SCIENCE CHINA
Earth Sciences

•REVIEW•

January 2024 Vol.67 No.1: 1–30
https://doi.org/10.1007/s11430-023-1210-5

Plate tectonics in the Archean: Observations versus interpretations

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Received August 8, 2023; revised September 7, 2023; accepted October 17, 2023; published online December 13, 2023

Abstract Plate tectonics theory, established in the 1960s, has been successful in explaining many geological phenomena, processes and events that occurred in the Phanerozoic. However, the theory has often struggled to provide a coherent framework in interpreting geological records in continental interior and Precambrian period. In dealing with the relationship between plate tectonics and continental geology, continental interior tectonics was often separated from continental margin tectonics in the inheritance and development of their structure and composition. This separation led to the illusion that the plate tectonics theory is not applicable to Precambrian geology, particularly in explaining the fundamental geological characteristics of Archean cratons. Although this illusion does not mean that the Archean continental crust did not originate from a regime of plate tectonics, it led to the development of alternative tectonic models, often involving vertical movements under a regime of stagnant lid tectonics, including not only endogenous processes such as gravitational sagduction, mantle plumes and heat pipes but also exogenous processes such as bolide impacts. These vertical processes were not unique to the Archean but persisted into the Phanerozoic. They result from mantle poloidal convection at different depths, not specific to any particular period. Upgrading the plate tectonics theory from the traditional kinematic model in the 20th century to a holistic kinematic-dynamic model in the 21st century and systematically examining the vertical transport of matter and energy at plate margins, it is evident that plate tectonics can explain the common geological characteristics of Archean cratons, such as lithological associations, structural patterns and metamorphic evolution. By deciphering the structure and composition of convergent plate margins as well as their dynamics, the formation and evolution of continental crust since the Archean can be divided into ancient plate tectonics in the Precambrian and modern plate tectonics in the Phanerozoic. In addition, there are the following three characteristic features in the Archean: (1) convective mantle temperatures were 200–300°C higher than in the Phanerozoic, (2) newly formed basaltic oceanic crust was as thick as 30–40 km, and (3) the asthenosphere had a composition similar to the primitive mantle rather than the depleted mantle at present. On this basis, the upgraded plate tectonics theory can successfully explain the major geological phenomena of Archean cratons. This approach provides a new perspective on and deep insights into the evolution of early Earth and the origin of continental crust. In detail, Archean tonalite-trondhjemite-granodiorite (TTG) rocks would result from partial melting of the over-thick basaltic oceanic crust at convergent plate margins. The structural patterns of gneissic domes and greenstone keels would result from the buoyancy-driven emplacement of TTG magmas and its interaction with the basaltic crust at convergent margins, and komatiites in greenstone belts would be the product of mantle plume activity in the regime of ancient plate tectonics. The widespread distribution of high-grade metamorphic rocks in a planar fashion, rather than in zones, is ascribe to separation of the gneissic domes from the greenstone belts. The shortage of calc-alkaline andesites in bimodal volcanic associations suggests the shortage of sediment accretionary wedges derived from weathering of granitic continental crust above oceanic subduction zones. The absence of Penrose-type ophiolites suggests that during the subduction initiation of microplates, only the upper volcanic rocks of the thick oceanic crust were offscrapped to form basalt accretionary wedges. The absence of blueschist and eclogite as well as classic paired metamorphic belts suggests that convergent plate margins were over-thickened through either warm subduction or hard collision of the thick oceanic crust at moderate geothermal gradients. Therefore, only by correctly recognizing and understanding the nature of Archean cartons can plate tectonics reasonably explain their fundamental geological characteristics.

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Keywords Plate tectonics, Archean geology, Continental origin, Crustal reworking, Plate interior, Plate margin

Citation: Zheng Y F. 2024. Plate tectonics in the Archean: Observations versus interpretations. Science China Earth Sciences, 67(1): 1–30, https://doi.org/10.1007/s11430-023-1210-5

1. Introduction

It is well known that terrestrial planets in the solar system experienced similar early accretion and subsequent core-mantle-crust differentiation processes during their formation. However, only Earth could have developed to form plate tectonics and continental crust through evolution from stagnant lid tectonics initially on early Earth to mobile lid tectonics popularly on modern Earth (Korenaga, 2013; Hawkesworth and Brown, 2018; Cawood et al., 2022). Therefore, to investigate the formation and evolution of plate tectonics in Earth's history, it is essential to study when mobile lid tectonics occurred on early Earth, and both mechanism and scale of its initiation (van Hunen and Moyen, 2012; Cawood et al., 2018; Kusky et al., 2018; Brown et al., 2020a; Windley et al., 2021; Zhao and Zhang, 2021; Zheng, 2023). This involves resolution to the relationship between the Archean tectonic regime and the origin of continental crust. In doing so, the most critical questions are asked as follows. Is there a causal relationship between plate tectonics and continental origin? In other words, did early granitic crust form within a regime of plate tectonics? If so, were there any differences in plate tectonics between early and modern Earth? If not, what kind of tectonic settings gave rise to early granitic crust? In view of both mass and momentum conservation in plate motion (Zheng, 2023), can plate tectonics initiate without coupling between subduction and spreading? In other words, can plates subduct successfully without fragmentation and dispersal of the lithosphere?

Because these questions are intimately related to the formation and evolution of Earth, they have become significant topics in the study of Earth science since the beginning of the 21st century. It is particularly so for the relationship between early plate tectonics and granitic continental origin (Hawkesworth and Brown, 2018; Brown et al., 2020a; Wang et al., 2020; Cawood et al., 2022; Kusky and Wang, 2022; Sotiriou et al., 2023; Zheng, 2023). More and more lines of geological evidence show that the traditional plate tectonics model established in the 1960s, while achieving significant success in explaining the origin and distribution of Pangea supercontinent in the Phanerozoic, faces serious challenges in explaining the issues of Precambrian continental geology (Dewey et al., 2021; Zhao and Zhang, 2021; Zheng et al., 2022; Zheng, 2023). These challenges are associated with the conundrum whether the tectonic regime governing the formation and evolution of Archean continental crust differs from modern plate tectonics (Zhai and Peng, 2020; Zheng and Zhao, 2020; Dewey et al., 2021; Zhao and Zhang, 2021; Zheng et al., 2022; Kuang et al., 2023; Zhao et al., 2023; Zheng, 2023). In other words, it remains to be clarified whether the Archean tectonic regime belongs to early plate tectonics or a pre-plate precursor. Therefore, it is necessary to have a systematic understanding of their spatiotemporal relationships in the Archean.

The plate tectonic theory established in the 20th century made revolutionary progress in understanding the kinematics of rigid lithospheres on Earth (e.g., Le Pichon et al., 1973; Cox and Hart, 1986; Oreskes, 2003, and references therein). However, this theory has faced significant challenges in explaining the Archean continental geology (e.g., Dewey et al., 2021; Zhao and Zhang, 2021; Zheng et al., 2022; Zhao et al., 2023). Therefore, this article aims to apply the upgraded theory of plate tectonics in the 21st century (Zheng, 2023) to decipher the inheritance and development relationships between early and modern plate tectonics regimes. The results will not only contribute to our understanding of the origin and evolution of continental crust on early Earth but also shed light on the geodynamic mechanism of how early Earth evolved from stagnant lid tectonics to mobile lid tectonics.

2. The importance of Archean tectonic regimes

Earth is the only planet in the solar system with active plate tectonics and the presence of granitic continental crust. Therefore, studying the origin of continental crust on early Earth is crucial for understanding the formation and evolution of our planet. Earth's long history is a mysterious story in itself, and the Archean Eon is one of its most enigmatic periods (Figure 1). The Archean represents the early stages of Earth's evolution, spanning from approximately 4 billion to 2.5 billion years ago, and serves as the first rock records to decipher the operation of plate tectonics on early Earth (e.g., van Hunen and Moyen, 2012; Korenaga, 2013; Cawood et al., 2018; Zheng and Zhao, 2020; Dewey et al., 2021). During this period, Earth existed under extreme environmental conditions, and geological processes and tectonic regimes were complex and diverse. Early plate tectonics may have even emerged in the Eoarchean (e.g., Ge et al., 2018, 2023; Keller and Schoene, 2018; Kusky et al., 2018; Nutman et al., 2021; Windley et al., 2021). However, due to the scarcity of Archean geological records and the difficulty in observing geological phenomena from this period, understanding geological processes during this time has been a

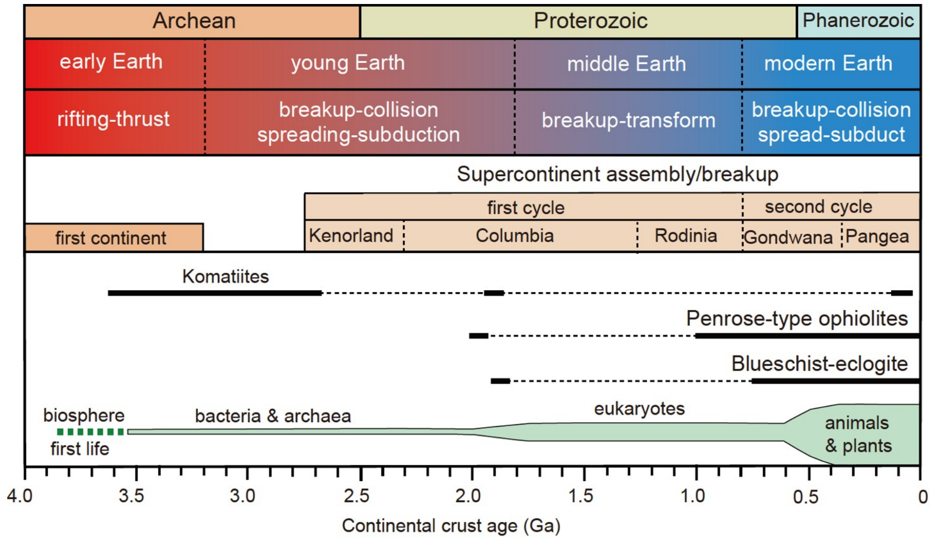


Figure 1 Schematic diagram showing the formation and evolution of continental crust in geological history (adapted after Cawood, 2020a).

challenging task for geologists. The question of whether plate tectonics existed in the Archean has been a contentious focal point (e.g., Sleep and Windley, 1982; Nisbet and Fowler, 1983; Kröner, 1985; Kerrich and Polat, 2006; Ernst, 2009; van Hunen and Moyen, 2012; Korenaga, 2013; Kusky et al., 2018; Brown et al., 2020a; Wang et al., 2020; Dewey et al., 2021; Kuang et al., 2023).

Archean cratons are one of the important subjects in the study of Archean tectonic regimes. Although cratons are relatively stable and lack intense tectonic activity after their generation (e.g., O'Reilly et al., 2001; Carlson et al., 2005; Foley, 2008; Şengör et al., 2022), their formation involves various types of tectonic processes (Bleeker, 2003; Ernst et al., 2016; Pearson et al., 2021; Zhu et al., 2021; Cawood et al., 2022). Archean cratons typically exhibit the following four major characteristics: (1) the extensive occurrence of granitic crust, mostly in the composition of tonalite-trondhjemite-granodiorite (TTG); (2) the lithotectonic association of gneissic domes and greenstone keels in the pinch-and-swell form; (3) the stable crust at present day, lacking active volcanoes and earthquakes; and (4) geological records rich in vertical movements but poor in large-scale horizontal movements. Are these major characteristics the products of plate tectonics? If so, are there differences in the tectonic regime between the Archean and the Phanerozoic? Questions about the mechanisms behind the formation of Archean TTG rocks, and the stability and evolution of cratonic crust, among others, have challenged researchers studying Precambrian geology. If the Archean indeed experienced plate tectonics, were these megaplates or microplates? Only through in-depth research into Archean tectonic processes and their products can we better understand the evolution of early Earth's history and uncover the mysteries of continental crust formation and plate tectonics evolution.

In the past, Earth scientists primarily have relied on geological observations and geochemical analyses of Archean rocks to study Archean tectonic regimes (e.g., Cawood et al., 2013, 2018; Kamber, 2015; Hawkesworth et al., 2017; Fisher and Vervoort, 2018; Ge et al., 2018, 2023; Moyen and Laurent, 2018; Dewey et al., 2021; Zhao and Zhang, 2021; Sotiriou et al., 2022, 2023; Wang et al., 2022a; Kuang et al., 2023). However, these ancient rocks were generally subjected to both physical and chemical modifications by multiple episodes of crustal movement and geodynamic processes, blurring their original geological features and making it difficult to unequivocally establish their tectonic settings. Thus, this necessitates an integrated study of structure, composition and age. Furthermore, due to the effects of heat flow beneath the lithosphere, Archean rocks have undergone multiple episodes of metamorphic dehydration/hydration and partial melting over the course of geological history, making their geological information more complicated and challenging to interpret. Nevertheless, with the deepening of research into convergent plate margins (Zheng et al., 2022) and the development of plate tectonics theory in the 21st century (Zheng, 2023), researchers have gradually begun to unveil the mysteries of Archean tectonic regimes. Rapid advancements in modern geology, geochemistry and geodynamics have provided new perspectives and tools for Archean tectonic regimes. For instance, the approach of petrological paragenesis in geology can identify the clues of Archean tectonic processes within the continental crust; the technique of isotopic analyses in geochemistry can reveal the origin and evolution of Archean rocks; and numerical simulations in geodynamics can model the dynamic processes in the early Earth. The combination of these technologies and methods presents both new opportunities and challenges for the study of Archean tectonics.

The study of Archean cratons is of paramount importance for understanding Archean tectonics and Earth's evolution processes (Dewey et al., 2021; Zhao and Zhang, 2021; Zhu et al., 2021; Cawood et al., 2022; Şengör et al., 2022). Through petrological and geochemical analyses of rocks from Archean cratons, insights into the heat flow and crustal movements in the Archean can be gained, shedding light on the early tectonics and geological processes of the Archean lithosphere. Moreover, Archean cratons serve as a natural laboratory for investigating the tectonic evolution of early Earth. By studying Archean cratons, we can make analogies and inferences about the processes of modern Earth's evolution, providing valuable insights for the development of Earth sciences. In the past 50 years, the plate tectonics theory has greatly developed and rationalized (Zheng et al., 2009, 2015, 2022; Li et al., 2018; Zheng, 2023), gradually allowing for researchers to peer into and uncover the mysteries of Archean tectonics. Although direct observations of geological processes in the Archean are not possible, the study of modern geology and geodynamic exploration enables us to make educated speculations about the tectonic regime and geological evolution of the lithosphere during this period. Understanding Archean tectonics is not only crucial for comprehending the evolution of early Earth but also holds significant relevance for explaining modern geological phenomena.

In terms of crustal composition, whether in the Archean or the Phanerozoic, oceanic crust is characterized by basaltic rocks, whereas continental crust is characterized by granitic rocks. Throughout geological history, the primary crust is characterized by basaltic compositions and may include mid-ocean ridge basalts (MORB), island arc basalts (IAB), ocean island basalts (OIB) and ocean plateau basalts (OPB). The secondary crust, on the other hand, is characterized by granitic compositions and primarily occurs at convergent plate margins and continental rift zones (either successful or failed). In the Archean, however, it is unclear how much of the primary crust was exposed on the Earth's surface, submerged beneath seawater, or exposed above it. If the Archean continental crust would also exhibit granitic compositions, then this secondary crust should truly constitute continents. In geological studies from any era, therefore, mafic crust can be considered representative of oceanic crust, and granitic crust can be considered representative of continental crust.

3. Difficulties of traditional plate tectonics in explaining Archean geology

Plate tectonics theory, established in the 1960s, marked a revolutionary development in the history of Earth science. Initially, this theory was primarily a kinematic model (e.g., Le Pichon et al., 1973; Cox and Hart, 1986; Oreskes, 2003, and references therein), which is capable of explaining many geological phenomena, processes and events observed in the Phanerozoic (Frisch et al., 2011). However, the traditional version of plate tectonics has faced challenges when explaining the geological records of continental interior and Precambrian period. Since it separates the continental interior tectonics from continental margin tectonics in the inheritance and development of their structure and composition, it has created the illusion that plate tectonics theory is not applicable to continental geology. This has led many researchers to lean towards alternative hypotheses such as mantle plumes to explain the formation and evolution of Archean cratons. Furthermore, the island arc accretion model within the traditional plate tectonics framework struggled to account for common characteristics of Archean cratons in the aspects of petrology, geochemistry and structural geology, resulting in challenges when explaining the origin of Archean continental crust (e.g., Dewey et al., 2021; Zhao and Zhang, 2021; Zhao et al., 2023). These challenges can be summarized in the following five aspects:

(1) Archean continental crust primarily consists of TTG rocks, comprising 60–70% of the exposed surface area in many Archean cratons (Arndt, 2013). In contrast, high-grade metamorphic supracrustal rocks or low-grade metamorphosed greenstones, formed from volcanic rocks and some sedimentary rocks, account for only 30–40%. This feature is difficult to reconcile with the continental arc accretion model in the traditional plate tectonics theory (e.g., Campbell et al., 1989; Bédard, 2006; Condie, 2006; Hamilton, 2020). In some of Archean cratons, additionally, the widely distributed TTG rocks seem to form in a relatively short timeframe and exhibit no systematic compositional variations (Zhao and Zhang, 2021).

(2) The structural analysis of typical granitoid-greenstone terranes within global Archean cratons indicates that the internal structures of early continental crust were characterized by greenstone keels surrounding gneissic TTG domes, forming what is termed as the dome-and-keel structure (Johnson et al., 2014; Nebel et al., 2018; Kusky et al., 2021). Such a structural pattern differs significantly from linear structural zones in continental crust that reflect horizontal movements observed at modern convergent plate margins, including large-scale thrust zones and ductile shear zones as well as tectonic melange zones (e.g., Cawood et al., 2018; Zhao and Zhang, 2021; Kusky and Şengör, 2023).

(3) In Archean greenstone belts, the most common volcanic rocks are basalt with the rare occurrence of bimodal associations in the form of komatiite-basalt and dacite-rhyolite, short of andesites that are common in Phanerozoic continental arcs (e.g., Hamilton, 1998, 2011, 2020; Bédard, 2006; Zhao and Zhang, 2021; Zhu et al., 2021; Sotiriou et al., 2022). Komatiites, characterized by high Mg contents

(MgO>18%), are a rare component of Archean volcanic rocks in greenstone belts. Their formation requires the partial melting of relatively anhydrous mantle rocks at temperatures exceeding 1600°C, conditions that are challenging to achieve in oceanic subduction zones within the traditional framework of plate tectonics (e.g., Campbell et al., 1989; Larson, 1991; Hill, 1993; Condie, 2006).

(4) The exposed metamorphic rocks in Archean cratons primarily exhibit a low-pressure (LP) greenschist facies through medium-pressure (MP) amphibolite facies to high-pressure (HP) granulite facies mineral assemblages. They are poor not only in low T/P blueschist and HP to ultrahigh-pressure (UHP) eclogite facies metamorphic rocks typical of cold subduction zones but also in classic Miyashiro-type paired metamorphic belts characteristic of modern oceanic subduction zones (Brown et al., 2020a; Kuang et al., 2023). Commonly observed high T/P Buchan type amphibolite-granulite facies high-temperature (HT) to ultrahigh-temperature (UHT) metamorphic rocks exhibit both clockwise and anticlockwise P-T paths (e.g., Zhao et al., 1998, 2001a, 2001b, 2005; Jayananda et al., 2000; Kramers et al., 2001; Zulbati and Harley, 2007; Halpin and Reid, 2016; Mvondo et al., 2017; Yu et al., 2022). Additionally, the Archean crust lacks the classic Penrose-type ophiolites that contain large intrusive sheets (e.g., Kusky and Polat, 1999; Furnes and Dilek, 2022; Condie and Stern, 2023).

(5) The exposure areas of metamorphic rocks in Archean cratons are generally extensive in scale (Zhao and Zhang, 2021), in contrast to the limited operation of metamorphic processes within linear tectonic zones (narrow orogenic belts) as defined by the traditional plate tectonics. Except for the occurrence of Alpine-style tectonic nappe stacking in the convergent plate margin of Archean (Zhong et al., 2021, 2022, 2023), the large-scale planar distribution of metamorphic basement in Archean cratons is difficult to explain by the tectonic setting of narrow suture zones defined by the traditional plate tectonics.

Because traditional plate tectonics models struggle to explain the rock assemblages, structural patterns and metamorphic characteristics of Archean cratons as outlined above, some scholars proposed that the granitic crust on early Earth would form prior to the initiation of plate tectonics and was the product of a pre-plate tectonic process (e.g., Campbell et al., 1989; Larson, 1991; Hill, 1993; Hamilton, 1998, 2011, 2020; Bédard, 2006; Condie, 2006; Brown et al., 2020a; Dewey et al., 2021). It was hypothesized that the existence of low-density continental crust could have induced subduction of the denser oceanic lithosphere beneath it, ultimately triggering the onset of plate tectonics. Therefore, the question of whether the appearance of continental crust on early Earth was a prerequisite for the initiation of plate tectonics has become a forefront and hotspot in the study of tectonic regimes on early Earth.

4. Pre-plate tectonic models interpreting Archean geology

4.1 Stagnant lid tectonics

The surface of all solid celestial bodies in the solar system (planets and satellites) is covered by a relatively rigid lithosphere, beneath which lies a ductile to convective asthenosphere. This rigid lithosphere, often referred to as the "lid," remains relatively stable and lacks strong interaction with the underlying asthenosphere, a regime known as stagnant lid tectonics (Nataf and Richter, 1982; Christensen, 1984; Solomatov, 1995). For most solid celestial bodies such as Mercury, Venus, Mars, Moon and Io, their lithospheres have lower temperatures but greater viscosity and strength compared to the underlying asthenosphere. As a result, the lithospheres do not take part in the convection of the asthenosphere (Beall et al., 2018; Bédard, 2018; Stern et al., 2018). In the stagnant lid regime (Figure 2), the lithosphere remains intact and is not distructed by the convection in the underlying asthenosphere. This leads to a single, continuous lithospheric cover on the surface of these celestial bodies. The release of internal heat from these bodies is usually assumed to occur in the form of hot spots through localized heat pipes or mantle plumes.

In contrast to stagnant lid tectonics, mobile lid tectonics occurs when the stresses from the convection in the asthenosphere exceed the strength of the lithosphere (Tackley, 2000; Stein et al., 2004). This results in the lithosphere breakup into several rigid plates, leading to horizontal movements, which is the essence of plate tectonics. Thus, plate tectonics belongs to mobile lid tectonics. Stern et al. (2018) proposed that the conditions for plate tectonics to occur are that the stresses from asthenospheric convection must exceed the strength limit of the lithosphere, causing it to fracture, but without exceeding a threshold that would decouple the upper and lower lithospheric layers. These conditions are stringent, and currently, only Earth's lithosphere satisfies the criteria for the emergence of plate tectonics, while other celestial bodies like Mercury, Venus, Mars, Moon and Io remain in the state of stagnant lid tectonics.

In the regime of stagnant lid tectonics, the crust is predominantly of basaltic composition. Only a very small amount of mantle-derived basaltic magmas would undergo fractional crystallization to form granitic rocks, or basaltic crust would undergo partial melting to produce granitic magmas. Before the formation of granitic crust, the thickness of basaltic oceanic crust can reach 20–50 km (Palin et al., 2016; Hawkesworth et al., 2017; Smithies et al., 2021), mostly at 30–40 km thick. Although the relationship between crustal composition and tectonic model is not straightforward, the composition of granitic crust is primarily related to chemical differentiation caused by bottom-up processes rather than fluid activity from top-down processes (Zheng et

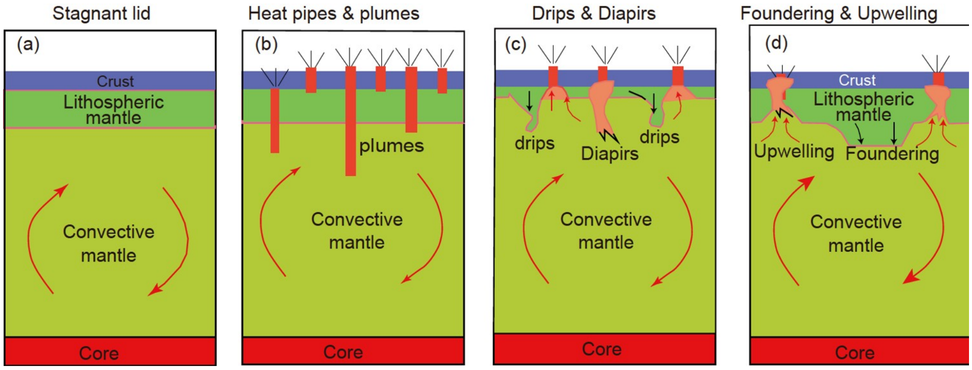


Figure 2 Schematic representation of early Earth's stagnant lid tectonics (revised from Stern et al., 2018).

al., 2022). Therefore, the formation of granitic crust is mainly associated with vertical tectonics from bottom to top (Moyen et al., 2021; Zheng et al., 2021; Kusky and Wang, 2022).

Vertical tectonic processes that can impact stagnant lid tectonics and even initiate plate tectonics include not only exogenous processes such as bolide impacts but also endogenous processes such as sagduction and drip, mantle plumes and heat pipes. While these vertical processes can explain certain geological features of Archean cratons to some extent, they do not fully account for all characteristics of Archean continental crust, including rock associations, geochemical compositions, structural patterns and metamorphic effects. Nevertheless, the transfer of internal heat from the Earth's interior into the lithosphere can take place through heat pipe and mantle plume processes (Tackley, 2023), depending on the mode of mantle convection (layered vs. whole on the one hand and poloidal vs toroidal on the other hand) and the thickness of the lithosphere above the thermal anomaly.

In order to understand the relationship between mantle convection and plate tectonics, geodynamic researchers have proposed various hypotheses related to lid tectonic regimes from numerical simulation perspectives (Tackley, 2023), such as the episodic lid hypothesis (Moresi and Solomatov, 1998) and the plutonic-squishy lid hypothesis (Lourenco et al., 2020). These hypotheses make different assumptions about the properties of the lithospheric lid and its underlying convective mantle. Concerning the time and mechanism for the initiation and evolution of plate tectonics in the Precambrian, the noteworthy hypotheses are converged to stagnant lid tectonics, while the other hypotheses remain still valid in the Phanerozoic.

4.2 Sagduction tectonics

Sagduction tectonics was first proposed by Macgregor (1951), referring to the coupled interaction between the overlying, denser basaltic greenstone belts sagging downwards due to gravity and the underlying, less dense granitic magmas diapiring in response to the sagging. Gorman et al. (1978) used the model of sagduction tectonics to explain the formation mechanism of gneissic domes and the origin of basaltic magmas in Archean granite-greenstone terranes in Western Australia, North America, and South Africa. The model hypothesizes that Archean greenstones, which were originally mafic to ultramafic volcanic shields with diameters exceeding 100 km and thicknesses of 5–7 km, erupted onto the felsic crust (Figure 3a). Due to the density difference and gravitational function, the central and marginal portions of the mafic-ultramafic volcanic shield began to sag downwards (Figure 3b). As sagging continued, the volcanic layer contracted, and the central sagging deepened to form basins that accumulated volcanic sediments (Figure 3c). With increasing sag depth, sediment thickness increased, and the central part of the mafic-ultramafic volcanic shield underwent greenschist facies metamorphism, resulting in the formation of greenstone belts (Figure 3d). Greenstone belts sagged downwards in a drop-shaped pattern (Figure 3e), with local metamorphic grades ranging from upper amphibolite facies to granulite facies, leading to partial melting and the formation of felsic volcanic rocks and granitic intrusions.

Lin and Beakhouse (2013) suggested that during the sagduction of greenstone belts, lower portions could form vertical extensional lineations or L-type tectonites, while the felsic crust between different greenstone belts would undergo partial melting and uplift diapirically, creating gneissic domes that appear as top-to-center thrusts (Figure 4). The premise for the operation of sagduction tectonics is the difference in crustal density. In detail, a low-density felsic crust would already exist on the Earth's surface and then mafic-ultramafic volcanics would erupt on its top. Afterwards, the high-density crust would sink into the low-density crust. Because such a sequence needs to be justified in nature, this model was questioned in explaining the origin of granitic crust on early Earth. Kusky et al. (2021) argued that Archean gneissic domes, similar to the tectonics in the Cordillian batholith belts of the western Americas, resulted from the

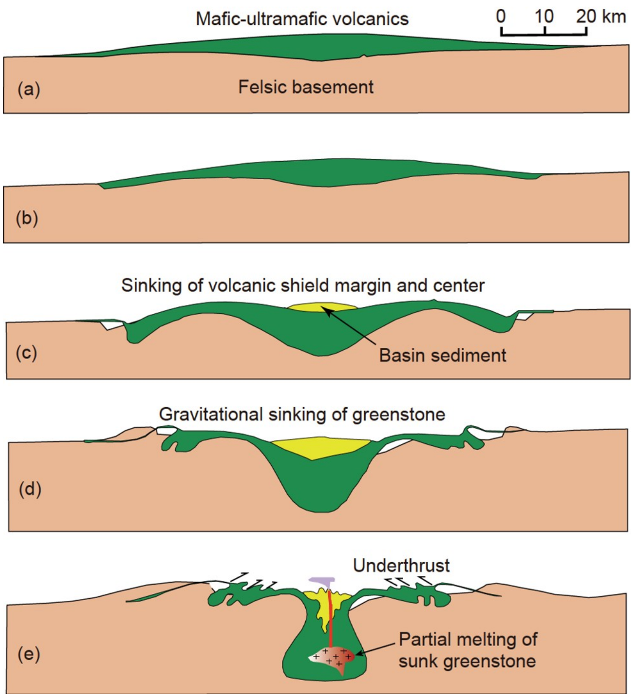


Figure 3 Schematic cartoons showing the model of sagduction tectonics (revised from Gorman et al., 1978).

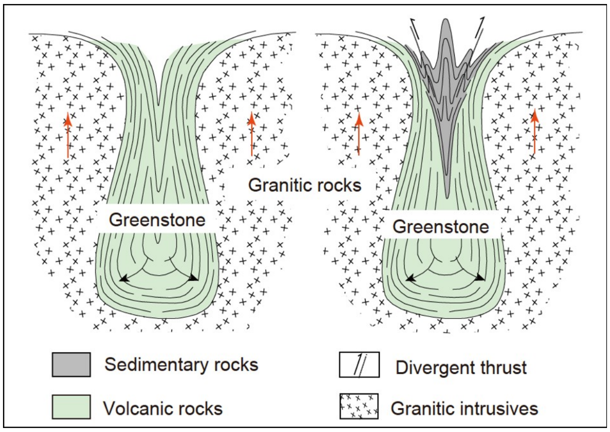


Figure 4 The structure pattern of gneissic domes in Archean cratons (adapted after Lin and Beakhouse, 2013). While low-density TTG magmas rose to form gneissic domes, the surrounding high-density greenstone belts sank to form the keels.

superimposition of horizontal movements in a plate tectonics system.

Detailed field geological survey and laboratory structural analysis indicate that the major tectonics of Archean cratons were formed by the upward movement of low-density TTG magmas in the form of uplifted domes, while the surrounding high-density greenstone belts underwent relative subsidence (e.g., Van Kranendonk et al., 2004; Lin, 2005; Parmenter et al., 2006; Van Kranendonk, 2010, 2011; Lin and Beakhouse, 2013; Zhang et al., 2014; Zhao et al., 2022). Therefore, this structural pattern of gneissic domes, reflecting vertical tectonism, is similar to that of metamorphic core complexes in the interior of orogenic belts in the Phanerozoic (Whitney et al., 2013; Platt et al., 2015), where gneisses result from metamorphism and deformation at a later time. Their formation is linked temporally and spatially to the crustal reworking that occurred when the lithospheric mantle was thinned at fossil plate margins after convergence, and thus driven by upwelling of the asthenosphere (Zheng and Chen, 2021; Zheng and Gao, 2021; Zheng et al., 2022).

4.3 Mantle plume tectonics

The concept of mantle plumes was initially proposed by Wilson (1963) and Morgan (1971) based on the idea of Hawaiian hotspots and was further developed with fluid dynamic models. Mantle plumes refer to massive columns of material and thermal upwelling that originate from the core-mantle boundary of Earth, specifically within the high-temperature, low-viscosity region known as the D″ layer (McNamara, 2019; Koppers et al., 2021). A typical mantle plume is composed of a narrow cylinder connected to the mantle bottom and a massive, mushroom-shaped head (Figure 5). The narrow cylinders extend down to the lower mantle, while the head expands as it rises through the convective mantle, entraining the surrounding material. When the mushroom-shaped head of mantle plumes reaches the relatively cold lithospheric base, it begins to flatten out and undergoes extensive melting due to decompression, forming high-temperature basaltic magma. On the other hand, gravity drives the deeply subducting oceanic slabs sinking to the mantle bottom and to form the D″ layer (McNamara, 2019; Jackson and Macdonald, 2022; White, 2022).

The scientific community has widely accepted since the 1980s that mantle plumes are the primary mechanism for the formation of hotspots and large igneous provinces, including oceanic plateaus and continental flood basalts (Larson, 1991; Koppers et al., 2021). It is generally assumed that such basaltic magmas can erupt abundantly onto the Earth's surface in a short period, typically less than one million years. This process results in the formation of continental flood basalts when erupted on continental landmasses or oceanic plateau basalts when erupted on the seafloor. However, there are alternative models for the origin of hotspots. Anderson (1982, 1994), for example, proposed that hotspots originate inside the mantle rather than at the core-mantle boundary. Veevers (1989) studied the thermal evolution of the supercontinent Pangaea, supporting the idea of a mantle source for hotspots. From the perspective of mantle convection scales, mantle plumes may originate in the core-mantle boundary in the case of whole mantle convection but are less likely to originate in the lower mantle in the case of layered mantle convection, possibly resulting from rapid upwelling of the asthenosphere below the lithosphere.

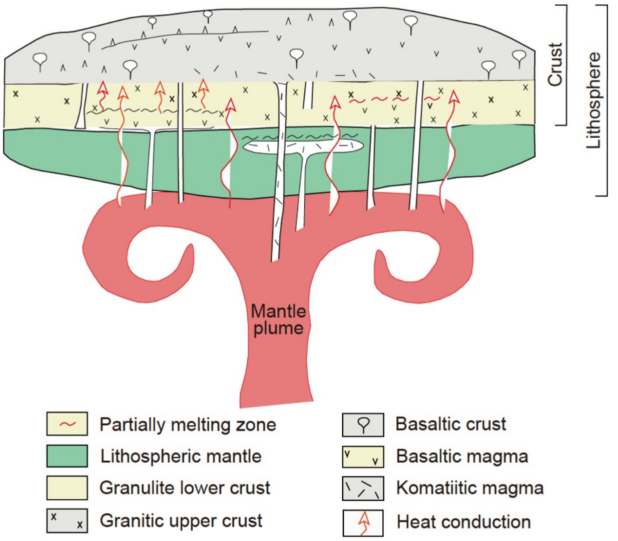


Figure 5 Schematic cartoon showing the mantle plume model for the formation of granite-greenstone terranes in the Archean (revised from Van Kranendonk, 2010).

It is known that there is a difference in magma formation temperature between ca. 1600°C for komatiites in the Archean and 1400–1300°C for tholeiitic basalts in the Phanerozoic. Assuming that the temperature difference corresponds to the origination of materials from mantle plume tail in the D″ layer at the core-mantle boundary and head beneath the lithosphere and that specific trace element ratios are comparable between the volcanic rocks derived from the mantle plume trial and head, respectively (Hofmann and White, 1982), Campbell et al. (1989) proposed that komatiites in Archean greenstone belts were derived from thermal melting of mantle plume tail channels, while basaltic rocks resulted from decompressional melting of massive, mushroom-shaped mantle plume heads beneath the lithosphere. Therefore, it seems to reach a consensus that komatiites in the Archean would have a mantle plume origin. The formation and evolution of oceanic plateaus through mantle plumes are also a common model for explanation of the volcanic rocks represented by greenstone belts and TTG gneissic domes in Archean cratons (Larson, 1991; Hill, 1993; Kent et al., 1996).

Van Kranendonk (2010) applied the mantle plume model to oceanic plateaus to explain the origin of the 3.6–3.2 Ga granite-greenstone terranes in the eastern Pilbara craton of western Australia. In this model, the massive head of the mantle plume would reach the lithospheric base and undergo decompressional melting, giving rise to basaltic magmas that erupt on the seafloor to form thick oceanic plateau basalts (Figure 5). The melting of the mantle plume's tail portion would give rise to komatiitic magmas. The higher temperatures led to multiple episodes of partial melting of the preexisting basaltic crust and the newly formed lower crust beneath the oceanic plateaus, producing TTG magmas at 3.53 to 3.24 Ga and contributing to the formation of a granite-rich continental crust. However, this explanation is at variance with the geology of the eastern Pilbara (Kusky et al., 2021). Bédard (2006) proposed a similar model for the origin of Archean continental crust. Gerya et al. (2015) suggested that mantle plume would induce the initiation of plate tectonics by causing partial melting of the lower crust in an oceanic plateau, leading to the emergence of low-density granitic crust, which could subsequently cause the dense oceanic lithosphere to subduct beneath the low-density continental lithosphere.

However, a major challenge in the mantle plume-derived oceanic plateau model for the origin of granitic crust in the Archean is to explain how the source basaltic rocks underwent hydration. This is because partial melting of basaltic rocks, required to produce TTG magmas, typically necessitates the presence of a given amount of water in the system (Foley et al., 2002; Arndt, 2013, 2023). In environments such as those proposed for mantle plume-derived oceanic plateaus, which are often considered to be relatively dry, the partial melting of basaltic rocks is difficult to achieve. Arndt (2013, 2023) considered this a fatal flaw in the mantle plume-derived oceanic plateau model for explaining the origin of ancient continental crust. However, Bédard (2006) suggested that basaltic rocks can contain water, there was limited horizontal movement in the early Earth's lithosphere, and the thick basaltic oceanic crust could form during eruption of basaltic magmas; with increasing burial depth and heating, such as the case when encountering a thermal mantle plume head, eclogitization and partial melting can occur, ultimately resulting in TTG magmatism after multiple episodes of evolution.

While the mantle plume model has been widely used to explain the origins of Archean komatiites (e.g., Campbell et al., 1989; Larson, 1991; Hill, 1993; Abbott and Mooney, 1995; Abbott, 1996; Bédard, 2006; Brown et al., 2020a), questions persist regarding the depth from which mantle plumes originate (Courtillot et al., 2003; Baes et al., 2021). In addition, the mantle plume-derived oceanic plateau model faces the challenge in explaining the genesis of gneissic domes in Archean cratons.

4.4 Heat pipe tectonics

The heat pipe model was initially introduced by O'Reilly and Davies (1981) to explain the extensive heat release from the interior of Jupiter's satellite Io and the formation of a thick lithosphere on Io. Io is a moon-sized silicate rock body. In 1979, NASA's Voyager 1 mission captured images of intense volcanic eruption on Io's surface and mountains as high as 10 km, suggesting the presence of a massive rocky lithosphere on Io. O'Reilly and Davies (1981) proposed that Io's exceptionally thick lithosphere was a result of the continuous eruption of magma along vertical heat pipe channels (vents). As the thick layer of volcanic lava accumulated on Io's surface between the heat pipe channels, the lithosphere between these channels experienced gravitational subsidence. The subsided lithospheric base returned to the asthenosphere, thus establishing a vertical and symmetric convective circulation of both energy and material. Subsequently, Turcotte (1989) also used the heat pipe model to explain the formation of Venus's thick lithosphere and heat release on its surface.

Building upon planetary dynamical models previously applied to Jupiter's volcanic activity and its satellite Io, Moore and Webb (2013) proposed that the early Earth would also undergo a phase of heat pipe tectonics. They argued that the heat pipe model could explain the heat transfer and lithospheric dynamics between the Hadean magma ocean and the stagnant lid (Figure 6). This model suggests that frequent volcanic eruptions might bring the hot mantle material into the Earth's surface, persisting a cold, thick stagnant lid tectonics. Over time, the reduction in heat sources could have led to a transition to a mobile lid tectonics. Moore et al. (2017) suggested that heat pipes are a common stage in the thermal evolution of terrestrial planets and represent a precursor to plate tectonics on Earth. Exoplanets much larger than Earth may have maintained the heat pipe tectonics for most of the lifespan of a sun-like star, and heat pipe cooling could explain geological features common to rocky planets beyond Earth.

Lately, Webb et al. (2020) applied the heat pipe model to explain the formation of the Eoarchean supracrustal belt in the Isua terrane, Greenland. They suggested that two sets of greenstone-TTG associations, with ages of 3.7 Ga and 3.8 Ga, respectively, represent two cycles of volcanic eruption and burial anatexis. These two cycles resulted in vertical superimposition due to volcanic rock accumulation and lithospheric drip within the heat pipe tectonics, rather than lateral collision and aggregation within a regime of plate tectonics. They also pointed out that the preservation of intact rocks from the Paleoarchean (<3.6 Ga) reflects the weakening of heat pipe activity and its associated lithospheric drip. When applied to Archean cratons, however, the heat pipe model does not explain how komatiitic rocks underwent partial melting to produce granitic crust, nor does it address the formation of gneissic domes. Furthermore, this explanation has overlooked decades of structural and petrological studies in Isua, leading to widespread critics by geologists who have worked there.

Similar to the mantle plume tectonics, the heat pipe tectonics is also the result of mantle poloidal convection (Tackley, 2023). Both models assume that high-temperature anomalies would initially gather beneath the lithosphere and then undergo decompressional melting at sites of lithospheric thinning to form basaltic magmas. Because of the spatial constraint on mantle convection, they mainly differ in their vertical scales. In the context of layered mantle convection, the heat pipe tectonics can only originate in the upper mantle above the transition zone rather than in the lower mantle. Under the conditions of whole mantle convection, it becomes difficult to distinguish between the products from the heat pipe and mantle plume tectonics, as high-temperature anomalies can accumulate beneath the lithosphere in both cases.

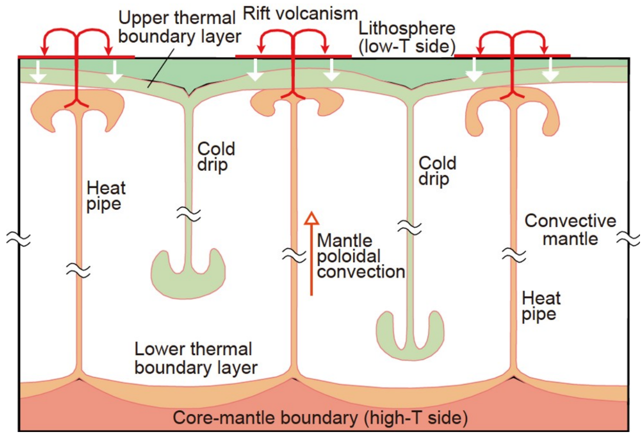


Figure 6 Schematic diagram showing for heat pipe tectonics in the interior of early Earth (adapted after Moore and Webb, 2013).

5. Archean geology in relation to plate tectonics

Regarding the pre-plate models for Archean geology, either mantle plumes (Figure 5) and heat pipes (Figure 6), or lithospheric foundering and asthenospheric upwelling, they all emphasize vertical movements of material within the regime of stagnant lid tectonics (Figure 2b, 2c, and 2d). This is in contrast to the traditional version of plate tectonics established in the 20th century, which emphasizes horizontal movements. In fact, these vertical processes have continued throughout geological history and are considered crucial mechanisms for the generation of granitic magmas (Moyen et al., 2021; Zheng and Gao, 2021). Because vertical tectonics is one of the two key characteristics of plate tectonics regimes (Zheng et al., 2022; Zheng, 2023), the origin and evolution of Archean continental crust can be explained as a result of plate tectonics processes.

Plate tectonics was established as a kinematic theory in the 20th century (e.g., Le Pichon et al., 1973; Cox and Hart, 1986; Oreskes, 2003, and references therein), but it already involves the vertical transport of matter and energy at subduction and rifting systems (Zheng et al., 2022). In the 21st century, plate tectonics has been advanced as a holistic kinematic-dynamic theory (Zheng, 2023), dealing with both horizontal and vertical transports of both matter and energy on different scales at plate margins. This upgraded version underscores the coupling between the subduction of oceanic plates at convergent plate boundaries and the upwelling of the asthenosphere at divergent plate boundaries, making plate tectonics a dynamic system on Earth. Both convergent and divergent plate margins involve vertical processes in the forms of lithospheric subduction and asthenospheric upwelling, respectively. In contrast, continental drift represents merely horizontal tectonics. Mantle plume and heat pipe tectonics can be the manefestination of mantle poloidal convection, and the buoyant rise of mantle-derived magmas is also a kind of vertical tectonics. Therefore, the development and rationalization of plate tectonics theory require abandoning the emphasis on a single horizontal motion in traditional plate tectonics models and taking into account such vertical movements as the lithopsheric subduction along convergent plate margins and the asthenospheric upwelling along divergent plate margins. In terms of dynamic sources, it is necessary to consider both the gravitational effects of subducting slabs and the buoyancy associated with mantle poloidal convection and its derived magmas. Investigating the temperature and pressure conditions for the formation of metamorphic rocks at convergent plate margins can provide clues to addressing these issues (Zheng and Chen, 2017, 2021).

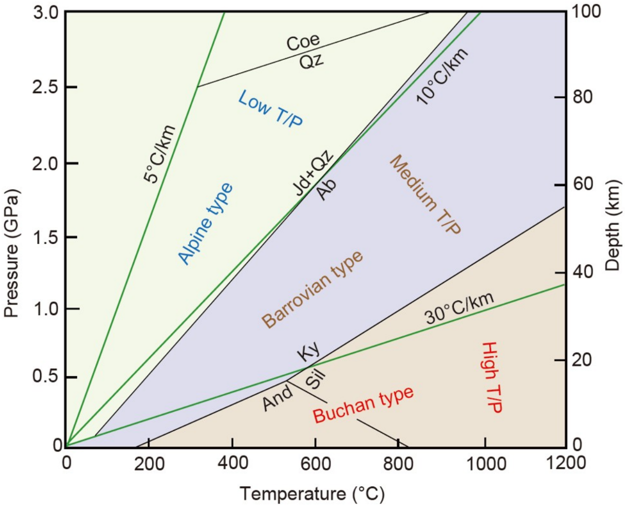


Figure 7 The relationship between metamorphic facies series and geothermal gradients at convergent plate margins (revised from Zheng and Chen, 2021). The boundary between Alpine and Barrovian facies series is defined by the metamorphic reaction of albite=jadeite and quartz (Brown, 2007; Zheng and Chen, 2017), and the boundary between Barrovian and Buchan facies series is defined by the polymorphic transition of Al_2SiO_5 between kyanite and andalusite at lower temperatures and between kyanite and sillimanite at higher temperatures (Zheng and Chen, 2021; Pattison and Goldsmith, 2022). Mineral abbreviations: Ab, albite; And, andalusite; Coe, coesite; Jd, jadeite; Ky, kyanite, Sill, sillimanite; Qz, quartz.

5.1 Regional metamorphic facies series and paired metamorphic belts

The types of regional metamorphism are closely related to the tectonic mechanisms of crustal thickening or thinning, destruction or growth, and the study of metamorphic dynamics can reveal the mechanisms of geodynamics at convergent plate margins. The types of metamorphism under regimes of vertical and horizontal tectonism can be effectively constrained by metamorphic geothermal gradients. For metamorphic rocks formed at convergent plate margins, they can be divided into three metamorphic facies series based on the ratio of metamorphic temperature (T) to pressure (P) (Figure 7): low T/P Alpine type, medium T/P Barrovian type, and high T/P Buchan type (Zheng and Chen, 2017, 2021). The low T/P Alpine type facies series is composed of blueschist to eclogite facies HP to UHP metamorphic rocks, and its boundary with Barrovian type facies series is marked by the breakdown of albite to form jadeite and quartz under high-pressure conditions (Brown, 2007; Zheng and Chen, 2017), corresponding to metamorphic T/P ratios of <335–375°C/GPa and geothermal gradients of <10–11°C/km. The medium T/P Barrovian type facies series is composed of kyanite-bearing moderate-pressure (MP) amphibolite to HP granulite facies metamorphic rocks, and its boundary with Buchan type facies series is marked by the polymorphic transition from kyanite to sillimanite at high temperature (Zheng and Chen, 2021; Pattison and Goldsmith, 2022) and to andalusite at low temperature, corresponding to metamorphic T/P ratios varying from 835 to 1175°C/GPa (average 1000°C/GPa) and geothermal gradients from 25 to 35°C/km (average 30°C/km). The high T/P Buchan type facies series is characterized by kyanite-absent LP amphibolite to granulite facies HT to UHT metamorphic rocks, with an upper limit of metamorphic T/P ratios varying from 835 to 1175°C/GPa and an upper limit of geothermal gradients varying from 25 to 35°C/km. The advantage of the threefold division of metamorphic facies series at convergent plate margins lies in its ability to transform simply the differences in metamorphic temperature and pressure as well as mineralogical and petrological characteristics into the differences in metamorphic T/P ratios and geothermal gradients (Zheng and Chen, 2017, 2021; Brown and Johnson, 2018, 2019). These three types of metamorphic facies series are common in continental collision zones of Phanerozoic age, and the temporal sequence of their formation is regular (Zhang et al., 2023; Ji et al., 2024).

The low T/P Alpine type metamorphic facies series were formed at low geothermal gradients in compressional settings characteristic of cold subduction zones, whereas the high T/P Buchan type metamorphic facies series were formed at high geothermal gradients in extensional settings characteristic of hot rifting zones (Zheng and Chen, 2017, 2021). If these two metamorphic facies series occur respectively in the accretionary wedge and backarc rift of the same oceanic subduction zone, they constitute the classic Miyashiro-type paired metamorphic belts (Miyashiro, 1973; Ernst, 1976), corresponding to a tectonic transition from cold

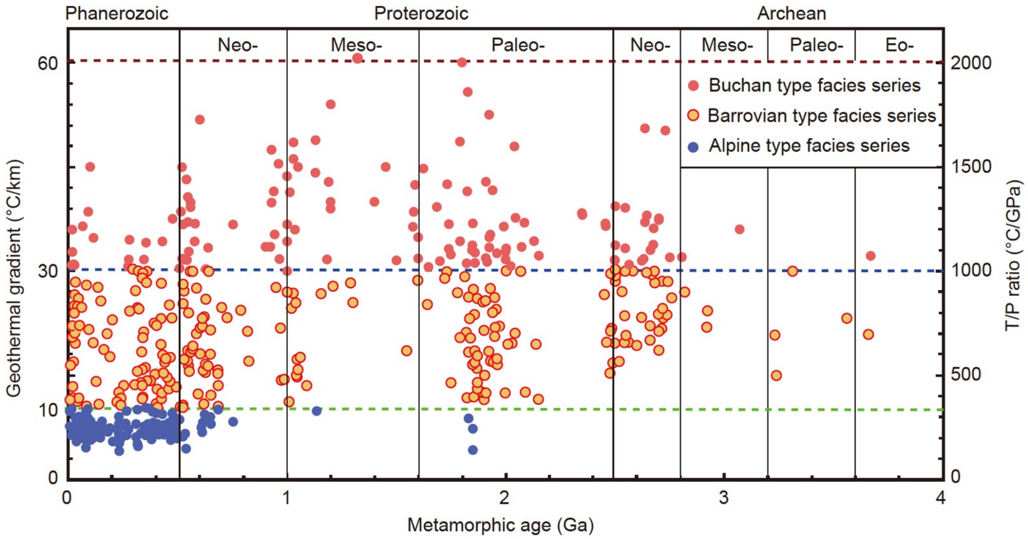


Figure 8 Plot of metamorphic age versus geothermal gradient (thermobaric ratio) grouped by metamorphic facies series (revised from Zheng and Zhao, 2020). Metamorphic P-T data are from Brown and Johnson (2019). The three types of metamorphic facies series at convergent plate margins are Alpine in blue, Barrovian in red-circled orange, and Buchan in red. The dashed lines denote the boundaries between the different facies series.

crustal subduction in the trench to hot rifting in the backarc. In this case, the occurrence of paired metamorphic belts marks the dynamic transition from compression to extension at the convergent plate margins (Zheng and Chen, 2021). As illustrated in Figure 8, nevertheless, pairing medium T/P Barrovian type facies series with high T/P Buchan type facies series as Brown-type paired metamorphic belts is popular from the Archean through the Proterozoic to the Phanerozoic (Brown and Johnson, 2018, 2019; Brown et al., 2020a; Holder et al., 2019; Zheng and Zhao, 2020; Kuang et al., 2023). This temporal sustainability indicates that convergent plate margins underwent the tectonic transition from hard collisional thickening of the crust in a compressional regime to hot rifting thinning of the lithospheric mantle in an extensional regime (Zheng and Chen, 2021). However, it is critical to demonstrate that the two metamorphic belts are coupled in both space and time along the convergent margins.

Brown (2006) paired the medium T/P Barrovian type facies series with high T/P Buchan type facies series, making their occurrence as indicating the operation of plate tectonics in the Neoarchean. The appearance of Brown-type paired metamorphic belts in Archean cratons is already evident from statistical data on metamorphic ages and geothermal gradients (e.g., Brown and Johnson, 2018, 2019; Brown et al., 2020a; Holder et al., 2019; Zheng and Zhao, 2020; Kuang et al., 2023). Ning et al. (2022) found Neoarchean garnet pyroxenite from the eastern Hebei region in the North China Craton and obtained its peak metamorphic T/P ratios of 372–400°C/GPa and corresponding geothermal gradients of 11.2–12.0°C/km. These values are the lowest within known Archean Barrovian metamorphic facies series. Although they have not reached the conditions of cold subduction zones, they may be produced by either warm subduction or hard collision at an ancient plate margin. In this regard, Neoarchean convergent margins were at moderate geothermal gradients to undergo either crustal thickening through hard collision or lithospheric stacking through warm subduction (Zheng et al., 2022).

The generation of classic Miyashiro-type paired metamorphic belts through the operation of plate tectonics reflects the secular change of geothermal gradients along convergent plate margins. It can be divided into two-stage processes in their relationship between tectonic evolution and petrogenetic mechanism (Figure 9). The early stage is characterized by compressional heating in subduction zones where basaltic oceanic crust subducts at low angles beneath the overlying lithospheric plate (Figure 9a), and low T/P Alpine type HP to UHP eclogite facies metamorphism occurs at low geothermal gradients. The later stage is characterized by extensional heating in rifting zones where rollback of the subducting oceanic slab results in its decoupling from the overlying lithospheric plate (Figure 9b), leading to upwelling of the asthenospheric mantle consequential to thinning of the overlying lithospheric mantle and giving rise to high T/P Buchan type HT to UHT granulite facies metamorphism at high geothermal gradients (Zheng and Chen, 2021; Zheng et al., 2022).

In the Archean, the convective mantle temperature was 200–300°C higher than in the Phanerozoic (Herzberg et al., 2010; Ganne and Feng, 2017; Aulbach and Arndt, 2019). This resulted in lower rheological strength at the margin of cratonic lithosphere, transforming rocks from rigidity to ductility and giving rise to different types of metamorphism and magmatism at convergent plate margins (Zheng and Zhao, 2020; Kusky, 2020; Wang, 2023). It is due to this high

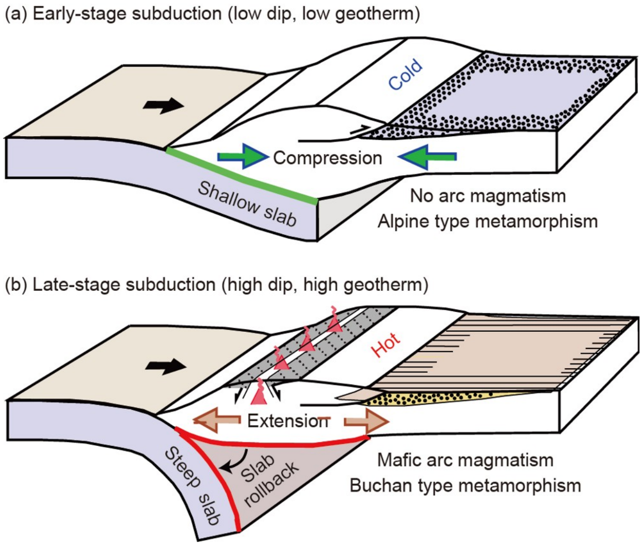


Figure 9 Schematic diagrams showing the difference in dynamic regime and thermal state between the different stages of plate subduction (revised from Zheng and Zhao, 2020). A. The early-stage subduction in compressional regime and at low dip. The plate interface is at low geothermal gradients, resulting in UHP eclogite facies metamorphic dehydration of the subducting crust at subarc depths, where partial melting of the hydrated mantle wedge does not immediately take place to cause arc magmatism. B. The late-stage subduction in extensional regime and at high dip. Rollback of the subducting slab results in its decoupling with the overlying mantle wedge at subarc depths, leading to elevation of the geothermal gradient at the plate interface and active rifting of the overlying plate. This would cause partial melting of metasomatites in the mantle wedge to form arc magmatism.

mantle temperature that the juvenile basaltic oceanic crust generated by seafloor spreading was not only as thick as 30–40 km (Foley et al., 2003; van Thienen et al., 2004; Herzberg and Rudnick, 2012), but also underwent hydration at spreading centers. When the thick basaltic crust was transported from divergent plate margins to convergent plate margins, it is expected to undergo hard collision on the one hand and thus further thickening to 60–70 km in a compressional regime (Zheng et al., 2022), resulting in medium T/P Barrovian type metamorphism at moderate geothermal gradients to form MP amphibolite to HP granulite (Zheng and Chen, 2021; Zheng et al., 2022). On the other hand, the metabasaltic crust could be warmly subducted to mantle depths exceeding 60–80 km beneath the overlying lithosphere, where it underwent not only medium T/P Barrovian type metamorphism to form garnet pyroxenite and mafic granulite beneath the overriding plate, but also fluid release into the mantle wedge. Because of the high temperature in the warm subduction zones, metasomatic rocks in the mantle wedge could undergo partial melting immediately after their formation. This gave rise to basaltic arc magmas that ascended and intruded, forming early oceanic arcs (Zheng and Zhao, 2020; Zheng et al., 2022). If the subducting oceanic slab underwent rollback, it would result in backarc extension to induce upwelling of the asthenospheric mantle and thus heating of the metabasaltic crust, leading to anatectic metamorphism in the coupled dehydration-hydration mechanism. This would bring about high T/P Buchan type granulite facies residues on the one hand and granitic melts rising and emplacing on the other hand (Zheng and Gao, 2021; Zheng et al., 2022).

There are two types of granulites in Archean cratons. One is Barrovian type HP granulites that formed during the compressional stage of collisional thickening between ancient oceanic plates. The other is Buchan type LP granulites that formed during the extensional phase consequential to thinning of the lithospheric mantle and upwelling of the asthenospheric mantle. Although high-grade metamorphic rocks in Archean cratons can exhibit both clockwise and anticlockwise P-T paths, it is essential to analyze the evolution relationships between peak pressure and peak temperature for these rocks. If the peak metamorphic pressure occurred within the stability field of kyanite and then experienced decompressional heating to enter the stability field of sillimanite, it indicates the transition from Barrovian type MP amphibolite and HP granulite facies to Buchan type LP granulite facies. This is associated with thinning of the lithospheric mantle at collisional zones to induce the asthenospheric upwelling, giving rise to continental rifting in an extensional setting. Therefore, the Buchan type metamorphic superimposition is caused by the influx of asthenospheric mantle-derived heat (Bohlen, 1991; Zheng and Chen, 2017). The influx of mantle-derived heat usually occurs in tectonic settings such as continental rift, backarc rift and intraplate hotspot consequential to thinning of the lithospheric mantle (Zheng and Chen, 2021), and this external heating may be the dominant mechanism for the occurrence of Buchan type HT to UHT metamorphism at convergent plate margins (Zheng et al., 2022). Afterwards, Buchan type metamorphic rocks exhibit anticlockwise P-T paths.

5.2 Petrogenesis of Archean TTG rocks

Previous studies have revealed that Archean TTG rocks exhibit an evolution trend toward more Na enrichment with increasing SiO_2 content, leading to an overall trondhjemitic trend (e.g., Martin and Moyen, 2002; Condie, 2006; Moyen, 2011; Arndt, 2013; Halla, 2018; Sotiriou et al., 2023). In contrast, Phanerozoic continental arc granitic rocks tend to become enriched in K with increasing SiO_2 contents, indicating a calc-alkaline evolution trend. In terms of trace element composition, Archean TTG rocks mostly display two geochemical patterns (Moyen, 2011; Moyen and Martin, 2012; van Hunen and Moyen, 2012; Sotiriou et al., 2023): (1) island arc type (Figure 10), characterized by relative enrichment in large ion lithophile elements (LILE) and light rare earth elements (LREE), as well as depletion in high field strength elements (HFSE) such as Nb, Tb and Ti; (2) adakitic

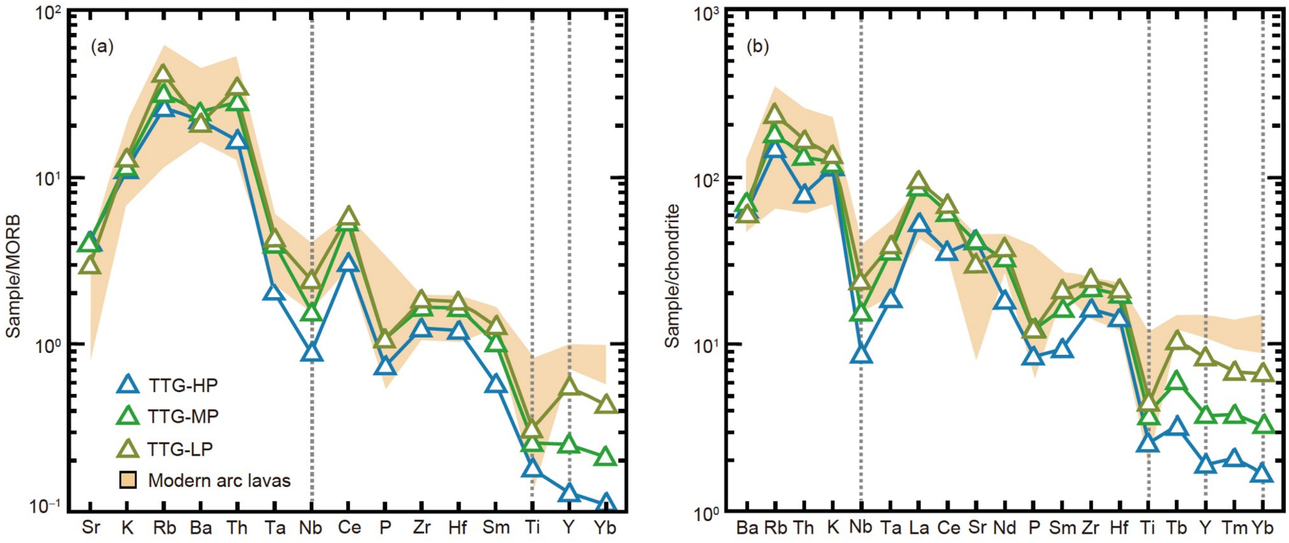


Figure 10 Diagram of trace and rare earth element distribution patterns for Archean TTG rocks (revised from van Hunen and Moyen, 2012).

type (Figure 11), indicated by extremely high La/Yb and Sr/Y ratios, high Sr contents, and significant depletion in heavy rare earth element (HREE). In contrast, Phanerozoic continental arc granites exhibit lower La/Yb and Sr/Y ratios as well as lower Sr contents, but higher HREE contents.

For Phanerozoic granites, although their origin is diverse, it mainly falls into two categories (Moyen et al., 2021; Zheng et al., 2021): one is the fractional crystallization of mafic magmas in continental arcs, and the other is the partial melting of orogenic crust. Since Archean crust lacks continental arc andesites (Zhao et al., 2023), TTG magmas would primarily result from partial melting of the basaltic crust. However, their composition is controlled by three factors: (1) differences in source composition, (2) differences in melting conditions, and (3) crystal fractionation during the migration and aggregation of TTG magmas. Therefore, the relative enrichment of LILE and LREE in Archean TTG rocks does not necessarily require the source rocks to be island arc basalts, as both partial melting and crystal fractionation can achieve this effect. With respect to the compositional feature of Archean TTG rocks, Archean TTG magmas could derive from partial melting of the basaltic crust at the base of oceanic plateaus (Martin et al., 2014). With respect to the tectonic mechanism of TTG magmatism, there are two schools of viewpoint. While one school maintains that TTG magmas cannot be generated in subduction zones (Martin et al., 2014; Johnson et al., 2017), the other school suggests that they can be produced in subduction zone (Foley et al., 2002; Hastie et al., 2023; Sotiriou et al., 2023).

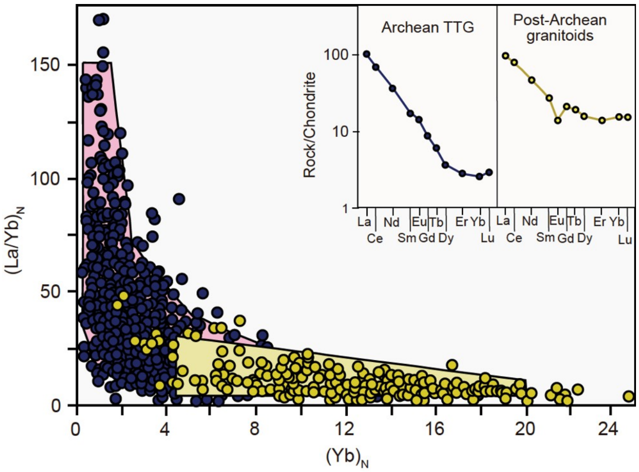


Figure 11 Diagram of La/Yb-Yb variations for Archean TTG and post-Archean granitic rocks (revised from Moyen and Martin, 2012).

While partial melting of the subducting basaltic oceanic crust, such as eclogite and garnet amphibolite, under high-pressure conditions can produce rocks with high La/Yb ratios similar to Archean TTG rocks, the degree of melting should not exceed 30%. Beyond this threshold, garnet enters the melt phase, resulting in TTG magmas that do not have high La/Yb ratios and low HREE contents (e.g., Martin, 1999; Martin and Moyen, 2002; Condie, 2006; Arndt, 2013; Martin et al., 2014). This degree of partial melting would require a source rock that is at least three times the volume of TTG magmas, which does not align with the 60–70% exposure area of TTG rocks in Archean cratons. Based on the initial compositions of Coucal basalt exposed in the eastern Pilbara craton, Johnson et al. (2017) estimated that this basalt would experience partial melting of about 20–30% at a T/P ratio of 900°C/GPa, resulting in melt compositions matching Archean TTG rocks. The T/P ratio of 900°C/GPa is confined to the transitional Barrovian-Buchan type metamorphism and thus evidently higher than that at modern oceanic subduction zones (<400°C/GPa), corresponding to thinning of the over-thick oceanic crust (Zheng et al., 2022). Therefore, the subduction of oceanic plates itself in the Archean period would not have generated TTG magmas.

Regarding the geochemical information of island arc basalts, it consists of three components on trace element distribution diagrams (Figure 12): (1) positive LILE and LREE anomalies, which are also prominent in ocean island basalts; (2) negative Nb, Ta and Ti anomalies, whereas ocean island basalts exhibit positive or no Nb, Ta and Ti anomalies; (3) a positive Pb anomaly, in contrast to a negative Pb anomaly in ocean island basalts. For most Archean TTG rocks, not only the positive LILE and LREE anomalies as well as the negative Nb, Ta and Ti anomalies significant (Figure 10), but also the positive Pb anomaly is common (Sotiriou et al., 2023). However, the interpretation of their origin is still controversial (van Hunen and Moyen, 2012; Moyen and Laurent, 2018; Sotiriou et al., 2023). The result of experimental petrology by Hastie et al. (2023) suggests that partial melting of basaltic crust at pressures of >1.4 GPa can produce felsic magmas with compositions similar to early continental crust, but the tectonic context cannot distinguish between subduction and collisional zones. This distinction was not made in the studies of Martin et al. (2014) and Johnson et al. (2017).

Regarding the depletion of Nb, Ta and Ti in Archean TTG rocks, it is required that the P-T conditions for partial melting of the basaltic crust fall within the garnet stability field (Zheng, 2019; Zheng et al., 2020). If the pressure played an effective role in dictating the Sr/Y and La/Yb ratios of TTG magmas (Moyen, 2011), high-pressure TTG magmas were formed at depths within the overthick lower crust. Although there is no necessary connection between the Archean TTG origin and ancient oceanic subduction (Martin et al., 2014; Johnson et al., 2017; Hastie et al., 2023), it is still closely related to convergent plate margins (Li et al., 2021; Wang et al., 2022a, 2022b; Zheng et al., 2022). Geochemically, the depletion of Nb, Ta and Ti in Archean TTG rocks is primarily controlled by rutile. Rutile is a characteristic accessory mineral in HP metamafic rocks such as eclogite, garnet amphibolite and mafic granulite at convergent plate margins. It can form under HP conditions through metamorphic reactions. If these metamafic rocks experience partial melting at HP conditions within the overthick basaltic oceanic crust of convergent plate margins (Rapp et al., 1991, 2003; Foley et al., 2002; Moyen and Martin, 2012; Hastie et al., 2023), not only can metamorphic rutile remain stable, but peritectic rutile can also be formed through peritectic reactions. In such cases, the resulting felsic melts are inevitably depleted in Nb, Ta and Ti. Therefore, the depletion of Nb, Ta and Ti in felsic rocks results from partial melting of the over-thick oceanic crust under HP conditions, and it is not related to island arc magmatism above oceanic subduction zones. If this conclusion holds, the characteristic Nb, Ta and Ti depletion in Archean TTG rocks can be used to indicate the source region of over-thick oceanic crust at convergent plate margins and its partial melting under HP conditions. The degree of depletion is controlled not only by the abundance of metamorphic rutile in the source region but also by the yield of peritectic rutile during the partial melting (pressure levels).

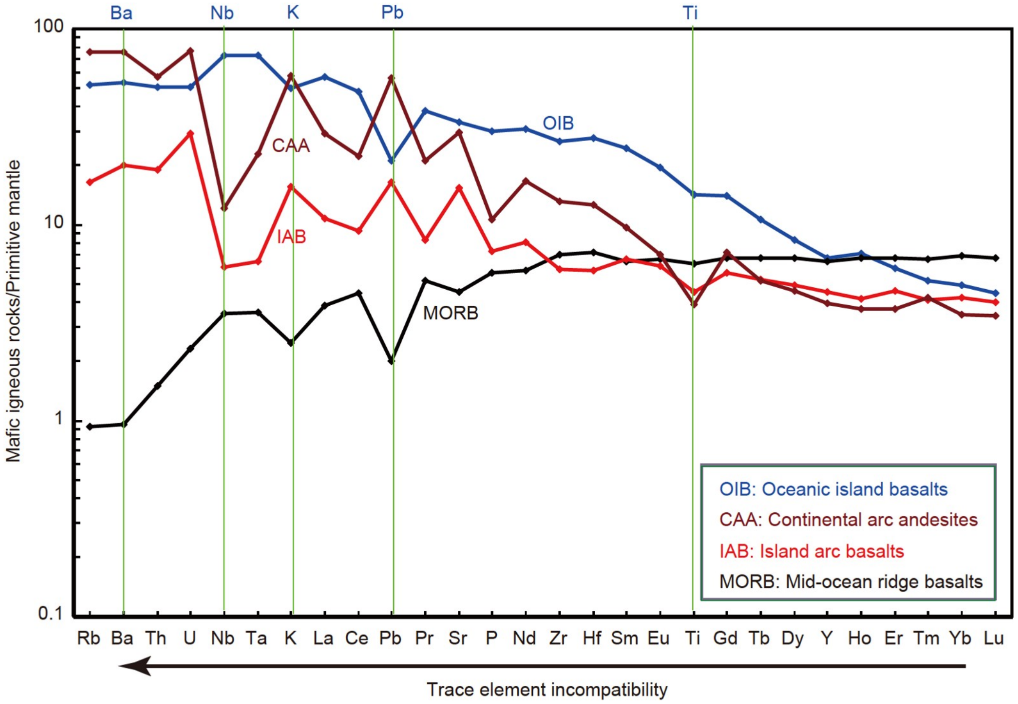


Figure 12 Diagram of trace element distribution patterns for modern oceanic basalts (revised from Zheng, 2019).

In general, there are two major mechanisms for the formation of Phanerozoic adakites through partial melting: (1) thickening of the oceanic crust in subduction zones (Defant and Drummond, 1990), and (2) thickening of the lower crust in continental collision zones (Chung et al., 2003; Wang et al., 2007). Regardless of crustal types, as long as the pressure conditions for partial melting fall within the garnet stability field and the plagioclase breakdown field, high La/Yb and Sr/Y ratios can be produced (Figure 11). Zheng et al. (2022) have combined these two mechanisms together to explain the genesis of Archean TTG rocks. They propose that in the Archean, not only was the basaltic crust itself thicker (30–40 km), but also the rheological properties of this thick basaltic crust at convergent plate margins were similar to Phanerozoic granitic crust. In the Archean, when oceanic plates converged toward each other, either the thick oceanic crust was further thickened by hard collision to 60–70 km (Figure 13a), or the oceanic lithosphere was stacked by warm subduction of one oceanic plate beneath another. Once the thick lithosphere at the convergent plate margin was thinned by unrooting (Figure 13b), the underlying asthenospheric mantle would upwell to cause active rifting and thus partial melting of the over-thick crust, resulting in Na-rich and K-poor TTG magmas, similar to the generation of adakitic magmatism in continental collision zones of Phanerozoic. This inference has also been validated by geochemical studies of Archean TTG and greenstone rocks by Li et al. (2021) and Wang et al. (2022a, 2022b).

Moreover, as two oceanic plates converge, oceanic plateau located on the subducting plate is accreted to the overlying plate margin, where it forms a basaltic accretionary wedge (Kusky, 1998), hindering further subduction of the oceanic plate. The thick oceanic crust and the underlying stacked lithospheric mantle were also form at convergent plate margins (Zheng et al., 2022). In nature, once this thick lithospheric mantle underwent thinning by unrooting, the overlying over-thick basaltic crust would partially melt, forming TTG magmas. This process would result in the formation of granitic crust on early Earth if collisional zones could replace subduction zones in the Archean (Martin et al., 2014; Johnson et al., 2017; Zheng, 2023). The formation of large-scale granitic crust indicates extensive partial melting of the basaltic crust (Tang et al., 2016), which would take place at convergent plate margins (collisional zones rather than subduction zones). This suggests that the lithospheric mantle was thinned at first and then underwent significant heating from the underlying convective mantle, leading to continental active rifting. During this continental rifting, low-density granitic melts rose and intruded (Rozel et al., 2017), forming TTG rocks that underwent regional metamorphism to become migmatites. Simultaneously, it led to the illusion that high-density greenstone belts seemed to have relatively subsided, giving rise to the dome-keel structure of Archean cratons (Zheng and Zhao, 2020; Kusky et al., 2021; Yu et al., 2022). Therefore, Archean gneissic domes are somehow analogous to those in metamorphic core complexes of Phanerozoic (Zheng and Chen, 2017, 2021; Zheng and Gao, 2021).

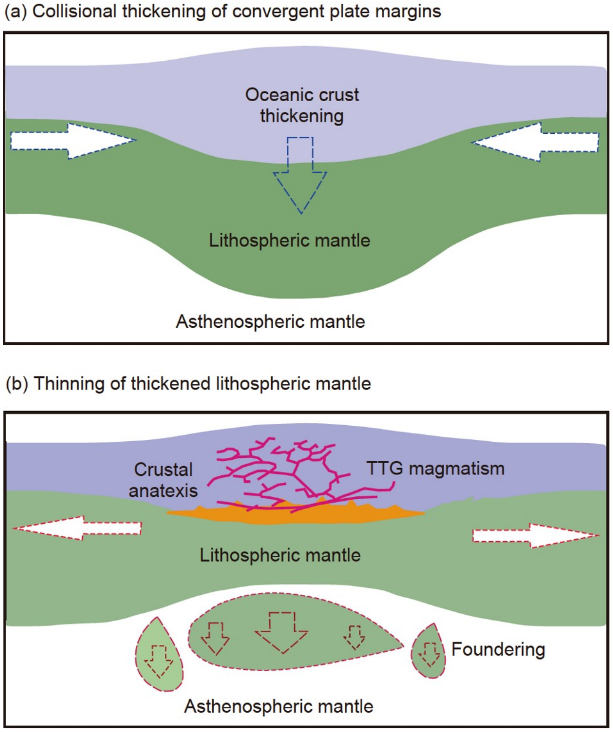


Figure 13 Schematic diagrams showing the origin of TTG magmas at convergent plate margins in the Archean (adapted after Zheng et al., 2022). (a) Further thickening of the thick basaltic oceanic crust through hard collision during oceanic plate convergence; (b) the generation of TTG magmas through partial melting of the over-thick oceanic crust due to upwelling of the asthenospheric mantle consequential to thinning of the lithospheric mantle in the collisional zone.

In many Archean cratons, greenstone belts and TTG rocks would have formed almost simultaneously, with the greenstone belts sometimes forming just slightly earlier. The formation of greenstone belts, the intrusion of TTG magmas, the metamorphism and deformation of the continental crust, and the intrusion of K-rich granites constitute a series of sequential processes within the same tectonomagmatic cycle. By comparing the geochemical compositions of Archean and Phanerozoic TTG rocks, Sotiriou et al. (2023) find similarities in their incompatible trace element compositions, suggesting that both were formed at convergent plate margins. According to the petrogenetic model of Zheng et al. (2022) for Archean TTG rocks (Figure 13), it is expected that at Archean convergent plate margins, there was the further collisional thickening of the thick basaltic oceanic crust at first. Subsequently, thinning of the underlying lithospheric mantle would induce the asthenospheric upwelling to heat the over-thick basaltic crust, leading to its partial melting at different depths. The resulted TTG magmas would ascend through and intrude into the greenstone belts, leading to the illusion that gravitational sagduction could operate to form the dome-keel structures. The basaltic crust that was exposed on the surface at convergent plate margins underwent greenschist facies metamorphism, forming greenstone belts. Continuous high heat flow from the convective mantle would cause extensive partial melting in the lower part of the over-thick basaltic crust, giving rise to TTG magmas that were diapirically emplaced within short timescales and then experienced the metamorphism and deformation, resulting in the observed gneissic domes. Therefore, in terms of the direction of crustal movement driven by the differences in both temperature and density, the opposite of gravitational sagduction tectonics is the buoyant uplift tectonics. This is also the fundamental reason why Archean gneissic domes have a similar petrogenetic mechanism to Phanerozoic metamorphic core complexes.

5.3 Ancient and modern plate tectonics

Many geological observations and geochemical data have been interpreted to record the operation of plate tectonics in the Archean. Nevertheless, the style of plate tectonics appears different from the Archean through the Proterozoic to Phanerozoic. Furthermore, numerical geodynamic models yield various possibilities for the tectonic regime of early Earth (e.g., Sizova et al., 2010, 2015, 2018; Perchuk et al., 2020, 2023; Korenaga, 2021). As a consequence, a large wealth of Archean geological records was not interpreted within the framework of plate tectonics, leading to a major controversy between plate and non-plate tectonic regimes. There are several possible solutions to this controversy, ranging from one extreme that the so-called geological evidence is due to mis-interpretation of the geological observations and geochemical data, to the opposite extreme that numerical geodynamic models are incorrect because they are tailored to contemporary geodynamics and starting conditions as well as relevant assumptions (Kuang et al., 2023). Typically, geodynamic models suggest that a hotter Earth could yield one of the following consequences: (1) short-lived regional subduction, a geodynamic setting commonly called sluggish tectonics (Korenaga, 2006), (2) tectonic trigger upwards migration of mantle-derived melts and their eruption on the lithospheric surface, referred to as heat pipe tectonics (Moore and Webb, 2013), and (3) fragmented sinking of the lithospheric mantle into the asthenosphere, called sagduction or drip tectonics (Nebel et al., 2018). Nevertheless, geological records and geodynamic models do converge toward significantly higher mantle temperatures in the Archean than in the Phanerozoic (Korenaga, 2008a, 2008b; Davies, 2009; Herzberg et al., 2010; Condie et al., 2016; Ganne and Feng, 2017; Aulbach and Arndt, 2019). Although the higher mantle temperatures do not reject the onset of plate tectonics, the mechanical behavior of plate margins has indeed changed considerably since the Archean. Therefore, one solution is that the styles of plate tectonics have evolved with time because of the decrease of mantle temperature since the Archean (Zheng and Zhao, 2020).

In the Archean, the thick crust at convergent plate margins exhibited primarily ductile behavior in terms of rheology and had moderate geothermal gradients, giving rise to hard collision or warm subduction (Figure 14). This behavior differs

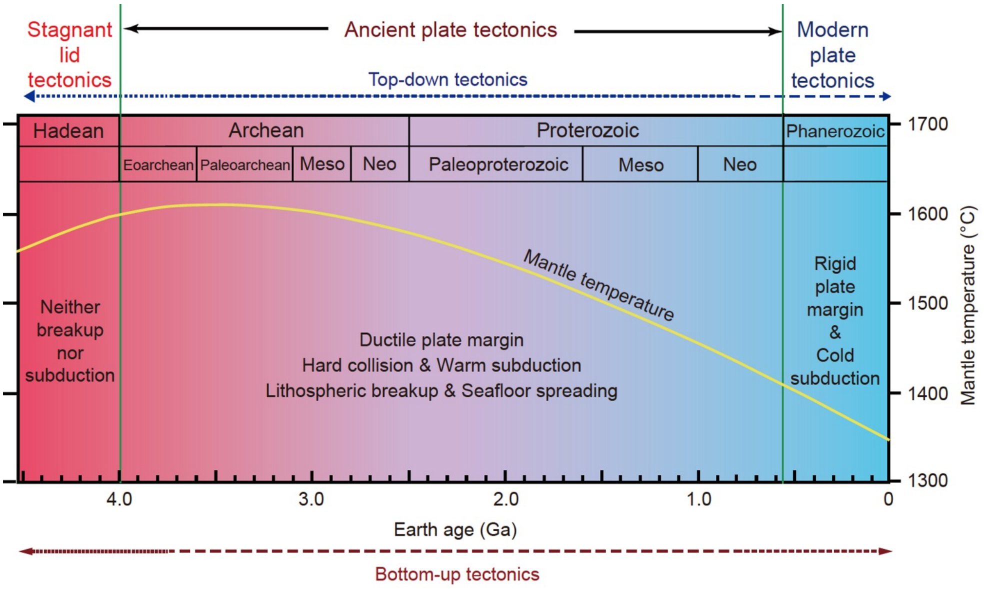
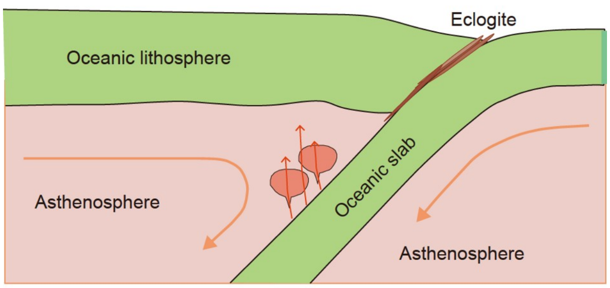


Figure 14 Secular changes of mantle temperature and tectonic regime in Earth's history (adapted after Cawood, 2020b). The temporal variation of thermal state in subduction and collisional zones since the Archean can be categorized into two phases, warm and cold, corresponding to ductile and rigid convergent plate margins, respectively (Zheng and Zhao, 2020).

significantly from the behavior of modern oceanic plates in the Phanerozoic, which are characterized by rigid plate margins resulting in cold subduction or soft collision. Combining this difference with the secular change of metamorphic T/P ratios at convergent plate margins (Brown and Johnson, 2019), Zheng and Zhao (2020) recognize that the significant difference in convective mantle temperature between the Phanerozoic and the Archean is a basic cause for the shortage of cold subduction products, represented by HP to UHP metamorphic rocks, such as low T/P Alpine type blueschists and eclogites, in the Precambrian. In contrast, warm subduction or hard collision processes, characterized by metamorphism at moderate geothermal gradients and metamorphic rocks such as medium T/P Barrovian type MP amphibolites and HP granulites, were prevalent from the Archean through the Proterozoic to the Phanerozoic (Figure 8). Therefore, Zheng and Zhao (2020) propose the classification of plate tectonics in Earth's history into two categories, ancient and modern (Table 1 and Figure 15), highlighting that cold subduction-dominated modern plate tectonics has prevailed in the Phanerozoic, whereas warm subduction- or hard collision-dominated ancient plate tectonics were more common in the Precambrian.

Although eclogites and blueschists of crustal cold subduction origin locally appear in the Paleoproterozoic (Glassley et al., 2014; Weller and St-Onge, 2017; Xu et al., 2018; Li et al., 2023) and Neoproterozoic (Stern, 2005, 2008; Brown, 2006; Brown and Johnson, 2019), they are far less voluminous than their counterparts in the Phanerozoic (Brown and Johnson, 2018, 2019; Holder et al., 2019). Combining this difference with the observation of Brown et al. (2020b) that metamorphic T/P ratios at convergent plate margins reach their lowest value around 540 Ma, Zheng (2023) placed the boundary between ancient and modern plate tectonics between the Phanerozoic and the Precambrian instead of within the Neoproterozoic or between the Neoproterozoic and Mesoproterozoic (Stern, 2005, 2008, 2018). Nevertheless, the Penrose-type ophiolites began to occur widely since 900 Ma (Condie and Stern, 2023), indicating that the oceanic crust has been significantly thinned since that time. In either case, ancient plate tectonics is generally equivalent to Precambrian plate tectonics, but its operational mode is different in the Mesoproterozoic (Roberts, 2013; Stern, 2020). Although cold subduction did take place in the Paleoproterozoic and Neoproterozoic, it has not been identified yet in the Mesoproterozoic. However, metamorphic T/P ratios reach their maximum in the Mesoproterozoic (Figure 8). This suggests that continental breakup metamorphism due to thinning of the lithospheric mantle was the most popular in this period, but it had not yet developed into the stage of seafloor spreading. Therefore, the tectonic move-

(a) Cold subduction/soft collision at rigid plate margin



(b) Warm subduction/hard collision at ductile plate margin

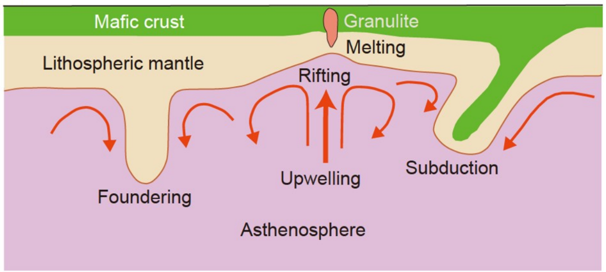


Figure 15 Schematic cartoons showing the relationship between thermal state and rheological property at convergent plate margins (revised from Zheng and Zhao, 2020). (a) Rigid plate margins in the Phanerozoic, resulting in cold subduction; (b) ductile plate margins in the Archean, resulting in warm subduction/hard collision.

Table 1 Differences between two styles of plate tectonics in Earth's history a)

Property	Modern plate tectonics	Ancient plate tectonics
Major operation time	Neoproterozoic	Archean
Convective mantle temperature	low	high
Thermal state of plat boundaries	cold	warm
Plate geometric size	huge	small
Rheology of plate margins	rigid	ductile
Width of mobile belts	small	large
Metamorphic facies series produced by subduction/collision	Alpine	Barrovian
Metamorphic rocks produced by subduction/collision	blueschist to eclogite	amphibolite to granulite

a) Revised from Zheng and Zhao (2020).

ment between continental plates in the Mesoproterozoic would primarily procced in the form of trandform faults on the basis of breakup-collision coupling systems (Zheng et al., 2022).

Moreover, ancient plate tectonics in the Archean is characterized by widespread TTG magmatism at convergent plate margins, whereas modern plate tectonics in the Phanerozoic is characterized by the appearance of basalt-andesite-dacite-rhyolite magmatism at active continental margins (Moreira et al., 2020; Zheng et al., 2022). Therefore, the significant difference between these two types of plate tectonics lies in the widespread occurrence of TTG crust and the existence of over-thick basaltic oceanic crust in the Archean, which are relatively lacking in the Phanerozoic. Although the compositional diversity of basaltic magmas above oceanic subduction zones is primarily determined by metasomatic reactions between subduction zone fluids and the mantle wedge (Zheng, 2019; Zheng et al., 2020), the amount of terrigeneous sediment components in the metasomatic agent is much lower in the Archean than in the Phanerozoic (Moreira et al., 2020). The andesitic component in continental crust can be produced in lithospheric rift zones, through either the crystal fractionation during the ascent of mantle-derived mafic magmas or the partial melting of basaltic intrusions (Zheng et al., 2022). For Archean plate tectonics, its distinguishing feature is not only the absence of low T/P Alpine type metamorphism (cold subduction) but also the scarcity of terrigeneous sediment components entering the mantle source of basaltic magmas, while the TTG rocks would widely result from partial melting of the thick and over-thick basaltic oceanic crust (Zheng et al., 2022).

While there are both large and small plates on modern Earth, traditional plate tectonics models emphasize the kinematics of large plates and often overlook the behavior of microplates (Li et al., 2018). Although microplates share similarities with large plates in terms of their kinematics, the tectonic transition from a stagnant lid to mobile lids depends on the nature of internal thermal expansion within the Earth (Tang et al., 2020). Uniform thermal expansion inside Earth leads to the formation of microplates, while non-uniform thermal expansion results in the formation of plates in various sizes. In any case, once the edge of a microplate is subjected to bolide impact, it becomes prone to subsidence. If the other end of the microplate is influenced by mantle poloidal convection, lithospheric rifting takes place. When both processes occur simultaneously, a coupled system of plate convergence and divergence can be established (Zheng, 2023), which is crucial for the initiation of ancient plate tectonics in the Eoarchean.

There is considerable controversy about the onset age of ancient plate tectonics in the Archean (e.g., Palin et al., 2020; Kuang et al., 2023; Zheng, 2023). The questions mainly focus on the following three aspects: (1) what are the similarities and differences between the Archean and Phanerozoic tectonic systems; (2) the proportions between objective and subjective components in the interpretations of geological observations and geochemical data; and (3) what are the problems in the methodology (including parameter adoption) of numerical geodynamic simulations. Therefore, there remain some uncertainties in the geological records and their interpretations for the initiation time of Archean plate tectonics (Korenaga, 2013; Cawood et al., 2018; Palin et al., 2020; Windley et al., 2021; Kuang et al., 2023; Zheng, 2023). The conundrum is what observations can serve as evidence for the existence of plate tectonics on early Earth? Generally, the oldest rock assemblages found on Earth, such as the western Pilbara superterrane in Australia (Smithies et al., 2005a, 2007) and the Isua greenstone belt in western Greenland (Nutman et al., 2021, 2022), are considered to be key pieces of evidence. Some studies interpret these rocks as products of plate tectonism, and others explain their geochemical data through subduction zone processes.

With respect to the island arc basalts-like trace element distribution patterns, they occur not only in Archean basaltic rocks (Sotiriou et al., 2022), but also in Archean granitic rocks (Sotiriou et al., 2023). In terms of the magma oxygen fugacity and water content, Ge et al. (2023) found similarities between Archean granitic rocks and modern island arc magmas, indicating the existence of Archean plate tectonics. On the other hand, some studies question the existence of plate tectonics in the Archean and emphasizes the existence of long-lived mantle plume volcanism in many Archean cratons (Hill et al., 1991; Smithies et al., 2005b). They argued that many TTG rocks are the product of intraplate reworking rather than originating from island arc magmatism (Bédard, 2006; Van Kranendonk et al., 2007, 2015; Johnson et al., 2014). In terms of trace element composition, the zircon of Hadean U-Pb ages exhibits some resemblance to zircon formed through crystal fractionation of modern island arc magmas, which has been used to argue for the existence of Hadean plate tectonics (Turner et al., 2020).

Zircon U-Pb ages and Hf-O isotope ratios have been used to estimate the growth rate of continental crust throughout Earth's history (e.g., Belousova et al., 2010; Dhuime et al., 2012; Korenaga, 2018). Zircon U-Pb ages were used to represent the time of crustal formation, zircon Hf isotope ratios were used to calculate the age of crustal extraction from the mantle (crust-mantle differentiation), and zircon O isotope ratios were used as filters for interactions between surface water and rocks. Indeed, zircon O isotope ratios reflect the O isotope composition of zircon and its crystallized magmatic rocks. Mantle-derived igneous rocks can change their O isotope ratios by incorporating crustal material that has interacted with surface water at either low or high temperatures. In general, higher O isotope ratios originate from either sedimentary rocks that have undergone chemical weathering or igneous rocks that have undergone water-rock interactions at low temperature. In contrast, lower O isotope ratios are only produced by hydrothermal alteration of igneous rocks at high temperatures. Through processes like crustal recycling in subduction zones or crustal reworking in rifting zones, crustal rocks can be introduced into the magmatic system, leading to the formation of zircons with either high or low O isotope ratios (e.g., Zheng et al., 2004; Valley et al., 2005; Wang et al., 2022b, 2022c).

In addition to magmatic zircon that grew from highly evolved silicate melts, peritectic zircon was often formed through peritectic reaction during crustal anatexis (Zheng and Gao, 2021). In either case, zircon U-Pb ages represent the timing of crustal reworking rather than the growth of juvenile basaltic crust. Therefore, zircon O isotope ratios cannot quantitatively track the crustal growth throughout Earth's history. However, zircon can form through magmatic crystallization, and magma emplacement can cause crustal reworking through the partial melting of either metasedimentary rocks or hydrothermally altered igneous rocks. Since this process does not lead to significant isotope fractionation in the rock-melt-magma-zircon system, zircon O isotope ratios serve as an effective indicator for assessing the crustal reworking in geological history. Nevertheless, this ratio is not a suitable indicator for the growth of juvenile crust.

Inspection of different proposed initiation ages for the operation of plate tectonics on early Earth suggests that the main issue lies in the growth mechanism of zircons and their host crust (Zheng, 2023). Although zircons are difficult to crystallize directly from primitive mantle-derived basaltic magmas, zircon growth can be achieved through either the crystal fractionation of basaltic magmas or the partial melting of basaltic rocks (Zheng and Gao, 2021). During the processes of stagnant lid breakup, not only magmatic differentiation but also crustal melting can take place (Kemp et al., 2010; Johnson et al., 2014). These two processes would occur when the stagnant lid could rupture without developing of distant microplate collision, or seafloor spreading not in concert with distant plate subduction, and a series of plate divergent-convergent coupling systems in both time and space would not be established on early Earth (Hansen, 2018; Capitanio et al., 2019a; Zheng, 2023). In this context, the earliest episodes of zircon growth and granitic crust formation in Earth's history could precede the first episode of ancient plate tectonism.

6. The operation of plate tectonics and the vertical motion of materials

After over half a century of effort, the traditional kinematic theory of plate tectonics established in the 20th century has evolved into a holistic kinematic-dynamic theory of plate tectonics in the 21st century (Zheng, 2023). This upgraded version emphasizes both vertical and lateral dimensions in terms of energy and material transport, both gravitational and buoyant forces in the dynamic framework, and early compressional and later extensional stages in the evolution of convergent plate margins. This version is applicable not only to Phanerozoic continental geology but also to Precambrian period (Zheng et al., 2022). For example, it can effectively explain the mechanisms and processes of growth and reworking of continental crust in the Phanerozoic, in which oceanic subduction zones and continental collision zones play major roles in the growth of continental crust (Moyen et al., 2021; Zheng and Gao, 2021). Subduction zones, through dehydration of the subducting oceanic slab and the metasomatism of the mantle wedge, form the source region of mafic arc magmas (Zheng, 2019; Zheng et al., 2020). These magmas, through fractional crystallization, give rise to the felsic crust (Moyen et al., 2021; Zheng et al., 2021). The closure of ocean basins leads to continental collision and deep subduction along convergent plate margins, where either rollback or breakoff of the subducting slab can induce upwelling of the asthenospheric mantle, resulting in lithospheric rifting and partial melting. Likewise, thinning of the lithospheric mantle through foundering processes such as delamination, dripping, sugduction and thermal erosion at fossil suture zones can also induce the asthenospheric upwelling, leading to continental rifting and crustal anatexis (Zheng et al., 2022, and references therein).

The origin of plates and continental crust in the Eoarchean represents two aspects of the same issue and is of the causal relationship in the mobile lid regime. In the Archean, oceanic crust and continental crust did not form simultaneously but grew sequentially. To be precise, the questions pertain to the origin of mafic crust (primarily basaltic) and felsic crust (primarily granitic). The mafic crust formed at first in the Hadean, and later transformed into the felsic crust. If we could define pre-plate tectonics using the stagnant lid framework (Figure 2), mantle plumes and heat pipes produced by mantle poloidal convection beneath the stagnant lid would be the dominant mechanisms for breakup of the stagnant lid into mobile lids. Bolide impacts might be the dominant mechanism for initiating subduction of the mobile lids. Vertical tectonics driven by buoyancy is related to mantle poloidal convection, and this process took place not only in the Archean but also in the Phanerozoic. Hence, vertical tectonism like mantle plumes and heat pipes is not the unique product of pre-plate tectonics. Once the stagnant lid splits into mobile lids, microplates are likely to form instead of large plates. Thus, Archean plate tectonics may be characterized by microplate tectonics (Ernst et al., 2016; Li et al., 2018). Plate convergence can lead either to further thickening of the pre-existing thick basaltic oceanic crust due to hard collision (Zheng et al., 2022) or to stacking when one plate subducts at a low angle beneath another plate (Perchuk et al., 2023).

The asthenosphere in early Earth was enclosed by a stagnant lid to have higher heat flow, whereas the lithosphere was of weak rigidity and strong ductility (Lenardic, 2018; Stern et al., 2018). Therefore, the stagnant lid underwent breakup due to endogenous processes like mantle plumes and heat pipes, subduction due to exogenous processes like bolide impacts, and localized vertical movements such as dripping and foundering at the lid base (Zheng et al., 2022). Although lithosphere breakup may be caused by thermal expansion due to mantle poloidal convection (Tang et al., 2020), the isolated processes of either divergence or convergence alone cannot achieve a successful transition from the stagnant lid regime to the mobile lid regime on early Earth, and thus, a system of plate tectonics characterized by the divergent-convergent coupling would not develop (Cawood et al., 2018; Hansen, 2018; Capitanio et al., 2019a; Zheng, 2023). It must evolve into a coupled system of breakup-collision or spreading-subduction (Figure 16) to achieve and maintain the conservation of both mass and momentum in plate motion. Only in this case can plate divergence be dynamically balanced with plate convergence in both time and space, allowing for plate tectonics to operate.

Is the mobile lid tectonic system equivalent to plate tectonics? If subduction is taken as the unique form of plate tectonism (Stern, 2005, 2008, 2018; Brown, 2006), then the mobile lid tectonics differs from plate tectonics. However, if the plate tectonics system follows the principles of divergent-convergent coupling (Cawood et al., 2018; Hansen, 2018; Capitanio et al., 2019a; Zheng, 2023), then mobile lid tectonics can be considered as a form of plate tectonics, albeit with significant differences in plate size. The earliest granitic crust may not necessarily be a product of plate tectonics but rather a result of partial melting of the basaltic crust during breakup of the stagnant lid, even before localized plate subduction had begun. Therefore, the origin of continental crust and the origin of plates were separate issues in the Hadean, but they became interconnected starting from the Eoarchean. Subduction on the one side must be complemented by spreading on the other side; otherwise, both processes cannot operate successfully. While bolide impacts on the plate margins can cause localized subsidence, they cannot enter a state of plate tectonism without complementary processes of breakup and spreading.

It is known that either heat pipes or mantle plumes cannot directly melt the mantle to generate large quantities of granitic magma for the formation of continental crust. Nevertheless, their heating of the basaltic crust overlying the thinned lithospheric mantle can induce partial melting through the dehydration-hydration coupling mechanism (Zheng and Gao, 2021), indirectly giving rise to granitic magmas. Once the lower part of the lithosphere beneath the stagnant lid underwent thinning, not only would its upper part undergo crustal anatexis to produce the granitic crust, but also would this thinned zone become a tectonic weak zone and even an active rift zone (Zheng and Chen, 2021; Zheng, 2023), which may further develop into the margin of mobile lids. Therefore, the generation of granitic crust on early Earth has witnessed the tectonic transition from the stagnant lid regime to the mobile lid regime, but the success or failure of this transition may be different in different regions.

Previous studies have found that most continental crust has grown relatively consistently between ca. 3.5 Ga and ca. 1.0 Ga (e.g., Condie et al., 2018; Garçon, 2021), and cratonic mantle was also formed in the same period (Pearson et al., 2021). Although granitic crust does not directly result from the partial melting of mantle peridotite (Zheng and Gao, 2021), it can be produced through the fractional crystallization of basaltic melts or the partial melting of basaltic

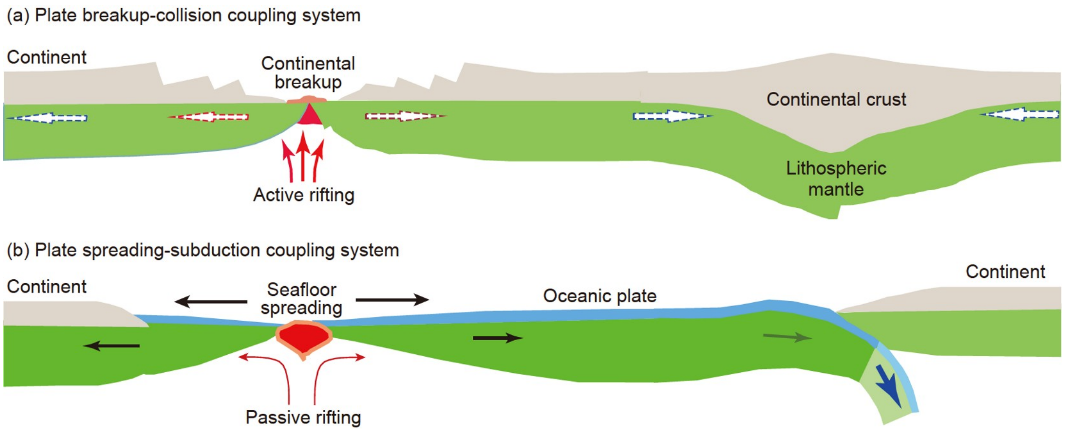


Figure 16 Schematic diagrams showing plate divergent-convergent coupling systems (revised from Zheng, 2023). The figure illustrates two types of plate tectonics systems: (a) the coupling between continental breakup and lithospheric collision resulting in compressional thickening; (b) the coupling between seafloor spreading and plate subduction to subarc depths.

crust (e.g., Moyen et al., 2021; Zheng et al., 2021). In particular, extraction of basaltic melts from the mantle leaves behind refractory peridotite as “keels” beneath Archean cratons (Perchuk et al., 2020). This melt-residue differentiation can explain the correspondence in age between continental crust growth and cratonic mantle formation from ~3.5 Ga to ~1.0 Ga (Pearson et al., 2021). Unfortunately, such coupled processes were separated into two independent processes in relevant studies: the production of ancient continental crust (Bauer et al., 2020) and the formation of cratonic lithospheric mantle (Timmerman et al., 2022). This led to the illusion that the production of ancient continental crust is not related to the formation of cratonic lithospheric mantle.

The appearance of granitic rocks in the Archean represents the vertical processes because they can result from either the fractional crystallization of mantle-derived basaltic magmas (Moyen et al., 2021) or the partial melting of basaltic crust (Zheng and Gao, 2021). The first generation of granitic crust on early Earth could be formed in the stagnant lid regime in the Hadean. It may be the product of magmatism due to the failure of lithospheric rifting in response to mantle plumes or heat pipes, or result from the partial melting of basaltic crust caused by bolide impacts. The second generation of granitic crust may be produced by lithospheric rifting magmatism during the tectonic transition from the stagnant lid regime to the mobile lid regime in the Eoarchean. Although neither of these processes is directly related to magmatism in subduction zones, the dynamic system in which they formed is not completely different from plate tectonics. Therefore, different tectonic systems can produce magmas with similar compositions, and similar tectonic systems can generate magmas with different compositions. This paradox needs to be considered when using mineralogical and geochemical compositions to reconstruct the initiation time of plate tectonics.

Subduction initiation is intimately related in both time and space to the onset of plate tectonics, but it is still not resolved how subduction starts on Earth. One possible mechanism is that the head of a hot, rising mantle plume impacts the base of the lithosphere, leading to the formation of a new subduction zone (Gerya et al., 2015; Whattam and Stern, 2015). Although numerical geodynamic simulations have been used to support mantle plume-induced subduction initiation (Baes et al., 2021), sinking of the cold lithosphere into the hot, ductile asthenosphere is an essential step in any model of subduction initiation. If the large low shear velocity provinces overlying the core-mantle boundary could serve as the source region of mantle plumes and their origin is related to accumulation of deeply subducted oceanic slabs (McNamara, 2019; Jackson and Macdonald, 2022; White, 2022), then there would be the causal relationship between plate subduction and mantle plume generation.

In nature, the impact of mantle plumes on the stagnant lid could first trigger rifting rather than subduction of the lid. After this, subduction initiation may take place through the gravitational sinking of one microplate beneath another, involving relatively vertical motion between two microplate margins (neither divergent mid-ocean ridges nor convergent collisional zones). It is only when one of the two microplates enters the ductile asthenosphere to form a coupled divergent-convergent system under the action of remote plate margin forces that subduction can further develop. In other words, the initiation of subduction is coupled with the initiation of spreading (Cawood et al., 2018; Hansen, 2018; Capitanio et al., 2019a; Zheng, 2023). Therefore, subduction initiation may be induced by the impact of mantle plume heads on the stagnant lid, leading to lithospheric rifting. As such, it is induced by the forces acting on the plates.

With the accumulation of studies focusing on magmatic processes in continental rift zones, it has been found that mantle hotspots are actually the manifestation of rapid rising of the anomalously hot asthenosphere (mantle poloidal convection) along former plate margins (Zheng, 2023), rather than hot deep-seated mantle plumes generated within plates (e.g., Foulger, 2010; Koppers et al., 2021). Similarly, upwelling of the asthenosphere along continental rifts, led to partial melting and the pinch-and-swell emplacement of granite-migmatite-granulite associations or metamorphic core complexes, which is the primary cause for the formation of intracontinental mountain ranges (Zheng and Chen, 2017, 2021). If the lithosphere contains mechanically weak zones, then this thermal impact mechanism is highly effective for active rifting (Zheng, 2023). Previous numerical geodynamic simulations on regional to global scales have suggested that floating of the asthenosphere above exceptionally hot mantle plumes and weakening of the lithosphere are prominent features in the formation of thinned and diverged plate margins (Gerya et al., 2015; Whattam and Stern, 2015; Baes et al., 2021). Although these studies provide valuable information on changes in lithospheric rheology due to mantle plume impacts, the rationality of concepts in models for the onset of plate tectonics is crucial for any geodynamic simulation of lithospheric breakup or subduction initiation in the context of plate divergent-convergent coupled systems (Cawood et al., 2018; Hansen, 2018; Capitanio et al., 2019a; Zheng, 2023). Therefore, caution must be exercised when interpreting certain geological observations and geochemical data as results of mantle plume-lithosphere interactions.

7. Plate tectonics interpretations of Archean geology

The application of the upgraded plate tectonics theory to explain the basic features of Archean geology is of significant importance for understanding of Archean tectonics and the Earth's evolution processes. Firstly, the distinctive setting of Archean tectonics is reflected in the occurrence of large-scale TTG rocks, gneissic dome-greenstone keel structures, the production of komatiites within greenstone belts, and the widespread distribution of high-grade metamorphic rocks in planar rather than zonal patterns. Secondly, the shortage of common Phanerozoic features such as the occurrence of Penrose-type ophiolites, blueschist-eclogite, and classic Miyashiro-type paired metamorphic belts indicates that Archean tectonics was considerably different from the modern one. Thirdly, these differences can provide insights into the internal state of the Archean Earth, which can help us understand the tectonic systems and heat flow at the margin of Archean plates. The mechanisms responsible for the formation of these features, and their differences and similarities with modern plate tectonics, can provide references for the study of the tectonic evolution on the modern Earth.

By examining the physical structure and chemical composition as well as the formation mechanisms of Archean crust and comparing them with Phanerozoic crust, we can figure out the following three characteristic features on the Archean Earth: (i) the convective mantle had temperature of about 200–300°C higher than that in the Phanerozoic (Herzberg et al., 2010; Ganne and Feng, 2017; Aulbach and Arndt, 2019); (ii) the juvenile basaltic oceanic crust had thickness of 30–40 km (Foley et al., 2003; van Thienen et al., 2004; Herzberg and Rudnick, 2012), significantly different from the 6–7 km thickness of Phanerozoic oceanic crust; (iii) the ordinary asthenosphere had composition similar to the primitive mantle rather than the depleted MORB mantle, giving rise to juvenile basaltic oceanic crust that is almost not depleted in melt-mobile incompatible trace elements (e.g., LILE and LREE), similar to transitional MORB and enriched MORB but different from normal MORB of Cenozoic age (Bickle et al., 1994; Pearce, 2008; Condie and Shearer, 2017; Furnes and Dilek, 2022). Only by combining these diagnostic characteristics with the upgraded plate tectonics theory can we reasonably explain the basic features of Archean geology.

(1) *The TTG rocks:* The origin of Archean TTG rocks can be explained as resulting from partial melting of the over-thick basaltic oceanic crust along Archean convergent plate margins (Li et al., 2021; Wang et al., 2022a, 2022b; Zheng et al., 2022). In Archean plate suture zones, the basaltic oceanic crust experienced hard collision for over-thickening before warm subduction (Figure 13a). Once the lithospheric mantle beneath the over-thick basaltic oceanic crust underwent thinning, the asthenospheric upwelling would heat the overlying crust, causing its partial melting under different P-T conditions and giving rise to felsic magmas with TTG compositions (Figure 13b). These magmas would then ascend and intrude into the overlying rocks due to buoyancy. According to the upgraded plate tectonics theory (Zheng, 2023), after the assembly of supercontinents, the lithospheric lid could remain relatively stagnant, and mantle plumes and heat pipes would be the result of abnormly high-temperature mantle poloidal convection. When applying this principle to Archean cratons, both mantle plumes and heat pipes could induce lithospheric rifting, heat the basaltic crust after thinning of the cratonic mantle, and cause partial melting to produce granitic magma, forming the TTG rocks. If high heat flow was transiently supplied to the lithospheric mantle after its thinning along convergent plate margins, the over-thick basaltic crust underwent rapid partial melting to produce massive TTG magmas forming the widely distributed TTG rocks in a relatively short timeframe with no systematic variations in composition.

(2) *The dome-keel structures:* The formation mechanism of Archean dome-keel structures is somehow similar in origin to the metamorphic core complexes in the plate suture zones of Phanerozoic. Both result from partial melting of the over-thick basaltic crust, which took place after thinning of the lithospheric mantle. This led to the production of granitic melts that entrained granulites and migmatites upwards. These granitic melts would then intrude into the overlying rocks due to their buoyancy (Zheng and Gao, 2021; Zheng et al., 2022). In this process, the greenstone belts look as if they would undergo the relatively gravitational subsidence. Therefore, both the generation of TTG magmas and the formation of gneissic domes are indirectly induced by asthenospheric upwelling consequential to thinning of the lithospheric mantle along fossil suture zones. Partial melting of the mantle material itself cannot form TTG magmas through the lithospheric thinning.

(3) *The komatiites:* These komatiites within greenstone belts may result from decompressional melting of the abnormly high-temperature convective mantle beneath divergent plate margins in the Archean. Their magma sources may contain deep-seated primitive mantle components. Because the Archean convective mantle temperature was 200–300°C higher than the Phanerozoic one, according to the upgraded plate tectonics theory (Zheng, 2023), material from the deep mantle can rapidly rise through poloidal convection onto the base of the lithosphere, where it causes active rifting and decompressional melting, giving rise to the komatiitic magmas.

(4) *The planar distribution of high-grade metamorphic rocks:* The formation mechanism of this feature involves the high heat flow along fossic suture zones. Compared to the modern Earth, the Archean convective mantle had a higher temperature, leading the plate suture zones affected by lithospheric rifting to much larger width in the Archean than in the Phanerozoic. Consequently, the formed dome-keel structures might also be much larger. If these dome-keel

structures could be later subjected to wrench faults, the exposed gneissic domes would tend to have a planar distribution.

(5) *The shortage of calc-alkaline andesites in bimodal volcanic associations:* This feature can be explained by the absence of modern-style oceanic-continental subduction zones in the Archean (Wang et al., 2022a). In the modern Earth, the formation of continental arc calc-alkaline andesites is strongly associated with oceanic-continental subduction zones where there are abundant accretionary wedges consisting of terrigeneous sediments (Chen and Zhao, 2017; Zheng et al., 2020; Chen et al., 2021). In the Archean, however, due to the crustal composition being basaltic rather than granitic and to the absence of continental lithosphere, there were short of oceanic-continental subduction zones. As a consequence, no magma source of andesitic magmas was generated by metasomatic reaction of the mantle wedge with subducting terrigeneous sediment-derived melts. Therefore the volcanic products of the Archean magmatism were short of the calc-alkaline andesites and instead consist of rare bimodal volcanic rocks.

(6) *The absence of Penrose-type ophiolites:* Ophiolites in the Phanerozoic are characterized by mid-ocean ridge rock assemblages in petrology, being mainly manifested as basaltic volcanic-intrusive rock sequences. They result from decompressional melting of asthenospheric mantle at shallow depth, giving rise to the oceanic crust with a thickness of only 6–7 km. In addition, they exhibit island arc type trace element compositions in geochemistry, which are attributable to fluid metasomatism subsequent to the tectonic transition from seafloor spreading along the mid-ocean ridge to oceanic subduction along the newly formed trench, making them indicative of modern subduction initiation (Furnes and Dilek, 2022; Zheng et al., 2022; Condie and Stern, 2023). The issue concerning the absence of Penrose-type ophiolites in the Archean is associated with the absence of large intrusive sheets, which has different explanations in the literature (Furnes and Dilek, 2022; Condie and Stern, 2023; Kusky and Şengör, 2023). A possible explanation is that during the subduction initiation of microplates through the tectonic transition from divergent margins (mid-ocean ridges) to convergent margins (subduction zones), only the upper volcanics of the basaltic crust as thick as 30–40 km were offscrapped to form basalt accretionary wedges, whereas the lower intrusives were subducted together with the underlying peridotites beneath the overlying microplates.

(7) *The absence of blueschists and eclogites:* Blueschists and eclogites are characteristic metamorphic products of cold subduction zones on the modern Earth, indicating the lowest geothermal gradients at plate interfaces when one lithosphere subducts beneath another (Zheng and Chen, 2017, 2021). The absence of these two types of metamorphic rocks in the Archean suggests that if plate subduction could occur in the Archean, the plate interface would have moderate geothermal gradients and thus bring about the features of warm subduction or hard collision of the thick oceanic crust (Zheng and Zhao, 2020; Zheng and Chen, 2021; Zheng et al., 2022).

(8) *The shortage of classic Miyashiro-type paired metamorphic belts:* Miyashiro-type paired metamorphic belts mostly occur in the Phanerozoic, whereas Brown-type paired metamorphic belts are popular from the Archean through the Proterozoic to the Pherozoic (Figure 8). This difference indicates that some of plates on the modern Earth would initially experience cold subduction to cause low T/P Alpine type metamorphism at low geothermal gradients and then undergo lithospheric hot rifting, causing the crust to undergo high T/P Buchan type metamorphism at high geothermal gradients (Zheng and Chen, 2021). In contrast, the occurrence of Brown-type paired metamorphic belts suggests that convergent plate margins underwent the tectonic evolution from medium T/P Barrovian type metamorphism at moderate geothermal gradients due to either warm subduction stacking of the oceanic lithosphere or hard collision thickening of the basaltic crust to high T/P Buchan type metamorphism at high geothermal gradients due to backarc or continental hot rifting consequential to thinning of the lithospheric mantle (Zheng and Chen, 2021).

A great deal of studies have been devoted to the magmatic rocks of Archean greenstone belts and gneissic domes, leading to various models for their petrogenesis. As far as the greenstone belt rocks are concerned, there are mainly the mid-ocean ridge model during seafloor spreading, the island arc model during oceanic subduction, and the oceanic plateau model during mantle plume ascent. For TTG rocks, the major models are the crystal fractionation of island arc basaltic magmas, the partial melting of oceanic plateau basalts, and the partial melting of the overthick oceanic crust along convergent plate margins. Regardless of the model, the basaltic magmas were basically generated at either divergent or converging plate boundaries, whereas TTG magmas were basically produced at converging plate margins. An integrated study of these observations and their interpretations provides geological evidence for the operation of ancient plate tectonics in the Archean.

Along the disvergent plate boundaries of Archean, the convective mantle would partially melt to form the oceanic crust of 30–40 km thick, which is mainly similar in composition to enriched MORB that are indistinguishable from modern oceanic plateaus on the one hand, and contain deep mantle-derived komatiites on the other hand. Along Archean convergent plate margins, the thick oceanic crust was further thickened to 60–70 km by hard collision to form the source area of TTG magmas, and its warm subduction would release fluids metasomatizing the overlying mantle wedge to form the source area of island arc basaltic magmas. Due to the high temperature of the Archean convective mantle, the oceanic slab was only subducted at low angles or even in flat subduction under the action of buoyancy, often forming stacked lithospheres. Although it was difficult to cause oceanic arc magmatism, it would lay a material foundation for lithospheric cratonization. If the plate convergent rate or the convective mantle temperature could change, the warmly subducting slab would roll back to induce the lateral convection of the asthenospheric mantle toward the bottom of the mantle wedge, leading to island arc magmatism. Therefore, whether it is the hard collision or the warm subduction, these two processes would lay the source foundation for the magmatiam along plate margins. With respect to the occurrence of overthick oceanic crust along the convergent plate margins, it can be caused by lateral accretion of either oceanic island arcs or oceanic plateaus, or the collision of thick oceanic crust. In this regard, the partial melting of the overthick oceanic crust itself to produce TTG magmas does not require subduction. As such, it appears that the origin of Archean continental crust is decoupled from plate subduction.

A growing number of geological observations and geochemical data point to the operation of plate tectonics in the Neoarchean (e.g., Brown et al., 2020a; Huang et al., 2020, 2022; Ning et al., 2022; Wang et al., 2022a; Wu et al., 2022; Zhong et al., 2023). However, it still remains to be confirmed how ancient plate tectonics would operate during the whole Archean period. Therefore, further studies are needed to deepen our understanding of Archean plate tectonics, specifically focusing on the following six aspects. (a) Even though ancient plate tectonics began in the Eoarchean, is the granitic crust of all Archean ages the product of ancient plate tectonism? (b) While ancient plate tectonics was established in the Archean, was there the difference in different stages of the entire Archean era? (c) Whether did both warm subduction and hard collision of microplates proceed contemporaneously in the Archean? (d) Which mechanism was predominated for Archean crust-mantle differentiation between tholeiitic magmatism along divergent plate margins and calc-alkaline basaltic magmatism along convergent plate margins? (e) Is there a coupling relationship in both time and space between the chemical differentiation of basaltic crust and the reorganization of ancient plates in the Archean? (f) Did mantle convection in the Archean proceed on the whole scale rather than the layered scale?

8. Conclusions

While the traditional plate tectonics theory established in the 20th century can explain the assembly and dispersion of supercontinents and relevant geological processes in the Phanerozoic, it has faced significant challenges in explaining the fundamental geological characteristics of Archean cratons. However, considering the characteristic features of the Archean Earth, such as the higher convective mantle temperature by 200–300°C compared to the Phanerozoic, the juvenile basaltic crust as thick as 30–40 km and the asthenosphere had composition similar to the primitive mantle rather than the depleted MORB mantle, these challenges find resolution in the face of plate tectonics theory upgraded in the 21st century. For instance, the origin of TTG rocks can be explained by partial melting of the over-thick basaltic crust at convergent plate margins. The vertical movement of materials reflected in the formation of gneissic domes can result from the ascent of TTG magmas due to their buoyancy. Komatiites within greenstone belts may derive from decompressional melting of the abnormally high temperature mantle due to its poloidal convection under the regime of ancient plate tectonics. The shortage of andesites in the bimodal volcanic rock associations can be ascribed to the shortage of sediment accretionary wedges derived from weathering and erosion of the hangwall continental crust in the trench of Archean. The absence of Penrose-type ophiolites suggests that during the subduction initiation of microplates, only the upper volcanic rocks of the thick oceanic crust was offscrapped to form basalt accretionary wedges. The absence of blueschists and eclogites, as well as the classic Miyashiro-type paired metamorphic belts, indicates that convergent plate margins in the Archean experienced either collisional thickening or warm subduction of the thick basaltic crust at moderate geothermal gradients. Similar geological features are commonly observed on the modern Earth, and the upgraded plate tectonics theory can provide reasonable explanations for these features. All of these suggest that continental crust on early Earth would not originate from subduction zones in the traditional plate tectonics theory. Instead, it would mostly originate from oceanic collision zones under the regime of ancient plate tectonics and minorly from lithospheric rifting zones during the tectonic transition from stagnant to mobile lid regimes.

The study of the relationship between ancient plate tectonics and the origin of continental crust has faced considerable challenges due to the relative scarcity of granitic crust on early Earth. The geological records reflecting the early Earth's conditions, such as rock assemblages, structural patterns and metamorphic evolution, are limited due to later physicochemical modifications and tectonic destruction. Some geological observations and geochemical data reflecting the tectonic settings often lack a unique interpretation and frequently possess multiple solutions. Numerical geodynamic simulations are a useful means in studying the regime of plate tectonics and the origin of continental crust. However, there is ample room for improvement in model selection and its integration with geological reality. In order to acquire innovative achievements for the operation of plate tectonics in the Archean, hence, it is essential to understand and comprehend the nature of plate tectonics and the origin of continental crust on early Earth. In doing so, it is necessary to enhance the interdisciplinary fusion between geology, geochemistry, geophysics and geodynamics from both macroscopic and microscopic perspectives. While Chinese scientists did not participate in the establishment of plate tectonics theory in the 1960s, they have been working hard in the study of plate tectonics regimes as well as the formation and evolution of continental crust over the past 40 years, making active contributions to the development and rationalization of plate tectonics theory in the 21st century.

Acknowledgements *Thanks are due to Peter CAWOOD, Tim KUSKY, Mingguo ZHAI, Guochun ZHAO, Yusheng WAN, Sanzhong LI, Xiaolei WANG, Bo WAN, Peng PENG, Shaobing ZHANG and Xi WANG for their comments on various versions of this article. This study was supported by the National Natural Science Foundation of China (Grant No. 92155306).*

Conflict of interest The authors declare that they have no conflict of interest.

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(Editorial handling: Maoyan ZHU)