed to widespread subduction and plate tectonics.
- Metamorphic asymmetry. Paired metamorphic belts in the recent geological past are associated in both space and time and they are widely taken as evidence of subduction and plate tectonics. This has encouraged studies seeking comparable evidence in Archean and Proterozoic geology. The term ‘paired metamorphism’ has been used in a generic sense for metamorphic events of the same age, but without spatial control at the time of metamorphism (Brown 2006; Brown and Johnson 2018; Holder *et al.* 2019). The extent to which tectonic regimes can be constrained by ‘paired metamorphism’ without spatial control remains a matter of debate.
- Palaeomagetism. Palaeomagnetic data have long been used to document the relative lateral movements of different crustal fragments (Cawood *et al.* 2006; 2018; Evans *et al.* 2016; Pesonen *et al.* 2021; Salminen *et al.* 2021; and references cited therein) and recent studies have obtained magnetic data from well-dated Eoarchaean to Mesoarchaean zircons from southern Africa (Tarduno *et al.* 2023).
- Complementary reservoirs. The continental crust and the depleted mantle have been regarded as complementary terrestrial reservoirs (Allègre *et al.* 1979; Jacobsen and Wasserburg 1979; DePaolo 1980; Hofmann 1988). This has encouraged models of crust formation based on the recognition of signatures in mantle-derived rocks that might be associated with the extraction of continental crust, such as depleted Sr, Nd and Hf isotope ratios, radiogenic Pb and elevated ^{142}Nd (Allègre *et al.* 1983; Jacobsen 1988; McCulloch and Bennett 1994; Kramers 2002; Korenaga 2021).

Zircon record

There is a long-standing discussion over how representative the zircon record is of the age distribution in the continental crust. Zircons mostly crystallize from relatively felsic magmas (see discussion in Keller *et al.* 2017) and they are sampled both directly from magmatic rocks and as detrital minerals in sediments and sedimentary rocks. They sample continental crust that is exposed and there will be a bias in that more felsic and hence zircon-bearing rocks are more common in the upper crust than at deeper crustal levels. Different studies have shown that similar zircon records have been observed from sediments and magmatic rocks in regional studies of relatively young orogenic systems, such as the western USA and the Andes (Capaldi *et al.* 2021; Schwartz *et al.* 2021). Similar age distributions are observed in sedimentary rocks of different ages, considering their different depositional ages (Hawkesworth *et al.* 2010; Parman 2015). The variations in Hf isotope ratios in detrital zircons and of whole-rock Nd isotopes with age for both sedimentary and granitic rocks are strikingly similar and both isotopic systems appeared to have sampled similar types of orogens (Condie and Aster 2013).

However, the key issue over the extent to which the zircon record is representative of the continental crust is likely to be the extent to which the age profiles in the upper crust are similar to those in the deeper crust. In some areas, the upper and lower crust have similar ages (James and Fouch 2002), whereas in others the lower crust has younger ages than the upper crust (Moyen *et al.* 2017) and, in collision zones, some of the deeper crust may be relatively old (Weller *et al.* 2021). It has been argued that the residence times of elements is shorter in the lower than in the upper crust (Hawkesworth and Kemp 2006) and, where there are differences in age between the upper and lower crust, it may be that the lower crust is, on average, more likely to be younger rather than older than the upper crust. If so, the zircon age record would be displaced to older ages than the 'true' age distribution curve of the continental crust.

Crustal recycling is used to describe the return of crustal material back into the mantle and crustal reworking is defined as the physical reprocessing of continental material by magmas, metamorphism or fluids within the crust, or by alteration, weathering, erosion or sedimentation processes at the Earth's surface (Kemp and Hawkesworth 2014).

Scale and tectonic processes

A key feature of the earth sciences is that information is available from a wide range of scales in both space and time and it can be difficult to integrate data from different scales. A common example is how to evaluate the global significance of the results of detailed local case studies and of the recognition of the oldest examples of inferred subduction-related rocks noted earlier. Are there ways of assessing whether evidence for subduction-related processes in one area can also be used as evidence for plate tectonics globally? The issue of scale highlights the question of how best to sample the continental crust and what we need to know and to measure in evaluating the processes involved in the generation and evolution of the continental crust. Our approach is to build up from regional studies to databases that can be taken as global, such as Hf and O isotopes in detrital zircons, and to identify when major changes in the geological record might reflect changing tectonic regimes. Where possible, we consider both the evidence for when particular tectonic regimes developed and for the effects of different regimes once they became dominant.

A linked issue is the scale of tectonic processes: some are on the scale of orogenic cycles constrained from regional geology and others are of global tectonic models, such as the development of plate tectonics. There is much discussion of models for the evolution of the continental crust (see later section) and the implications are, in part, to constrain the global tectonic regimes at different stages in Earth history.

Archean geology retains marked differences in both hard and soft rock associations and in geochemistry compared with younger terranes. The intrusive rocks typically consist of trondhjemite, tonalite and granodiorite (TTG) suites, often in association with mafic rocks and komatiites (Fig. 2), and the sedimentary rocks include banded iron formations and relatively few carbonates. The distinctive aspects of Archean rocks have been readily recognized in the field since the 1850s (e.g. Logan 1857; Sutton and Watson 1950; MacGregor 1951). The sedimentary rocks are taken to reflect changing surface environments and there is continuing discussion over whether the TTG suites reflect different thermal conditions and/or different tectonic processes from those in younger terranes (Kamber 2015; Moyen and Laurent 2018; Arndt 2023).

Relative strength of the crust and tectonic style

Geodynamic models highlight that the subduction of one lithospheric plate below another requires a certain rigidity in the crust. Lithospheric strength is sensitive to lithospheric thickness and the amount and distribution of radiogenic heating (Copley and Weller 2024). Moreover, the lithosphere is weaker at higher temperatures and it has been argued that plate tectonics may only take place once the mantle potential temperature is within *c.* 100°C of that at the present day (Sizova *et al.* 2014). Some geological features reflect the strength of the crust or, in some cases, the lithosphere. These features include the oldest regional dyke swarms and the oldest major sedimentary basins, both at or after *c.* 2.8 Ga (Cawood *et al.* 2018, 2022). Archean granulites tend to be formed by high-temperature or ultra-high-temperature metamorphism at relatively low pressures (Kelly and Harley 2005; Touret *et al.* 2016; Tucker *et al.* 2024), but their appearance from *c.* 3.3 Ga to the late Archean (Fig. 3) (Holder *et al.* 2019) suggests that, by that time, the

Fig. 2. Students on a road-cut north of Loch Laxford (NW Highlands, Scotland) showing Mesoarchean and Neoarchean grey gneiss (Lewisian) cut by Paleoproterozoic mafic intrusions (Scourie dykes, now foliated and metamorphosed within the amphibolite facies) and discordant sheets of *c.* 1.85 Ga (Laxfordian) granite and pegmatite.

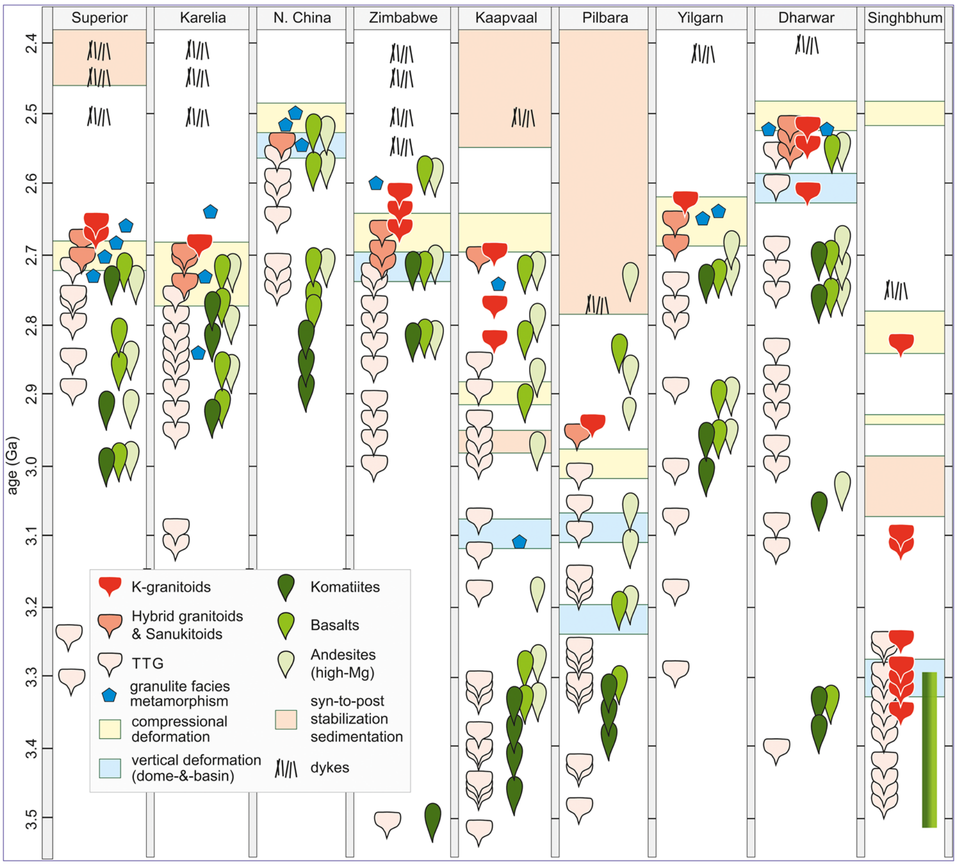

Fig. 3. Time–space plot for the Superior, Karelian, Dhawar, North China, Pilbara, Yilgarn, Zimbabwe and Kaapvaal cratons for the time period 3.5–2.4 Ga showing the time of major felsic and mafic/ultramafic igneous activity, deformation events that are late in the orogenic cycle of the craton, granulite facies metamorphism, mafic dyke emplacement and major late sedimentary basin deposition. Source: after Cawood *et al.* (2022). The distribution of felsic magmatism is adapted from Laurent *et al.* (2014) and mafic magmatism from Gao *et al.* (2022). The timing of granulite facies metamorphism is from Sorjonen-Ward and Luukkonen (2005), Dirks and Jelsma (2006) and Kuang *et al.* (2023).

crust was locally strong enough to sustain relatively deep crustal metamorphism (Rey and Coltice 2008).

If the crust was relatively weak through much of the Archean, then there may have been little in the way of mountain building, or even significant topographic relief, in continental areas before the late Archean (Cawood and Hawkesworth 2019). Most Archean sedimentary rocks are preserved in greenstone belts and they were deposited in shallow water, often in coastal plain type environments (Eriksson *et al.* 1994), and so there are concerns over the extent to which Archean and younger sediments do, or do not, sample similar depths of material in their source regions (Kamber *et al.* 2005).

Western Australia provides a good example of changing tectonic styles in the Archean and into the early Proterozoic (Fig. 4). The East Pilbara Terrane of NW Australia is characterized by dome and basin tectonics reflecting vertical tectonic movements and associated with intraplate-like volcanic rocks (Collins *et al.* 1998; Hickman 2004; Smithies *et al.* 2007). At *c.* 3.1 Ga the magmatic and structural records of the terrane indicate a shift to more lateral tectonics along the NW margin, with the appearance of volcanic rocks with subduction-like geochemical signatures (Smithies *et al.* 2005). In the eastern portion of the Yilgarn craton, north–south-trending belts of *c.* 2.7 Ga magmatic rocks, and associated ores, display inferred subduction-related signatures (e.g. Champion and Cassidy 2007; McCuaig *et al.* 2010). Regional dyke swarms cut the Pilbara crust by *c.* 2.77 Ga (Wingate 1999) and the Yilgarn crust by *c.* 2.4 Ga (Nemchin and Pidgeon 1998), providing minimum ages for the stabilization of these cratons (Fig. 3). These changes occurred at different times in different Archean terranes (discussed later).

Magmatic associations

Minor and trace element discriminant diagrams of basaltic rocks are widely used to constrain the tectonic setting in which magmas were generated (e.g. Pearce and Cann 1973; Pearce 2008). The approach is based on comparing rocks from known modern tectonic settings with ancient examples and has been widely applied to the Archean. Discriminant diagrams have also been developed for granitic rocks (Pearce *et al.* 1984), but these are more difficult to interpret because of the role of source rocks in determining the minor and trace element contents of felsic magmas. The discussion can therefore come down to the extent to which granites were generated in similar tectonic regimes to their source rocks (Pearce *et al.* 1984).

Many Archean suites are bimodal in SiO_2 and MgO (Kamber and Ossa 2023) and it is striking that this is independent of whether they were generated in dome and basin terranes, implying a component of vertical movement, or in more linear belts associated with compressive tectonics (such as the West Pilbara Terrane and the Ylgarn craton; Fig. 4). In the recent geological past, such bimodal distributions are a feature of intraplate volcanism, but not of subduction-related magmas. The tectonic settings of granite–greenstone terranes have been investigated based on the recognition of boninite-like magmas (Cameron *et al.* 1979; Polat *et al.* 2002; Smithies *et al.* 2004) and on the stratigraphic associations (Turner *et al.* 2014) that are found in recent subduction-related settings.

Many rely on distinctive, relatively immobile trace elements and ratios, such as Th/Nb. This ratio is elevated in modern subduction-related magmas, reflecting their distinctive negative anomalies in Nb and Ta due to fluid-fluxed melting in the mantle wedge between the down-going oceanic lithosphere and the overriding magmatic arc (e.g. Zheng 2019). There is evidence for a continuum in Th/Nb ratios in Archean rocks between those that appear to have been generated at constructive plate boundary and within-plate settings (Moyen and Laurent 2018), than is observed in more recent examples. Nonetheless, there are differences in the Th/Nb ratios between different Archean suites (Fig. 5). Th/Nb ratios are used in this discussion in part because they are widely applied, but primarily just to illustrate the conclusions of different studies in terms of the tectonic settings in which different Archean suites were generated.

Figure 5 summarizes the mean Th/Nb ratios of suites of Archean, predominantly mafic, rocks that appear not to have been modified

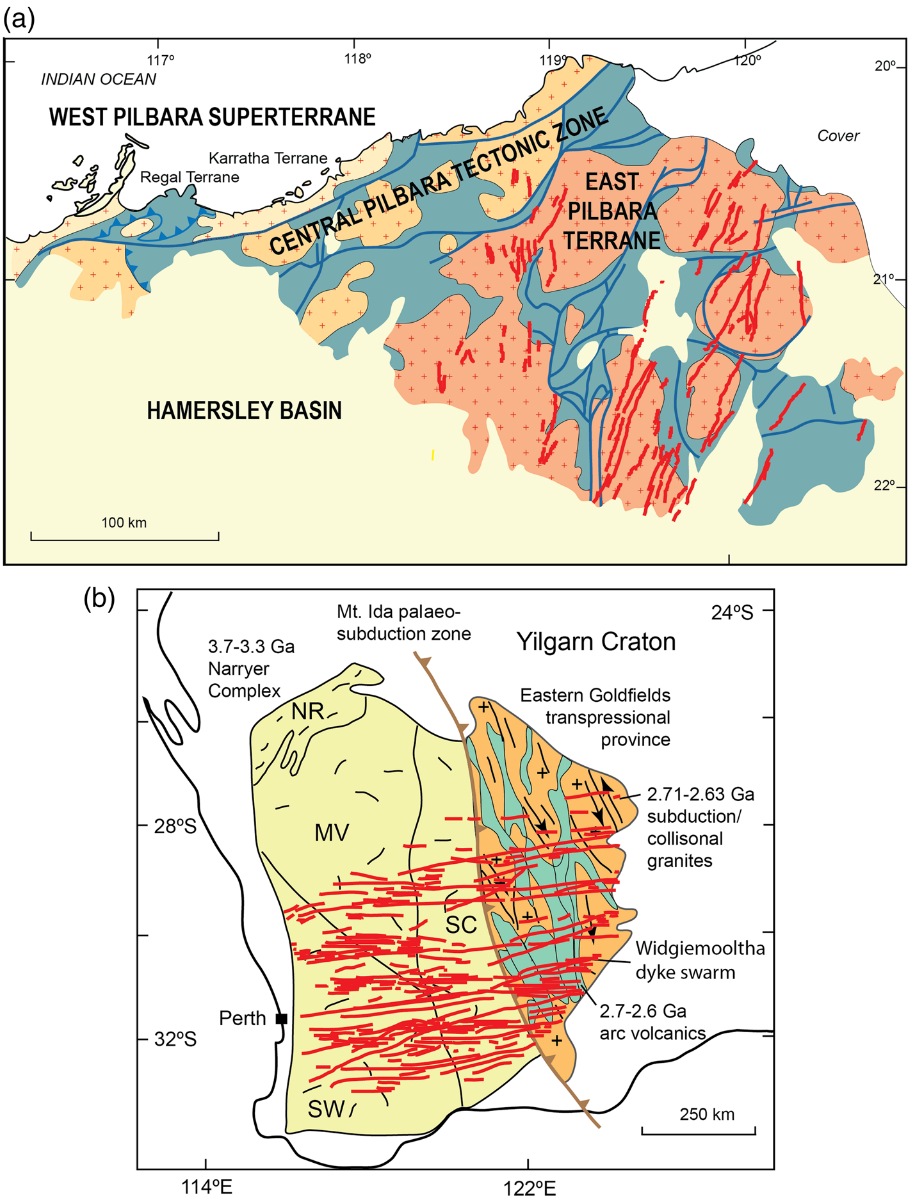

Fig. 4. The changing tectonic styles from 3.5 to 2.4 Ga in Western Australia. (**a**) Sketch map of the dome and basin terrane of Pilbara, NW Australia, after Hickman (2004) and Van Kranendonk (2010), highlighting the *c.* 2.77 Ma Black Range dykes that extend across the craton and feed the Mt Roe Basalt of the Fortescue Group (Wingate 1999). (**b**) Geological sketch map of the Yilgarn craton and the north–south-trending mobile belts in the East Yilgarn (after Kusky *et al.* 2018) and the *c.* 2.4 Ga Widgiemooltha dyke swarm in the SW Yilgarn (after Hawkesworth *et al.* 2020).

significantly by crustal contamination. Most crustal contamination models result in increases in Th/Nb ratios because elevated Th/Nb values are a feature of the continental crust and so the suites with low Th/Nb values are very unlikely to have had their Th/Nb ratios modified by crustal contamination. The simplest interpretation is that suites of high Th/Nb (subduction-related) and low Th/Nb (non-subduction-related) magmas were generated at similar times in different locations in the time period 3.8–2.7 Ga (Fig. 5). It is striking that all the low Th/Nb suites plotted are from dome and basin terranes characterized by vertical tectonics. For some of the older, higher Th/Nb suites, it is not possible to evaluate the regional tectonic regime at the time of magmatism because the rocks analysed are older than the prevailing tectonic fabrics, but, where this is possible, the higher Th/Nb ratios are in magmatic rocks from more linear tectonic belts (e.g. the West Pilbara Superterrane and the younger belts in the Yilgarn craton; Fig. 4). Overall, it is encouraging that the available evidence suggests a link between tectonic style and the trace element signatures of the associated mafic rocks (Hawkesworth *et al.* 2020).

Blueschist facies metamorphism typically reflects low geothermal gradients and pressures corresponding to depths >15 km. There has been much discussion of the nature of lithospheric recycling prior to the onset of blueschist facies metamorphism, which has been termed ‘cold’ subduction, and the extent to which ‘hot’ subduction prevailed (cf. Hawkesworth *et al.* 2016). Recent island arc magmas have relatively high water contents (Plank *et al.* 2013) and one aspect is how the water contents of greenstone belt volcanic rocks compare with those of recent island arc magmas. Elevated water contents suppress plagioclase crystallization, and hence fractionation, and are therefore associated with higher maximum whole-rock Al_2O_3 contents (Pichavant and Macdonald 2007). Strikingly, most greenstone belt volcanic rocks are not characterized by high Al_2O_3 contents and yet these are a feature of recent island arc rocks (e.g. Kelemen *et al.* 2003). The maximum Al_2O_3 contents of the Pilbara volcanic rocks is *c.* 18 wt%, significantly lower than equivalent values in the Aleutians (*c.* 21 wt%; Hawkesworth and Kemp 2021). Hawkesworth *et al.* (2020) noted that the suites with higher Th/Nb ratios tended to have higher maximum Al_2O_3 values, consistent with higher water contents in magmas with a subduction-related trace element signature.

Although there are data from a relatively small number of studies, the mean maximum Al_2O_3 values for within-plate and subduction-related suites are 15.1 and 17.2 wt%, suggesting water contents of <2 and <4 wt%, respectively (Pichavant and Macdonald 2007). Hawkesworth and Kemp (2021) concluded that the water contents of the mafic Pilbara volcanic rocks were low, perhaps <2 wt% H_2O,

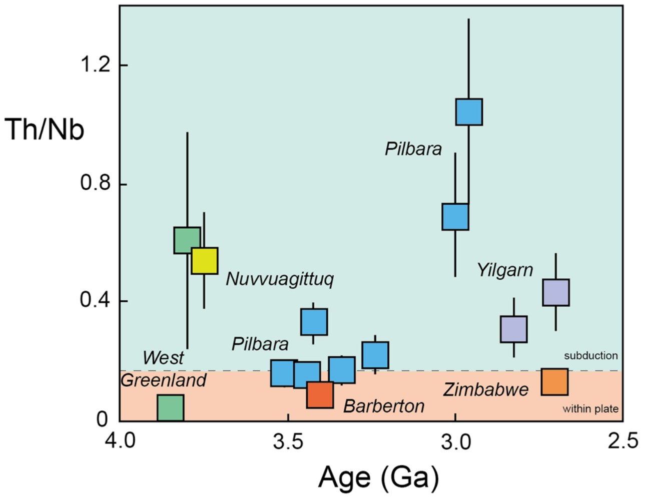

Fig. 5. Mean Th/Nb ratios of suites of Archean predominantly mafic rocks plotted against eruption ages, for suites which are thought not to have been modified significantly by crustal contamination. Green field is for elevated Th/Nb ratios, which are attributed to subduction-related processes, and the orange field is for within-plate magmas. Data from Barley *et al.* (1998), Smithies *et al.* (2004, 2005), O'Neil *et al.* (2007), Jenner *et al.* (2009, 2013), Puchtel *et al.* (2013), Shimizu *et al.* (2005), de Joux *et al.* (2014) and Lowrey *et al.* (2019). The colours in the small squares reflect the different locations plotted (after Hawkesworth *et al.* 2019).

compared with an average of 4 wt% H_2O in younger subduction-related magmatic rocks (Plank *et al.* 2013). It is not clear when the water contents increased to the values now seen in recent island arcs, but that too may be linked to the onset of 'cold' subduction and the generation of more mafic juvenile crust from *c.* 700 Ma (see later discussion).

Trondhjemite, tonalite and granodiorite suites

TTG suites are a distinctive feature of Archean terranes. They are much less common in the post-Archean and there has been a lengthy debate over whether their presence in the Archean reflects different tectonic processes at that time and/or differences in the thermal state of the crust (Kamber 2015; Moyen and Laurent 2018; Arndt 2023). TTG suites typically have a quartz + plagioclase + biotite mineral assemblage, with little or no K-feldspar. They have distinctive trace element signatures, with high light rare earth element contents, but very low heavy rare earth element and Y contents, resulting in high La/Yb ratios (mean La/Yb = 49, corresponding to $La/Yb_N = 32.4$) (Moyen and Martin 2012). They lack significant Eu and Sr anomalies, but have negative Nb–Ta and Ti anomalies, low Lu/Hf ratios and high Zr/Sm ratios. TTG suites therefore differ from the modern continental crust, which has higher heavy rare earth element contents and negative Eu, Nb–Ta, Sr and Ti anomalies (Rudnick and Gao 2003). The lack of Eu and Sr anomalies, together with the low heavy rare earth element content, have been interpreted as reflecting the presence of garnet and amphibole, as well as the lack of plagioclase, as residual or fractionating phases. TTG suites have been subdivided into low-, medium- and high-pressure groups (Moyen 2011) and their geochemical diversity has been attributed to a range of melting depths from *c.* 5 to >20 kbar (e.g. Moyen and Laurent 2018), although Smithies *et al.* (2019) have argued that there is no compelling evidence for depths of melting >40 km.

Models for the generation of TTG suites typically invoke the partial melting of hydrated basalt (e.g. Foley *et al.* 2003; Rapp *et al.* 2003; Moyen 2011). Thus, TTG suites are crustal melts, consistent with the marked SiO_2 and MgO gaps observed in many Archean terranes (Kamber and Ossa 2023) and, as such, it can be difficult to resolve which minor and trace element signatures are inherited from their source rocks and which might in some way reflect the tectonic setting in which the TTG suites were generated. There is widespread agreement that the source basalts for TTG suites were more enriched in incompatible elements than mid-ocean ridge basalts (Kemp and Hawkesworth 2003; Martin *et al.* 2014), which might be interpreted to reflect smaller degrees of partial melting of the mantle in the formation of those basalts than for mid-ocean ridge basalts, despite the hotter regimes in the Archean. Overall, TTG suites associated with dome and basin and more linear tectonic belts appear to be intriguingly similar, although there is evidence that their Ba contents are different (Johnson *et al.* 2019; Huang *et al.* 2022).

Huang *et al.* (2022) explored the extent to which the high Ba contents in TTG suites can be used as a proxy for subduction. They attribute high Ba contents to the conditions under which partial melting took place, little affected by subsequent magma differentiation processes. High Ba contents reflect the suppression of biotite and epidote during melting and, using an average enriched Archean basaltic source composition (107 ppm Ba), Huang *et al.* (2022) modelled Ba concentrations in TTG suites and concluded that only low geothermal gradients corresponding to hot subduction zones produce Ba-rich TTG suites. They used Ba as a proxy for the onset of subduction and identified significant increases in the Ba contents of TTG suites worldwide, from regionally at 4 Ga to globally complete sometime after 2.7 Ga.

TTG suites dominate the records of Archean cratons and the stabilization of the cratons appears to be linked to the late-stage generation of granite and sanukitoids. Typically, the granites are attributed to partial melting in response to crustal thickening, whereas the sanukitoids are attributed to the introduction of crustal material via subduction into their source regions (Martin *et al.* 2009; Halla *et al.* 2017; Moyen *et al.* 2024). Different cratons often have similar magmatic records, but over different time periods, indicating that craton stabilization occurred at different times in different places (Fig. 3; Cawood *et al.* 2022). Most TTG to sanukitoid records are Archean in age, but they are as young as 2.3–2.1 Ga in the Mineiro Belt of the São Francisco craton (Moreira *et al.* 2020).

Supercontinents and supercratons

Much of the early evidence for supercontinents came from palaeomagnetic reconstructions (Evans *et al.* 2016; Pesonen *et al.* 2021; Salminen *et al.* 2021; and references cited therein). There is strong support for at least three supercontinents since 2 Ga (Pangaea, Rodinia and Columbia/Nuna, plus or minus Gondwana) and less agreement about the data from older terranes. There appear to be two issues related to interpretations of the older terranes: (1) whether supercontinents can be reconstructed from the available data; and (2) how much evidence there is for significant lateral movement as predicted by plate tectonics. The former is restricted in that the only palaeomagnetic reconstructions of the proposed supercontinent Kenorland (*c.* 2.7 Ga) are single-pole comparisons – that is, of palaeomagnetic poles of one age, which effectively compare palaeolatitudes, but are unconstrained in terms of relative palaeolongitude (Mitchell *et al.* 2021). Cawood *et al.* (2018) used coeval reliable palaeopoles for the late Archean to early Paleoproterozoic time interval to show significant relative movements of the Kaapvaal and Pilbara cratons and of the Superior, Kaapvaal and Kola–Karelia cratons. The discussion has therefore tended to be about the extent to which different fragments of Archean crust might be linked up on the basis of shared geology. This tends to restrict the scale of inferred Archean supercratons and it has been suggested that, on average, about four cratons are contained within the area of each Proterozoic continent (Bleeker 2003). It is difficult to establish whether any of these warrant the term supercontinent.

Zircons are widely analysed because they preserve robust U–Pb ages and the zircon record has recently been explored for variations in Lu/Hf ratios and palaeomagnetism. ^{176}Lu/^{177}Hf ratios in >120 000 zircons worldwide are characterized by cyclical oscillations since *c.* 3 Ga (Moreira *et al.* 2023). ^{176}Lu/^{177}Hf ratios vary with the proportions of residual garnet and with the degree of fractionation, such that low values reflect greater depths. They vary inversely with δ^{18}O and their cyclical variations are consistent with the presence of supercontinent cycles since *c.* 3 Ga. Tarduno *et al.* (2023) reported palaeointensity and palaeofield data on single 3.9–3.4 Ga zircons with magnetite inclusions from southern Africa. The palaeofield values are nearly constant between *c.* 3.9 Ga and *c.* 3.4 Ga, indicating unvarying latitudes over 600 Ma, more consistent with stagnant lid than plate tectonics, although this conclusion has recently been questioned in a re-analysis of the data by Fu *et al.* (2024). Zircons also retain a record of Sr isotope ratios in that apatite inclusions in zircon have been analysed for ^{87}Sr/^{86}Sr to constrain the initial Sr isotope ratios and hence Rb/Sr in the precursor rocks of new continental crust (see later discussion; Boehnke *et al.* 2018; Emo *et al.* 2018; Buzenchi 2023; Chatterjee *et al.* 2023). Thus, zircons continue to provide exciting opportunities for new insights into the geological record.

Metamorphic asymmetry

The asymmetry of modern destructive plate margins and the degrees of shortening associated with old mobile belts reflect lateral movements. They are therefore widely taken to be features of plate tectonics, as exemplified by the linear late Archean north–south belts in the Yilgarn craton of Western Australia (Fig. 4). There tend to be relatively few sources of heat for metamorphism and thermal history is closely linked to tectonic setting. Thus metamorphic rocks may usefully inform discussions of the prevalent tectonic settings.

On the modern Earth, paired metamorphic belts, as proposed by Miyashiro (1961), are coeval adjacent belts found along destructive plate margins, such as in the Pacific ring of fire. These paired metamorphic belts are of low T/P (i.e. high-pressure eclogites and blueschists) and coeval high T/P (i.e. high-temperature and low-pressure environments) domains based on the ratio of metamorphic temperature to pressure, with the former being related to the accretionary prism lying immediately inboard of the convergent plate interface and the latter to the arc–back-arc domain located further inboard of the plate margin (Miyashiro 1973). Paired metamorphic belts, defined in both space and time, have therefore been regarded as indicative of destructive plate margins and hence of plate tectonics.

Brown and colleagues (e.g. Brown 2006; Brown and Johnson 2018) compiled records of metamorphic conditions in rocks ranging in age from 3.6 to 0.02 Ga (Fig. 6a). Such compilations attempt to understand metamorphic patterns globally and the rocks are subdivided into high T/P, medium T/P and low T/P series (cf. Kuang *et al.* 2023) based on the ratio of metamorphic temperature to pressure. Given the curvature of metamorphic geotherms, such ratios are in effect a shorthand for different metamorphic regimes. Low T/P rocks are for the most part restricted to the last 700 Ma and some retain pressures equated to depths of 200 km (Fig. 6b). Such depths are greater than can reasonably be achieved by crustal thickening and so they provide evidence for tectonic processes dragging material down into the upper mantle (and their subsequent return to the surface). As these rocks tend to be linked to destructive plate margins, there is general agreement that the low T/P facies rocks are associated with subduction. There are relatively few examples of metamorphic pressure corresponding to depths >50 km in rocks older than 700 Ma and thus little evidence from the metamorphic record of material being dragged down to mantle depths.

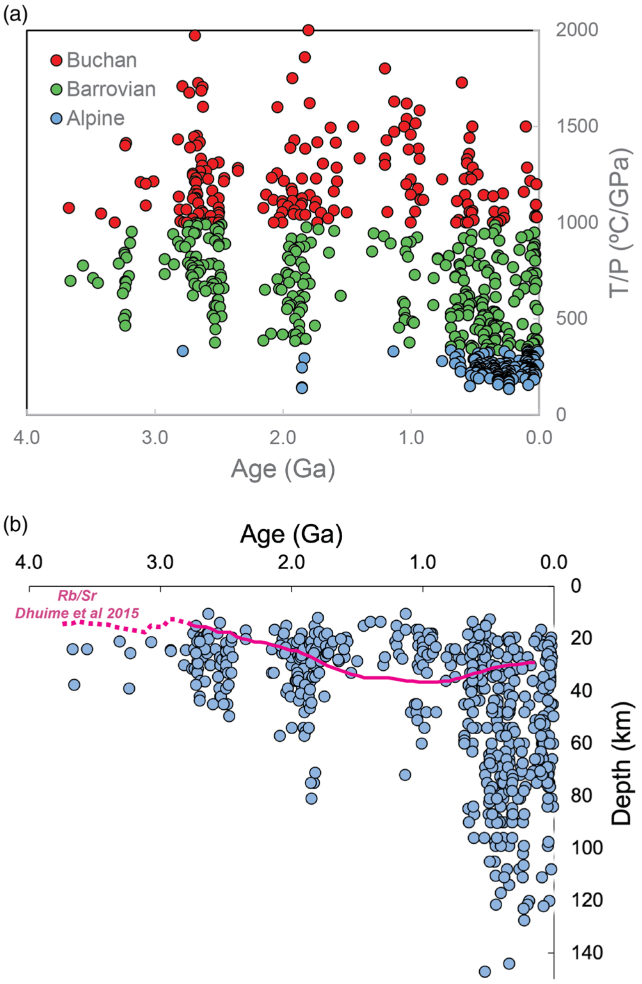

Fig. 6. (**a**) Relationship between metamorphic age, geothermal gradient and metamorphic facies series (revised after Zheng and Zhao 2020). The metamorphic temperature and pressure data are taken from Brown and Johnson (2019*a*) and Kuang *et al.* (2023) and the geothermal gradient boundaries for the metamorphic facies series are taken from Zheng and Chen (2017) at $T/P = 335$°C/GPa and 1000°C/GPa. (**b**) Plot of depth, estimated from metamorphic pressure estimates, v. age based on the data from Brown and Johnson (2019*a*) and Kuang *et al.* (2023). The pink curve is the thickness of juvenile crust, estimated from the Rb/Sr ratios of new crust from Dhuime *et al.* (2015).

The frequency of data points for the different apparent average thermal gradients in Figure 6a are grouped in age clusters that broadly correspond to the ages of supercontinents. These age clusters are more pronounced in older terranes and we have argued that the distributions of ages, as of zircons in Figure 1, are influenced by preservation bias and that the clusters of ages reflect collision tectonics in the development of supercontinents (e.g. Cawood *et al.* 2013). As such, rocks formed in subduction environments (i.e. low T/P rocks) might be lost and, particularly in older terranes, there would be a preferential bias for collision (Barrovian, medium T/P) and post-collision extension (Buchan, high T/P) metamorphic records.

Brown (2010) broadened the concept of paired metamorphic belts to one of paired metamorphism to include subduction-to-collision orogens. Paired metamorphism couples rocks of different T/P regimes, but similar ages; there is little emphasis on spatial control and so the shift from paired metamorphic belts to paired metamorphism is from belts paired in space and time to those that are of similar ages worldwide. It is unclear that pairing belts in time without spatial control offers much constraint on tectonic settings. Nonetheless, further analysis sought to evaluate the extent to which the distribution of T/P in Figure 6a was bimodal. It was argued that the modern bimodal distribution of metamorphic T/P developed gradually since *c.* 2.5 Gyr ago and that this was a proxy for the emergence of Earth's modern plate tectonic regime at that time (Holder *et al.* 2019).

The high- and medium-T/P suites are broadly equivalent to Buchan and Barrovian metamorphism (cf. Zheng *et al.* 2022). An alternative view is that the data illustrated in Figure 6a primarily indicate that, at any one time, Barrovian and Buchan metamorphism occurred, often at different locations, somewhere in the world (cf. Cawood *et al.* 2018). There is no evidence that the examples were spatially related, and yet spatial controls remain central to any interpretation of tectonic processes (e.g. Marimon *et al.* 2022). In effect, these data reopen the long-standing debate (Brown and Johnson 2019*b*; Zheng and Zhao 2020; Weller *et al.* 2021) about the controls on Barrovian and Buchan metamorphism, with the former often linked to crustal thickening and the latter to crustal extension, typically with a magmatic contribution. In some cases, they may be linked tectonically, but there is no *a priori* evidence that they are necessarily linked in particular regions, nor that they provide compelling evidence of plate tectonics.

Composition of bulk and new crust

The composition of the continental crust, and the extent to which that has changed with time, has been of considerable interest for many decades. Present day compositions can be constrained from geophysical studies, such as seismic profiles, and from geochemical data. The present day continental crust is widely accepted to be andesitic in composition (Taylor and McLennan 1985; Rudnick and Gao 2003). The upper crust is sampled by sediments and analyses of sedimentary rocks, including diamictites (e.g. Taylor and McLennan 1981; Chen *et al.* 2020), have been used to argue that at least the upper crust was more mafic in the Archean and that there has been little in the way of significant change thereafter. It remains difficult to estimate the composition of the bulk crust from the composition of the upper crust. There are concerns that the Archean lithosphere was relatively weak and so the topographic relief, and hence the range of rock types sampled by sediments, may have been more restricted.

More direct estimates of bulk crustal compositions can be made from seismic velocities and heat flow. Average P-wave velocities constrain the composition of the middle and lower crust and hence of the bulk crust (Rudnick and Fountain 1995; Rudnick and Gao 2003). Heat flow is relatively low in Archean terranes and Hawkesworth and Jaupart (2021) highlighted the correlation between surface heat flow data and the calculated average bulk crustal heat production. Average crustal heat production values were described in terms of two-component mixtures of felsic crust with >57% SiO_2 and mafic crust with <57% SiO_2. It was concluded that the Archean terranes, for which there are heat flow data, were more mafic than the bulk crust at the present day, perhaps up to 10% MgO. Reassuringly, the more mafic compositions in the Archean have therefore been observed or inferred for both the upper and the bulk continental crust. Heat production increases with Rb/Sr and so heat production values can be used to estimate bulk Rb/Sr ratios in crust of different ages (Fig. 7; Hawkesworth and Jaupart 2021). This remains a very useful ratio for tracking crustal evolutionary processes, as discussed in the following sections.

The conditions and the tectonic regimes under which the continental crust was generated are clearly best recorded in the composition of new (or juvenile) continental crust. Yet most rocks available for sampling are in the upper crust and they are largely derived from pre-existing crustal rocks (e.g. Hutton 1788). In Archean terranes the composition of new crust may be reflected in the composition of greenstone belt volcanic rocks and the associated TTG suites, although the relative proportion of these two lithologies at the time of their formation remains difficult to establish. By contrast, the composition of the juvenile continental crust through time can be estimated from a combination of Nd and Sr isotopes to evaluate the Rb/Sr ratios of the juvenile crustal source rocks for the evolved crustal rocks. This approach is summarized in Box 1.

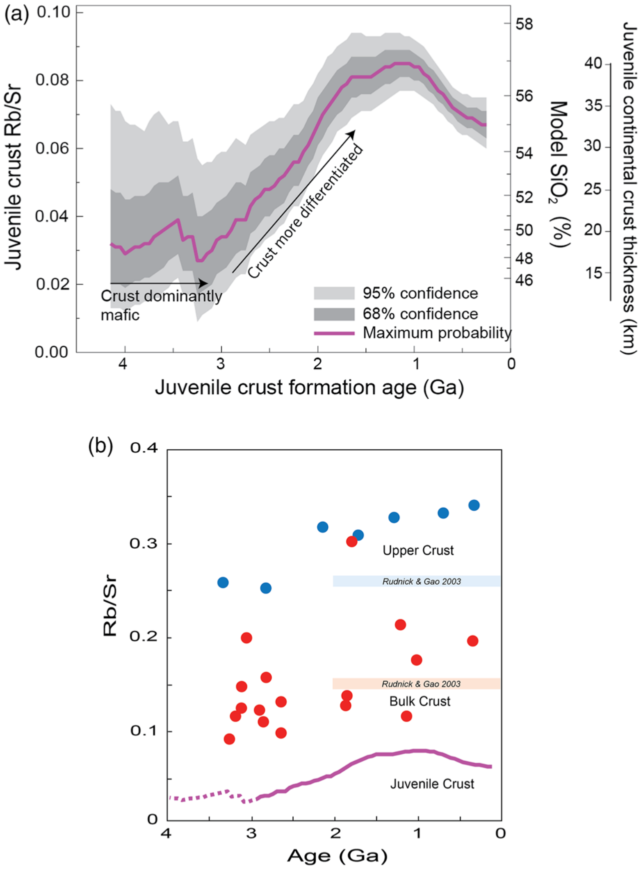

Fig. 7. (**a**) Rb/Sr ratios in juvenile crust plotted against Nd model ages, regarded as crust formation ages, from Dhuime *et al.* (2015). The estimated SiO_2 and crustal thickness values are from plots of Rb/Sr–SiO_2 and Rb/Sr–crustal thickness from central and south America summarized in Box 1 (Dhuime *et al.* 2015). (**b**) Estimated changes in the Rb/Sr ratios of the upper crust (map normalized) (Condie 1993), juvenile continental crust (Dhuime *et al.* 2015) and bulk crust (after Hawkesworth and Jaupart 2021) with time. The upper crust value of Rudnick and Gao (2003) is for average crust which has an age of *c.* 2 Ga.

Nd model ages are prone to significant uncertainties (Arndt and Goldstein 1987), but they provide a mean estimate of when segments of new crust were generated. Combined with Sr isotopes, the Rb/Sr ratios of new crust has been calculated over the time period between crust generation (i.e. the Nd model age) and the age of any later crustal reworking event (Fig. 8) (Dhuime *et al.* 2015). In both ancient and recent igneous rocks, Rb/Sr ratios increase systematically with increasing silica contents (Dhuime *et al.* 2015), particularly at SiO_2 values <60%, and so the Rb/Sr ratios of new crust are also a proxy for its SiO_2 content (Fig. 9).

Dhuime *et al.* (2015) estimated the Rb/Sr ratios, and hence the silica content, of new continental crust using the initial Sr isotope ratios and Nd model ages of *c.* 13 000 whole-rock samples. Formally, new continental crust is the composition of juvenile material crossing the Moho, irrespective of whether it was in equilibrium with the mantle or had already differentiated to some degree. The Archean data are highly scattered, but the median Rb/Sr values for crust formation ages older than 3 Ga are similar to the upper mantle at *c.* 0.03 and the silica contents (*c.* 48–49% SiO_2) are similar to that of many greenstone belt volcanic rocks. Strikingly, at

Box 1. Rb/Sr ratios in juvenile continental crust

The upper continental crust consists predominantly of granitic and sedimentary rocks generated from pre-existing crustal source rocks. Sr and Nd whole-rock isotope ratios can be used to evaluate the Rb/Sr ratios of those crustal source rocks at the time they were generated from the mantle. Sm/Nd ratios are fractionated in the processes responsible for the generation of continental crust and they are relatively insensitive to changes within the continental crust. By contrast, and a reason why Sr isotope ratios are useful indices of crustal processes, the Rb/Sr ratios are little affected by melting in the upper mantle, but they are highly sensitive to processes within the crust. Rb tends to be more incompatible than Sr in crustal magmatic processes, in part because Sr is partitioned into plagioclase feldspar, and so bulk-rock Rb/Sr ratios tend to increase with increasing magma differentiation. Felsic igneous suites evolve differently – for example, due to different tectonic settings, crustal thickness and sediment reworking – and this approach sees back through those differences to the nature of their source rocks.

^{87}Rb decays to ^{87}Sr with a long half-life (*c.* 48.8 Ga) compared with the age of Earth and rocks with different ^{87}Rb/^{86}Sr ratios develop a range of ^{87}Sr/^{86}Sr isotope ratios along linear evolution paths with time (Fig. 8). These time-integrated ^{87}Rb/^{86}Sr ratios are calculated from changes in Sr isotopes with time and used as a proxy for the bulk composition of the newly formed continental crust. The approach is in two stages. Stage 1 is the period of Sr isotope evolution of juvenile crust, from its extraction from the mantle until the formation of a derivative crustal melt. Stage 2 is the period from the crystallization of those crustal melts (typically with higher ^{87}Rb/^{86}Sr ratios) until the present day. Nd model ages (T_{DM}) for given crustal samples are taken to reflect the time when new continental crust separated from the mantle and that juvenile continental crust is assumed to have had the Sr isotope composition of the depleted mantle reservoir (Fig. 8, brown curve) at the time of its formation. The Rb/Sr ratios of newly formed continental crust are therefore calculated from the linear evolution of Sr isotope ratios in Stage 1.

Whole-rock Rb/Sr ratios tend to increase with the SiO_2 content and with crustal thickness. Figure 9a summarizes the increase in Rb/Sr ratios with crustal thickness in central and south America, which is taken as a representative 'modern' site for the generation of new continental crust (Dhuime *et al.* 2015). For thicknesses of 20–60 km, there is a positive correlation between the average Rb/Sr ratio of magmatic rocks and crustal thickness, with Rb/Sr ratios increasing from *c.* 0.04 at *c.* 20 km to *c.* 0.15 at *c.* 60 km. The sharp increase in the Rb/Sr ratio for crust >60 km, which has an Rb/Sr ration of *c.* 0.25, is attributed to enhanced crustal melting. Figure 9b illustrates the correlation between the Rb/Sr ratio and SiO_2 in crustal rocks from a compilation of 96 465 magmatic rocks (Dhuime *et al.* 2015) and, in this discussion, we are concerned with compositions with <60% SiO_2.

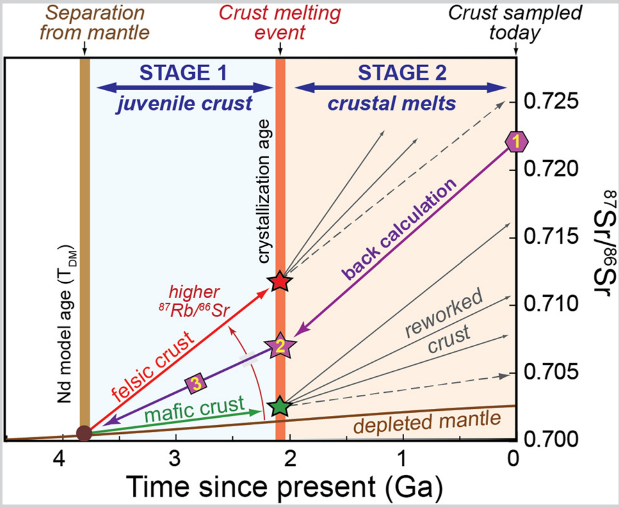

Fig. 8. Sr isotope evolution diagram illustrating the calculation of Rb/Sr in juvenile continental crust. The purple arrows with associated yellow numbers indicate how the 'juvenile crust' (Stage 1) ^{87}Rb/^{86}Sr values were back-calculated: the ^{87}Sr/^{86}Sr of the rock is measured (hexagon); the ^{87}Sr/^{86}Sr ratio at the time of crystallization is calculated (star); the Stage 1 ^{87}Rb/^{86}Sr is calculated from the slope of the segment between the ^{87}Sr/^{86}Sr ratio of the mantle at the time of crust formation (brown dot) and the Sr isotope ratio of the crustal melt at the time it crystallized (stars). Examples for a mafic source (^{87}Rb/^{86}Sr = 0.087, green path) and a more felsic source (^{87}Rb/^{86}Sr = 0.44, red path) are presented. For a step-by-step method for the calculation of Rb/Sr ratios in Stage 1, along with the parameters and references used in those calculations, is given in Dhuime *et al.* (2015).

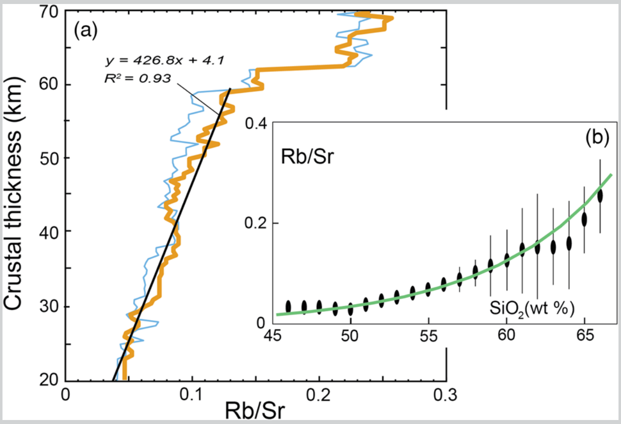

Fig. 9. (**a**) Correlation between Rb/Sr ratios and crustal thickness in central and southwestern America. The plots are based on a compilation of 7916 magmatic rocks (Dhuime *et al.* 2015) and the crustal thickness is calculated from the latitude and longitude coordinates of the samples and the Crust 1.0 model (http://igppweb.ucsd.edu/~gabi/crust1.html). The orange curve is the maximum probability function of the data with sliding windows of 10 km (Dhuime *et al.* 2015). The thinner blue curve is the running median and both statistical methods give similar results. (**b**) The correlation between Rb/Sr and SiO_2 values in crustal magmatic rocks from Dhuime *et al.* (2015). The oval dots (vertical error bars indicate 2 SEM) represent median Rb/Sr values calculated for each 1% SiO_2 interval. The best fit to the data is represented by the green curve and was fitted through the data up to 75% SiO_2 (Dhuime *et al.* 2015).

c. 3 Ga, there is a marked change in the Rb/Sr ratio and, by implication, the silica content, with a progressive increase in the Rb/Sr ratios of new crust to 0.08 and to *c.* 57% SiO_2 by 1.4 Ga. New continental crust appears to have been mafic before *c.* 3 Ga and the evolution towards more intermediate compositions is likely to reflect changes in the tectonic conditions (Dhuime *et al.* 2015). Since *c.* 1 Ga the Rb/Sr ratios of new crust, and hence its inferred silica content, have decreased. This return to more mafic compositions was perhaps linked to the onset of 'cold' subduction and the development of blueschists in the late Proterozoic (Fig. 6; Ernst 1972; Brown and Johnson 2018).

Estimates of Rb/Sr ratios in the upper continental crust from sedimentary rocks (after Condie 1993), the bulk continental crust from heat flow (Hawkesworth and Jaupart 2021) and new continental crust from Nd/Sr isotope ratios (Dhuime *et al.* 2015) all tend to increase with decreasing geological age (Fig. 7b). It is reassuring that broadly consistent variations in Rb/Sr ratios have been obtained using these different approaches. The variations in Rb/Sr ratios in juvenile, bulk and upper crust continental crust reflect intra-crustal differentiation in the evolution of the continental crust. The Rb/Sr ratios in new, bulk and upper crust were all lower in the Archean than in younger rocks, consistent with the inferred more mafic composition of Archean continental crust.

Increases in the thickness of continental crust are likely to be linked to increases in its volume (Cawood and Hawkesworth 2019) and to the emergence of continental crust above sea-level (Flament *et al.* 2013). Crustal thickness has been estimated from a number of chemical parameters (see review in Luffi and Ducea 2022) – including estimated whole-rock Rb/Sr ratios (Dhuime *et al.* 2015), Sr/Y ratios (Chapman *et al.* 2015), La/Yb ratios (Profeta *et al.* 2015), $(La/Yb)_N$ ratios (Balica *et al.* 2020) and Eu/Eu* ratios in zircons (Tang *et al.* 2021) – and depths of magma crystallization have been constrained from Lu/Hf ratios in zircon (Moreira *et al.* 2023). The Rb/Sr ratios strikingly increase with crustal thickness in central and south America (Dhuime *et al.* 2015). They also increase with the degree of fractionation in crustal rocks and it is geologically consistent that thicker continental crust is characterized by more fractionated magma types. More fractionated higher Rb/Sr and lower Lu/Hf ratios are associated with thicker continental crust and/or greater depths of magma crystallization; however, for reasons that are not clear, more fractionated Eu/Eu* ratios appear to be associated with thinner crust. The Ce/Y and La/Yb ratios in primitive magmatic rocks increase with crustal thickness (Mantle and Collins 2008; Lieu and Stern 2019) and the average Ce/Y = 1.1 and $La/Yb_n = 3.7$ (Hawkesworth and Kemp 2021) of volcanic rocks with <53% SiO_2 from the Pilbara Archean rocks suggest crustal thicknesses <30 km.

Figure 7a plots the thickness of new continental crust from the estimated Rb/Sr ratios of new crust using the variation of Rb/Sr with crustal thickness for recent magmatic rocks from central and south America (Dhuime *et al.* 2015). Crustal thickness increases from 3 to 2 Ga; this should result in an increased contribution of continental crust to the chemistry of the oceans and, in particular, an increase in the Sr isotope ratio of seawater. However, there are relatively few marine carbonate samples available from the Archean as direct records of seawater composition. Figure 10 illustrates two curves for the Sr isotope ratios in seawater through time. The green curve (CYS), displaced to higher Sr isotope ratios than the Shields and Veizer (2002) curve (SV), is from X. Chen *et al.* (2022); however, many of the Archean samples are of barite and it remains difficult to resolve barite from volcanogenic and marine origins. Crustal emergence is further reflected in the proportion of large igneous provinces erupted on land (Kump and Barley 2007) (Fig. 10). At this stage, there is broad agreement in the inferences drawn from the different approaches and the inferred crustal thicknesses (at the site of crust generation) of Dhuime *et al.* (2015) start to increase from *c.* 20 km at *c.* 3 Ga. More widely, the emergence of significant areas of continental crust remains a key constraint as to when significant volumes of reasonably long-lasting felsic continental crust were developed on Earth, which is independent of how continental crust was generated at that time.

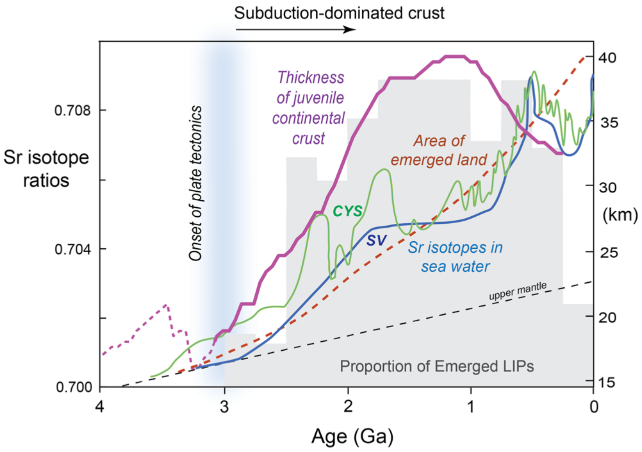

Fig. 10. Variations in the thickness of continental crust at the sites of crust generation through time, as estimated from the Rb/Sr ratios of juvenile crust (Figs 7, 8) and the changes in Rb/Sr v. crustal thickness in recent magmatic rocks, from the Central and South America (Fig. 9) (Dhuime *et al.* 2015), compared with indices of when land emerged. The SV curve for Sr isotopes in seawater is from Shields and Veizer (2002) and CYS curve is from X. Chen *et al.* (2022). The grey shaded histogram illustrates the secular variation in the proportion of subaerial large igneous provinces (Kump and Barley 2007). The proportion is the percentage of the total subaerial large igneous province occurrences in the age range divided by the sum of the percentage of the total occurrences of both subaerial and submarine large igneous provinces in that age range, with 1.0 being the maximum value plotted. The curve for the proportion of emerged land is from Flament *et al.* (2013) and it increases from 0% at 3.5 Ga to the present day value of 27.5%.

Crustal evolution models

The growth of the continental crust reflects the balance between the rates at which new crust is generated and the rates at which it is later destroyed. There has been much discussion of different crustal growth models, many of which were developed from different geological perspectives. Continental growth can be inferred from variations in mantle compositions and from crustal archives. The mantle-based models tend to rely on inferred links between the development of depleted mantle and the formation of the continental crust (Allègre *et al.* 1983; Jacobsen 1988; McCulloch and Bennett 1994; Kramers 2002; Rosas and Korenaga 2021; Guo and Korenaga 2023). This is particularly an issue for models seeking to explain variations in ^{142}Nd, which developed very early in Earth history (Korenaga 2021). Both positive and negative μ^{142}Nd are recorded in mantle-derived rocks (Hyung and Jacobsen 2020), suggesting that both are generated by processes within the mantle and there is no obvious test of whether the elevated ^{142}Nd signatures are linked to the extraction of the continental crust. If it is assumed that they are linked, then it follows that large volumes of continental crust were generated early in Earth history and that significant volumes of crust have been recycled, following Armstrong (1981, 1991). Similar arguments have been developed to link the depleted Sr and Nd isotope signature of the mantle sampled by mid-ocean ridge basalts, and Nb/U ratios, with the generation of continental crust (Campbell 2003). Such signals are not as old and so the linked models for crust generation involve significant volumes of crust later in Earth history.

The second set of models is based on records preserved within the continental crust. Recent models have relied on the Hf and O isotope records in well-dated and often detrital zircons and these appear to provide a representative record of at least the more felsic rocks in the continental crust (Kemp *et al.* 2006; Dhuime *et al.* 2012). Initial studies developed age distribution models based on the distribution of crystallization and Hf model ages at the present day. Given the lengthy tectonic history of the planet, it is unlikely that the present day age distributions reflect when the crust was generated and hence the relative volumes of crust back in time.

Following Belousova *et al.* (2010), Hf isotope ratios were used to identify contributions from juvenile crust and the ratio of reworked crust/total crust was used as a proxy for the generation rate of new crust. Crustal growth models were developed based on the cumulative proportions of juvenile crust through time. These provide estimates of the volumes of crust that were present at different times in Earth history. The difference between these crustal growth curves and the present day distribution of model ages is an indication of the minimum amounts of crust that have been recycled back into the mantle. Crustal growth rates are, in turn, simply those calculated from changes in the slope of the growth curve.

Mantle- and crust-based records provide complementary evidence as to when and perhaps how the continental crust was generated and it is unfortunate that this discussion has been sidetracked by interventions about the perceived logic underlying the different approaches. A more useful discussion might be about the contributions from backward and forward modelling curves.

Dhuime *et al.* (2012) used a backward modelling approach to reconstruct missing segments of ancient crust from the present day crustal record. Models by Rosas and Korenaga (2018), Dhuime *et al.* (2018) and Kumari *et al.* (2019), for example, use forward modelling approaches to try and match the present day compositions of mantle and/or crustal rocks by changing the rates of crust formation and destruction through time. Both approaches develop crustal growth curves in different ways and both provide insights relevant to this discussion. The Rosas and Korenaga (2018) model follows that of Armstrong (1981, 1991) in that volumes of continental crust similar to those at the present day were generated early in the Hadean. Given that there is little evidence for preserved Hadean crust, and only small volumes of early Archean crust are preserved, Armstrong (1981, 1991) emphasized that the early crust was not stable, rather it was readily recycled and it did not last for long enough to develop a distinct radiogenic isotope signature. Thus, it left no evidence in the Sr isotope ratio of seawater, which remains a key test of when reasonably long-lasting and stable continental crust emerged above sea-level (Fig. 10).

By contrast, the zircon-based models have been developed on a relatively detailed record of hundreds of thousand analyses of zircon preserved in the continental crust today. The variations in Hf isotope ratios indicate that, whereas 14% have Archean crystallization ages (from the Spencer *et al.* 2022 database of 9200 zircon analyses), 34% have Archean model Hf isotope ages. Thus the record indicates that the Archean crust sampled by zircons had relatively high proportions of juvenile continental crust. Models by Belousova *et al.* (2010) and Dhuime *et al.* (2012) estimate that 50–75% of the present volume of the continental crust had been generated by *c.* 3 Ga (Fig. 1). The difference between the estimated volumes of crust present at 3 Ga and the volumes of such crust preserved today highlight the volumes of crust that have been destroyed, starting in the late Archean in the model of Dhuime *et al.* (2018).

Reimink *et al.* (2023) sought to integrate records from both mantle and crustal rocks to develop a model for the evolution of the continental lithosphere. This is a welcome development as there are increasing amounts of data from both crust- and mantle-derived rocks and significant evidence that the mantle and crustal lithosphere are coupled. They addressed concerns over the application of O isotopes to identify crustal reworking, given that they are only sensitive to the reworking of ^{18}O-enriched or ^{18}O-depleted supracrustal material, by introducing a whole-rock index of crustal reworking using input from the ACNK/ANK diagram of Shand (1943). Their analysis suggests that the degree of crustal reworking, and hence the contribution from juvenile magmas, changed little over the history of the continental crust. Broadly, this analysis suggests that rocks with relatively low K_2O/Na_2O ratios are less likely to reflect crustal reworking and it is therefore something of a surprise that some Archean terranes, which are apparently dominated by TTG suites, show significant degrees of crustal reworking in the Reimink *et al.* (2023) analysis. However, it may be that the proportion of TTG suites relative to more granitic rocks is poorly constrained in the Archean terranes.

Reimink *et al.* (2023) used the derived ratios of new crust/total crust from whole-rock data and applied it to an age distribution to obtain cumulative juvenile ages through time, which were then cumulatively summed to obtain a growth curve through time. Given that their analysis has relatively little juvenile material in the Archean, and that it is linked to the zircon record, it perhaps predictably results in a crustal growth curve that is relatively similar to the preserved age distribution of rocks with juvenile Nd isotope ratios of Condie and Aster (2010) (Fig. 1).

This discussion highlights the need to further develop indices of crustal reworking in the Archean, as well as the need to test whether proxies using the distribution of ages, or proxies based solely on the ratios between new and reworked crustal ages, such as in the Belousova *et al.* (2010) and Dhuime *et al.* (2012) approaches, provide the most reliable estimates of ancient volumes of crust. Overall, the different crustal growth curves summarized in Figure 1, in significant part, reflect the geological decision to rely on variations in ^{142}Nd and the balance on new v. reworked crust on the basis of O isotopes, or on differences in major element compositions.

Onset of plate tectonics

Archean geology is characterized by different rock suites (TTG suites, komatiites, banded iron formations and relatively few carbonates) from younger terranes. The late Archean was a time of mantle cooling (Herzberg *et al.* 2010; Ganne and Feng 2017) and was marked by a number of changes that are likely to reflect global tectonics (Fig. 11), including the following.

- A shift from more mafic to more felsic new and bulk continental crust.
- An increase in the Rb/Sr ratios and SiO_2 contents of new continental crust and an inferred increase in the thickness of new continental crust.
- An increase in the Sr isotope ratios of seawater relative to those of the upper mantle.
- Palaeomagnetic evidence for lateral tectonics and perhaps the development of supercontinents.
- A shift from dome and basin to lateral tectonics over the interval 3.3–2.6 Ga worldwide.
- The stabilization of cratons linked to the development of the oldest known sedimentary basins, increased granulite facies metamorphism and dyke swarms, together with higher volumes of high-K granites and sanukitoids. These occur at different times in different places from 3.3 to 2.6 Ga.
- The stabilization of continental mantle lithosphere as recorded by Re–Os ages (Pearson *et al.* 2021).
- A reduction in the rate of crustal growth, which is taken to reflect the onset of the significant destruction of continental crust through plate tectonics, rather than a reduction in the volumes of new crust generated.
- Stepwise increases in atmospheric oxygen, possibly linked to supercontinent formation (G. Chen *et al.* 2022).

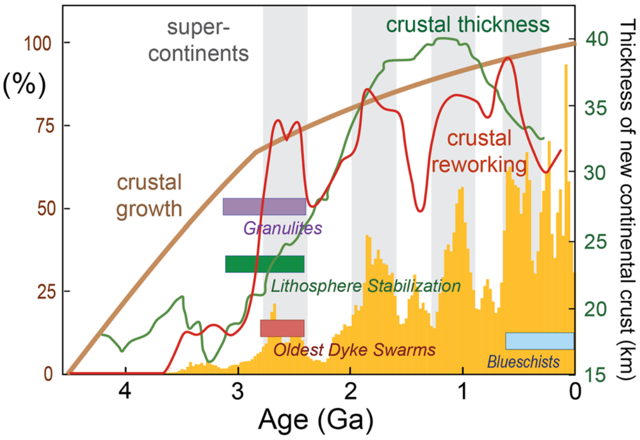

Fig. 11. A summary of some the features that inform models of crustal evolution including the crust evolution model based on Hf and O isotopes and U–Pb ages of zircons, with changes in the degrees of crustal reworking from Dhuime *et al.* (2012), the ages of the oldest dyke swarms, increasingly widespread granulite facies metamorphism (Fig. 3) and estimates of lithosphere stabilization from Re–Os isotope data on samples of the mantle lithosphere (Pearson *et al.* 2021). The ages of supercontinents and the age distribution in 906 218 zircons (in orange, from Puetz *et al.* 2021) are also illustrated.

We argue that these changes should be considered in discussions of the tectonic style at the end of the Archean and the extent to which significant changes in tectonic processes took place. The changes suggest that there was an increase in the strength of the lithosphere in the late Archean, which encourages suggestions that the lithosphere was then strong enough to form plates and to be subducted back into the mantle. Although there is geochemical evidence for both subduction-related and non-subduction magmatism throughout the Archean, the changes in lithosphere strength and the reduction in the rates of crustal growth are taken as geological evidence that plate tectonics became dominant in the late Archean in a system of globally linked plates, as opposed to the localized and episodic recycling of lithosphere.

As often in geology, much of the judgement is over which observations to prioritize in discussions of global processes and this can vary depending on the perspective of the people involved. There may be no smoking gun, but we hope to have usefully summarized the geological evidence for when plate tectonics may have started on Earth.

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Data availability Data sharing is not applicable to this article as no datasets were generated during the current study. Datasets from published papers were analysed and referenced.

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