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GR focus review

Precambrian geodynamics: Concepts and models

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ABSTRACT

In contrast to modern-day plate tectonics, studying Precambrian geodynamics presents a unique challenge as currently there is no agreement upon paradigm concerning the global geodynamics and lithosphere tectonics for the early Earth. This review is focused on discussing results of recent modeling studies in the context of existing concepts and constraints for Precambrian geodynamics with an emphasis placed on three critical aspects: (1) subduction and plate tectonics, (2) collision and orogeny, and (3) craton formation and stability. The three key features of Precambrian Earth evolution are outlined based on combining available observations and numerical and analogue models. These are summarized below:

- Archean geodynamics was dominated by plume tectonics and the development of hot accretionary orogens with low topography, three-dimensional deformation and pronounced gravitational tectonics. Mantle downwellings and lithospheric delamination (dripping-off) processes are likely to have played a key role in assembling and stabilizing the hot orogens on a timescale up to hundreds of millions of years. Both oceanic-like and continental-like lithospheres were rheologically weak due to the high Moho temperature (>800 °C) and melt percolation from hot partially molten sublithospheric mantle.
- Wide spread development of modern-style subduction on Earth started during Mesoarchean–Neoarchean at 3.2–2.5 Ga. This is marked by the appearance of paired metamorphic complexes and oldest eclogite ages in subcontinental lithospheric mantle. Numerical models suggest that the transition occurred at mantle temperatures 175–250 °C higher than present day values, and was triggered by stabilization of rheologically strong plates of both continental and oceanic type. Due to the hot mantle temperature, slab break-off was more frequent in the Precambrian time causing more episodic subduction compared to present day.
- Wide spread development of modern-style (cold) collision on Earth started during Neoproterozoic at 600–800 Ma and is thus decoupled from the onset of modern-style subduction. Cold collision created favorable conditions for the generation of ultrahigh-pressure (UHP) metamorphic complexes which become widespread in Phanerozoic orogens. Numerical models suggest that the transition occurred at mantle temperatures 80–150 °C higher than present day values and was associated with stabilization of the continental subduction. Frequent shallow slab break-off limited occurrence of UHP rocks in the Precambrian time.

Further progress in understanding Precambrian geodynamics requires cross-disciplinary efforts with a special emphasis placed upon quantitative testing of existing geodynamic concepts and extrapolating back in geological time, using both global and regional scale thermomechanical numerical models, which have been validated for present day Earth conditions.

Contents

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1. Introduction

Precambrian geodynamics stands as an intriguing and controversial issue and currently represents a fundamental barrier in furthering our understanding of how the Earth evolved through time. The lack of consensus regarding Precambrian geodynamics and the continuing controversy primarily can be associated to the scarcity of natural data related to this tectonic regime. Geodynamics aims at understanding the evolution of the Earth's interior and surface over time. A time–depth diagram (see Fig. 1) covering the entire Earth's history and interior can schematically represent this evolution. For a systematic characterization of geodynamic relationships, the entire diagram should be "covered" by data points characterizing the physical–chemical state of the Earth at different depths (ranging from 0 to 6000 km), for different moments in geological time (ranging from 0 to around 4.5 billion years ago). However, the unfortunate fact for geodynamics is that observations for such a systematic coverage are only available along two axes: geophysical data provides the present-day Earth structure and the geological record preserved in rocks formed close (typically within few tens of kilometers) to the Earth's surface. The rest of the diagram is fundamentally devoid of observational data (see the time span of the Precambrian geodynamics in Fig. 1). Not surprisingly, therefore, the topic of Precambrian geodynamics remains controversial. One should also note that four critical questions strongly linked to the evolution of the Precambrian Earth appear among the top 10 questions defining 21st century Earth sciences (DePaolo et al., 2008):

- "What happened during Earth's "dark age" (the first 500 million years)? Scientists believe that another planet collided with Earth during the late stages of its formation, creating debris that became the moon and causing Earth to melt down to its core. This period is critical to understanding planetary evolution, especially how the Earth developed its atmosphere and oceans, however scientists have little information because few rocks from this age are preserved."
- "How did life begin? The origin of life is one of the most intriguing, difficult, and enduring questions in science. The only remaining evidence of where, when, and in what form life first appeared springs from geological investigations of rocks and minerals."
- "How does the Earth's interior work, and how does it affect the surface? Scientists know that the mantle and core are in constant convective motion. Core convection produces the Earth's magnetic field, which may influence surface conditions, and mantle convection causes volcanism, seafloor generation, and mountain building. However, scientists can neither precisely describe these motions, nor calculate how they were different in the past, hindering scientific understanding of the past and prediction of Earth's future surface environment."
- "Why does Earth have plate tectonics and continents? Although plate tectonic theory is well established, scientists wonder why Earth has plate tectonics and how closely it is related to other aspects of Earth, such as the abundance of water and the existence of the continents, oceans, and life. Moreover, scientists still do not know how and when continents first formed, how they remained preserved for billions of years, or how they are likely to evolve in the future."

In this review, I will concentrate on the last two questions where significant progress has occurred in the recent decade. This progress has been fueled by both the dramatic increase in the quality and the quantity of geological, geochemical, petrological and geochronological data for Precambrian rock complexes and the ongoing development of analogue and numerical models for the early Earth dynamics (e.g., Benn et al., 2006; van Kranendonk, 2011; van Hunen and Moyen, 2012 and references therein). Taking into account the

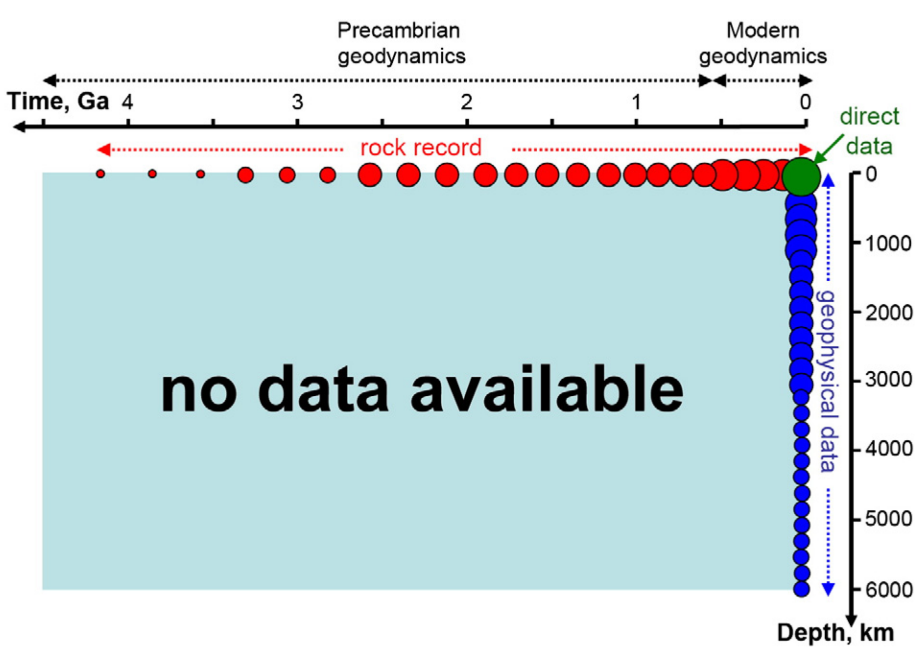

Fig. 1. Time–depth diagram presenting availability of data for constraining geodynamic relationship for the Earth. Size of data points reflect abundance of available data. This is obviously a simplified view since for a spherical Earth such a diagram should be four-dimensional.

fundamental scarcity of observational constrains (Fig. 1), modeling naturally plays an ever increasingly important role in developing and testing geodynamic hypotheses aimed at explaining the evolution of the early Earth. Indeed, as pointed out by Benn et al. (2006) the remaining special challenge of Precambrian geodynamics is that we do not necessarily have a successful paradigm of global geodynamics and lithosphere tectonics for the early Earth (c.f. modern-day plate tectonics) within which we can integrate and validate using our continually expanding set of observational and analytical data.

Since the comprehensive overview of Archean geodynamics by Benn et al. (2006), a number of new important results have been obtained to address this special challenge based mainly on combining geochemical, geological, petrological and geophysical data with results of analogue and numerical models that stimulated this relatively short, up to date synthesis of Precambrian geodynamics. The focus of this review is on discussing results of recent modeling studies in the context of existing concepts and constraints for Precambrian geodynamics. Due to the very broad scope of the topic, this review will primarily concentrate on recent advances in the following three critical topics:

- Subduction and plate tectonics,
- Collision and orogeny,
- Craton formation and stability.

2. Subduction and plate tectonics

Modern-style plate tectonics can be tracked into the geologic past using petrotectonic assemblages and other platetectonic indicators (e.g., Brown, 2006, 2007; Stern, 2007; Condie and Kröner, 2008; van Hunen and Moyen, 2012 and references therein). These indicators suggest that modern plate tectonics were operational, at least in some locations on the planet, by 3.0 Ga, or even earlier, and that they became widespread by 2.7 Ga (Condie and Kröner, 2008). The following fundamental questions regarding Precambrian plate tectonics and subduction have been the subject of much recent debate (e.g., Davies, 1992; Hamilton, 1998; de Wit, 1998; Griffin et al., 2003; Davies, 2006; Brown, 2006, 2007; Stern, 2007; O'Neill et al., 2007a, b; van Hunen and van den Berg, 2008; Condie, 2008; Halla et al., 2009; Sizova et al., 2010; Gerya, 2011; van Hunen and Moyen, 2012):

- What was the reason that the Earth developed a plate tectonic regime?
- What was the timing of the transition to the plate tectonic regime on Earth?
- What were the differences between Precambrian subduction compared to modern day subduction?

The main arguments about the timing of plate tectonic initiation have been based on the interpretation of geological, petrological and geochemical observations (Benn et al., 2006; Condie and Pease, 2008; Condie and Kröner, 2008). However, the interpretation of these geological observations has not yet achieved a consensus regarding the style of the tectonic regime in the Precambrian. On one hand, there is a variety of evidence for Archean, particularly Mesoarchean-to-Neoarchean, plate tectonics and subduction settings (e.g., de Wit, 1998; Brown, 2006; Condie and Pease, 2008; Moyen and van Hunen, 2012), however some authors argue that the modern style of subduction has only been active since the appearance of ophiolites in the Proterozoic and ultrahigh-pressure metamorphism in the late Neoproterozoic (Hamilton, 1998; Stern, 2005, 2007). It has also been suggested that it is unlikely that plate tectonics began on Earth as a single global "event" at a distinct time, but rather it is probable that it began locally and progressively became more widespread from the early to the late Archean (Condie and Kröner, 2008).

Recent reviews by Gerya (2011) and van Hunen and Moyen (2012) identify the necessity for the integration of observational constraints from a wide range of disciplines, together with results of geodynamic modeling, for a complete understanding of Precambrian geodynamics. It should be emphasized that only recently have thermomechanical numerical experiments been used to investigate the onset and the styles of Precambrian plate tectonics and subduction (e.g., van Thienen et al., 2004; Davies, 2006; O'Neill et al., 2007a, b; Sleep, 2007; van Hunen and van den Berg, 2008; Halla et al., 2009; Moyen and van Hunen, 2012; Sizova et al., 2010, this volume). Consequently, numerical models of Precambrian plate tectonics and possible styles of subduction in a hotter, early Earth are a relatively recent area of research in the computational geodynamics community. Van Thienen et al. (2004) published one of the prominent efforts to use numerical modeling to investigate global tectonic styles of the early Earth. This study was motivated by the idea that present-day geodynamics cannot simply be extrapolated back to the early history of the Earth because of the highly different temperature and viscosity conditions present within the mantle of the early Earth. Van Thienen et al. (2004) used numerical thermochemical convection models, including partial melting and a simple mechanism for melt segregation and oceanic crust production, to investigate an alternative suite of dynamics which may have been operational in the early Earth. The numerical experiments suggested that three processes may have played an important role in the production and recycling of oceanic crust (Fig. 2):

(1) Small-scale convection involving the lower crust and shallow upper mantle. Partial melting and thus crustal production takes place in the upwelling limb and delamination of the eclogitic lower crust in the downwelling limb.
(2) Large-scale resurfacing events in which (nearly) the complete crust sinks into the (eventually lower) mantle, thereby forming a stable reservoir enriched in incompatible elements in the deep mantle. New crust is simultaneously formed at the surface from segregating melt.
(3) Intrusion of lower mantle diapirs with a high excess temperature (about 250 K) into the upper mantle, causing massive melting and crustal growth. This allows for plumes in the Archean upper mantle with a much higher excess temperature than previously expected from theoretical considerations.

Numerical models also suggested that large-scale crustal sinking generates an enriched reservoir in the lower mantle which remains stable for approximately hundreds of millions of years (Fig. 2). A number of geodynamical models have been proposed which feature a dense enriched layer at the base of the mantle (Coltice and Ricard, 1999; Kellogg et al., 1999; Van der Hilst and Karason, 1999; Albarede and Van der Hilst, 2002). Van Thienen et al. (2004) suggested that such a layer may have been formed during a short time window in the early evolution of the Earth's mantle by large scale sinking of the thick basaltic/eclogitic crust produced by decompression melting of mantle peridotite. The large scale crustal sinking model of Van Thienen et al. (2004) may thus represent an alternative (or precursor) of the subduction model proposed by Albarede and Van der Hilst (2002). It should be noted that large scale sinking (delamination) of the lower crust in numerical models often resembles subduction (Fig. 2, 232.2 Myr) and may indeed represent a Precambrian precursor of modern day plate tectonics.

Further numerical exploration of the early mantle depletion was performed by Davies (2006) on the basis of 2D models with kinematically prescribed motion of the oceanic plates, thereby mimicking subduction (Fig. 3a, b). These models were aimed at addressing the extent of mixing of subducted mafic (oceanic) crust in the hot, early mantle. The results of these experiments, performed at different mantle temperatures ranging from 1300 °C to 1650 °C, suggested that for the hotter mantle temperature (characteristic for the early

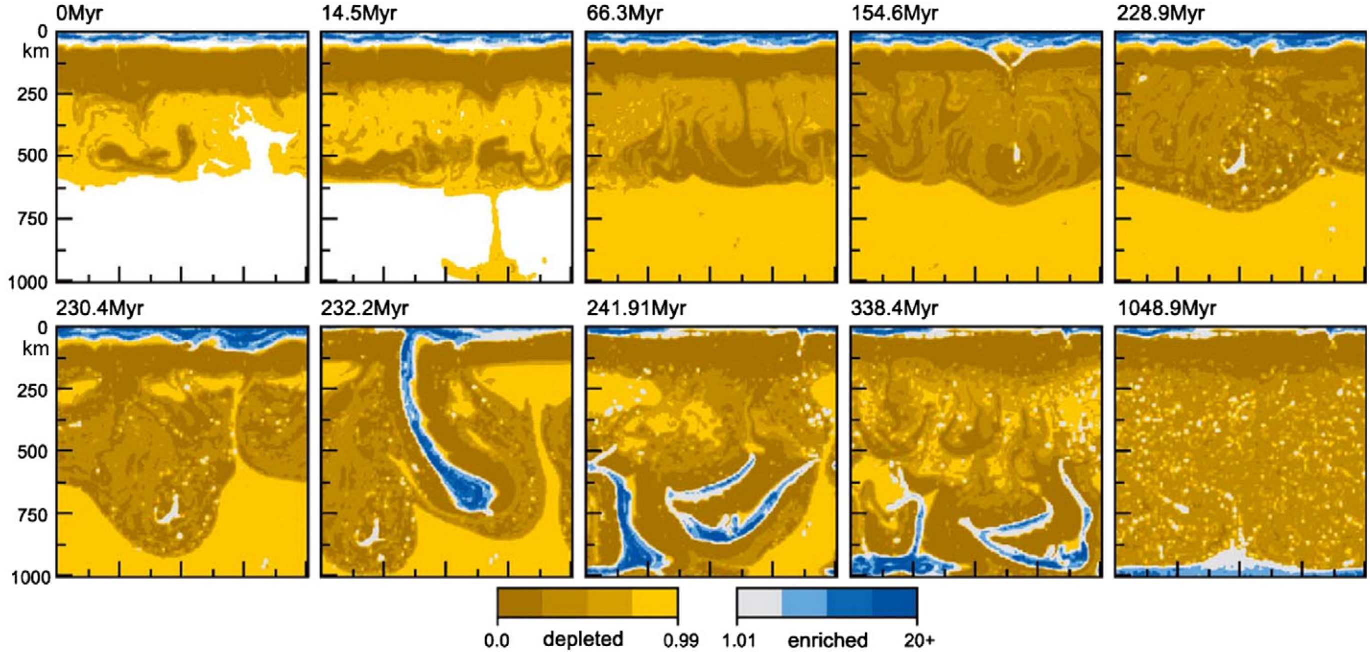

Fig. 2. 2D numerical model of coupled crust–mantle dynamics in the early Earth showing the large-scale sinking of the eclogitic crust into the mantle (van Thienen et al., 2004). Color code shows the geochemical differentiation of the model. Fertile mantle is white, mantle depleted in trace elements is yellow, and the enriched melt products (crust) are blue.

Earth), the upper mantle is strongly depleted of mafic components due to gravitational settling, while the lower mantle becomes marginally enriched, with a thin dense layer at the base (Fig. 3c,d). These results are in accordance with the very early and strong depletion of incompatible trace elements in the mantle source of the oldest rocks (Harrison et al., 2005). The results also support a geochemical argument (Campbell, 2002) that the depletion is associated more to the extraction of mafic material, rather than of continental crust. An important prediction from these models (Fig. 3e) is that the strong depletion would yield a thin (~3 km) oceanic crust, despite the high temperature of the mantle, which would make early plate tectonics more viable (Davies, 2006). Davies (2006) however does state that the numerical results and inferences draw upon them need to be confirmed by a more extensive examination of the parameter space, and that 3D models are also required.

The possible episodicity of Precambrian subduction has been investigated numerically by O'Neill et al. (2007a). This study was motivated by the observation that the Precambrian geological record shows peaks of activity at 1.1, 1.9–2.1, 2.7 and 3.5 Ga, often associated with massive crustal production, orogenesis and supercontinent cycles (e.g., Condie, 2004; Kemp et al., 2006). These periods of activity have been previously attributed to mantle overturn (avalanche) events, where the dynamic layering of the mantle, induced by the spinel to perovskite + magnesiowustite phase transition at 670 km, periodically breaks down and a catastrophic breakthrough of slabs occurs within a short-lived period of whole mantle convection. The hypothesis predicting an increase in plume activity associated with these overturns is supported by Nd and Sr isotope ratios of many juvenile terrains (Stein and Hofmann, 1994), and also provides a scenario for the cratonization of these terrains. Other alternatives have been put forward to explain this episodicity, such as superplumes (Condie, 2004). In contrast to previous studies, O'Neill et al. (2007a) presented paleomagnetic evidence for periods of rapid plate motions coinciding with the observed peaks in crustal age distribution and suggested an alternative explanation for the crustal growth episodicity. According to their concept supported by 2D numerical simulations, higher mantle temperatures result in lower lithospheric stresses, causing rapid pulses of subduction interspersed with periods of relative quiescence. Plate-driven episodicity naturally arises for hotter mantle temperatures of the early Earth and can thus explain rapid pulses of plate motion and crustal production without the need to invoke mantle overturn events (O'Neill et al., 2007a).

The viability of subduction in the hotter Precambrian Earth was recently investigated numerically by van Hunen and van den Berg (2008) using 2D thermomechanical models containing a single subduction zone, prescribed by a weak fault (Fig. 4). In contrast to Davies (2006) this model did not take into account early depletion of the upper mantle, but instead tested possible variations in crustal thickness ranging from 10 to 22 km. According to this study, it was not the influence of compositional buoyancy, but lithospheric weakness caused by the mantle temperature increase, which could be the principal factor in controlling the viability of plate tectonics in a hotter Earth. Numerical results, suggested a new explanation for the absence of ultrahigh-pressure metamorphism (UHPM) and blueschists in most of the Precambrian: early slabs were too weak (rather than too buoyant) to provide a mechanism for UHPM and exhumation. Modeling by van Hunen and van den Berg (2008) suggests that the lower viscosity and higher degree of melting for a hotter, fertile mantle might have led to both a thicker crust and a thicker depleted harzburgite layer making up the oceanic lithosphere. A thicker lithosphere might have been a serious limitation to the initiation of subduction, and a different mode of downwelling (Davies, 1992) or "sub-lithospheric" subduction (van Hunen and van den Berg, 2008) might have characterized Earth in the Precambrian, although the conversion of basalt to eclogite may significantly relax this limitation (e.g., van Thienen et al., 2004; Ueda et al., 2008). The intrinsic lower viscosity of the oceanic lithosphere on a hotter Earth would also lead to more frequent slab breakoff (Fig. 4), and in some cases crustal separation from the mantle lithosphere. Therefore, lithospheric weakness could be the principal limitation on the viability of modern-style plate tectonics on a hotter Earth.

Inferences from the numerical study by van Hunen and van den Berg (2008) were further explored by Halla et al. (2009) for constraining the early Neoarchean (2.8–2.7 Ga) plate tectonics by integrating knowledge from geochemical observations and numerical models. Based on numerical experiments, a possible tectonic scenario for the genesis of three groups of Archean granitoids from the Karelian and Kola cratons of the Fennoscandian Shield was suggested; namely, an incipient

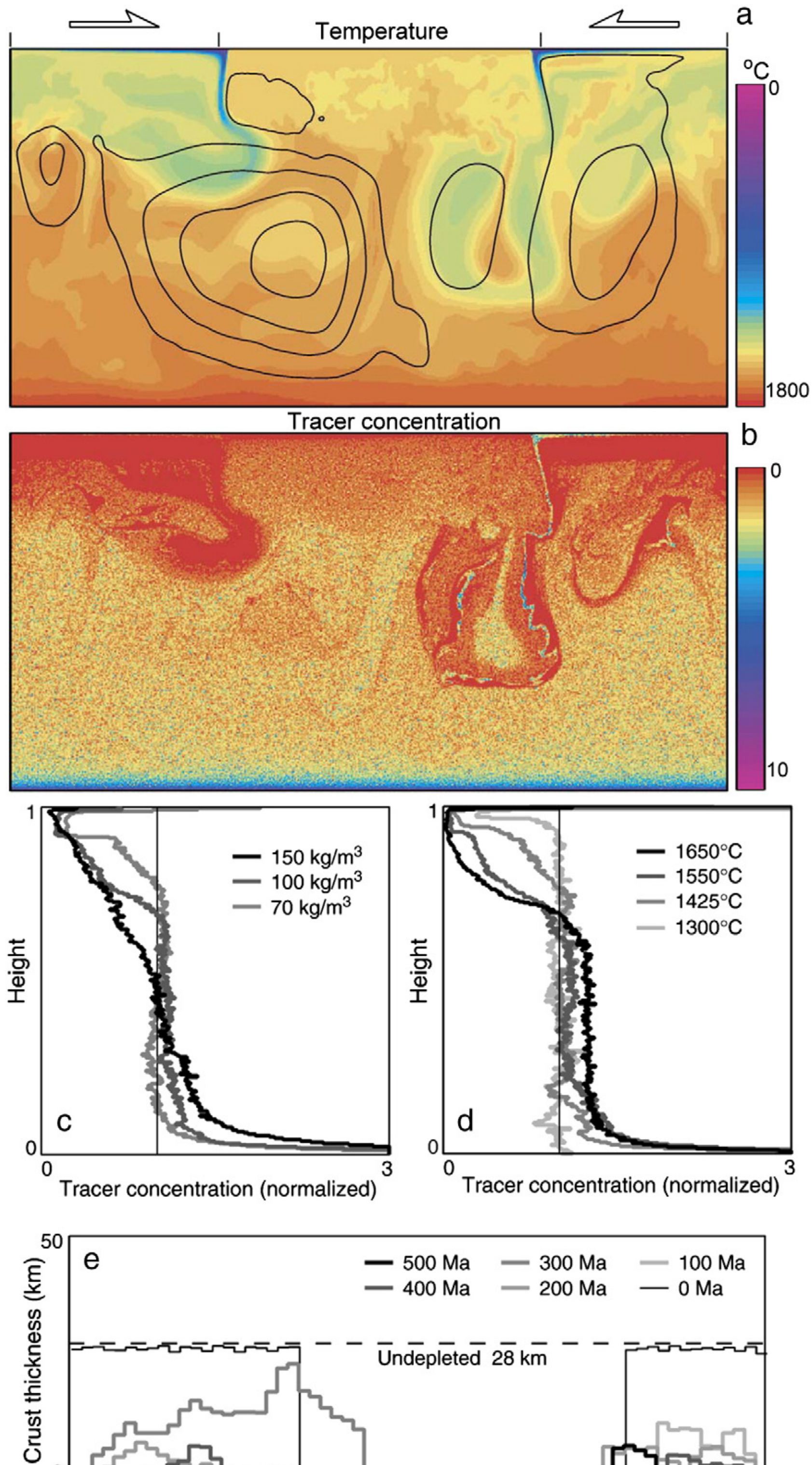

Fig. 3. 2D numerical model of subduction and convective stirring in the mantle (Davies, 2006). The model features two "oceanic" plates converging towards and subducting under a central "continental" region. The tracers represent the mafic (crustal) component of the mantle, and simulate both its melting near the surface and its excess density in the mantle. (a), (b) Temperature and streamlines (a) and tracer concentration (b) at 500 Ma of model development. (c), (d) Tracer profiles for different excess densities of subducted oceanic crust (c) and at different mantle temperatures (d). (e) Nominal crustal thickness at various times of model development.

hot Neoarchean subduction underneath a thick oceanic plateau/ protocrust. Melting in the lower part of thick basaltic oceanic crust could produce tonalite–trondhjemite–granodiorites (TTGs) of the low-HREE type, whereas low-pressure melting of the subducting slab and possible interactions with the mantle wedge at shallow depths would be capable of generating high-HREE TTGs. The third group of Archean high Ba–Sr sanukitoids was formed after the TTGs from an enriched (metasomatized) mantle source, probably as a result of slab

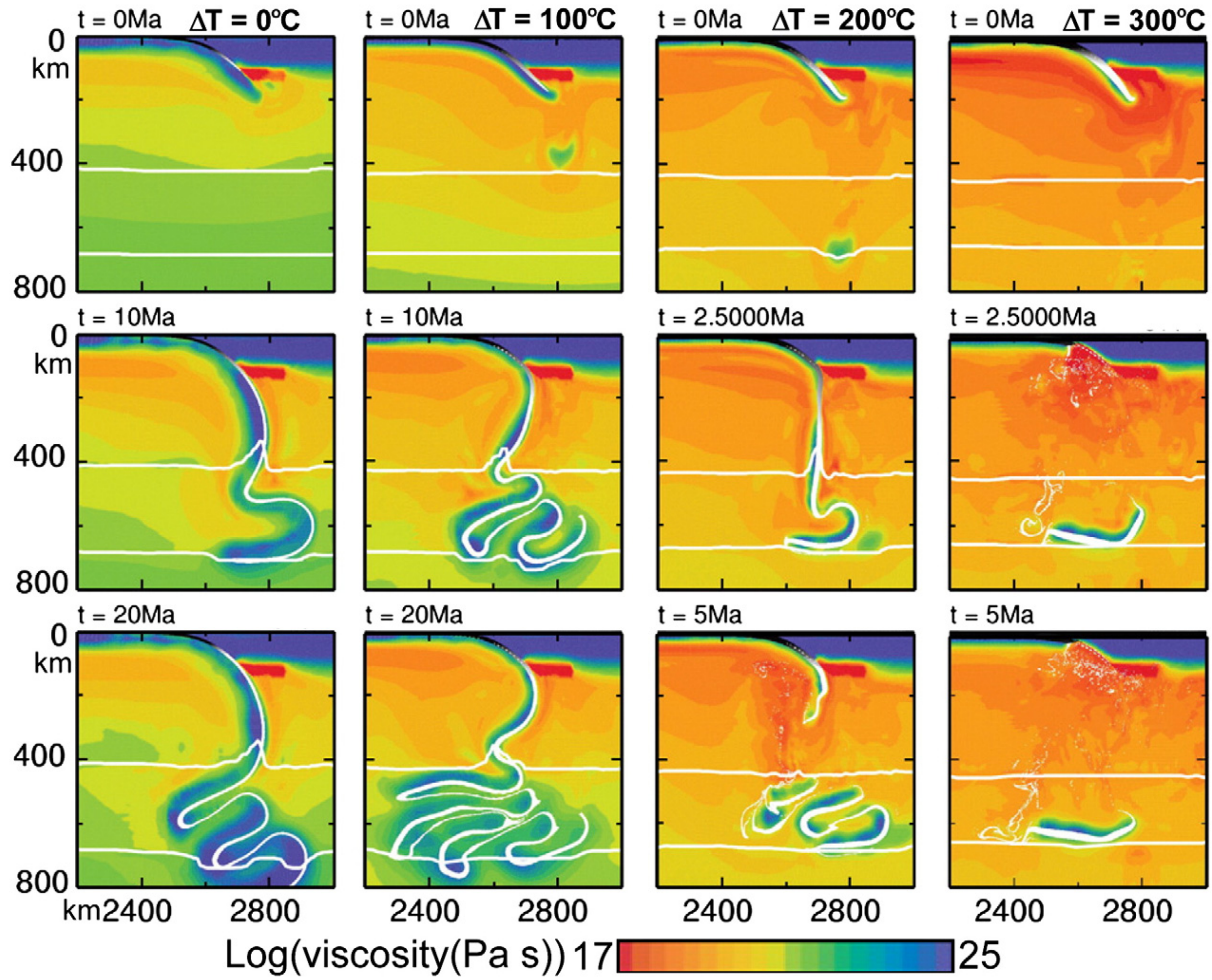

Fig. 4. Variations in tectonic style of subduction with changing mantle temperature (van Hunen and van den Berg, 2008). Four columns show time evolution (t) for cases with various mantle temperature difference (ΔT) above present day values. The olivine–spinel and perovskite transitions are denoted by the thin white lines, crustal material by black areas, and eclogite by white areas.

breakoff. Such a hypothesis is supported by numerical modeling results (van Hunen and van den Berg, 2008) that suggest an increased occurrence of slab breakoff in the Archean.

Another combined numerical-geochemical study (Moyen and van Hunen, 2012) studied the implications of a hotter Archean subduction on the origin of magmatic rocks. Natural data from the Superior Province in Canada were compared to a series of numerical model calculations for various mantle temperatures, ranging from today's mantle temperature for a Phanerozoic setting, to a 200 °C hotter mantle for an Archaean setting. The Phanerozoic model produced continuous subduction with typically a convergence rate of 5–10 cm/yr, which is representative for modern subduction. The Archaean setting displayed a different behavior, as slabs frequently break off from the trailing plate and sink down into the transition zone (see also van Hunen and van den Berg, 2008). This change in subduction behavior is a consequence of several effects:

(1) the thicker oceanic crust creates a larger tensile stress between the buoyant crust near the surface and the dense (eclogitic) crust at depth;
(2) due to the larger average subduction velocity, oceanic plates are younger and therefore thinner and weaker when arriving at the trench;
(3) a weaker mantle leads to more vigorous sublithospheric small-scale convection and subsequent lithospheric thinning (van Hunen et al., 2005);
(4) the thick, intrinsically weaker oceanic crust leads to a reduced integrated strength of the subducting plate; and
(5) the weaker mantle provides less support for the sinking slab.

This combination of effects leads to weaker slabs, which cannot maintain the tensile stresses encountered during subduction, and therefore frequently yield in the form of slab breakoff (Fig. 4). Such breakoff would lead to a temporary loss of slab pull, and a period in which subduction would be absent or very slow, with no or very little volatile input in the mantle and subsequent magmatic quiescence. Geodynamic modeling thus revealed that a hotter Archaean mantle would result in a more irregular style of subduction with frequent slab break-off and consequently a more episodic plate tectonic style. This would result in "arc" rocks forming as short, repeated bursts rather than laterally extensive and long term stable magmatic arcs. According to Moyen and van Hunen (2012), the distribution of igneous rocks in the Superior Province is consistent with this prediction, although continuity of the Archean arc-style volcanism was also proposed for this region (e.g., Card and Ciesielski, 1986; Wyman et al., 2002; Ketchum et al., 2008; Wyman and Kerrich, 2009). Moyen and van Hunen (2012) further suggested that a short-term episodic style of subduction could provide the link between early stagnant-lid convection and modern-style plate tectonics. A punctuated onset of global plate tectonics is unlikely to have occurred, but rather short-term episodes of proto-subduction in the late Archaean evolved over time into longer-term, more successful style of plate tectonics as mantle temperature decayed (Moyen and van Hunen, 2012). Moyen and van Hunen (2012) also demonstrated that Archean shallow flat subduction (e.g. Abbott et al., 1994) is neither geochemically required, nor geodynamically viable and proposed to abandon this concept.

Recently, Sizova et al. (2010) performed a series of high-resolution experiments using a 2D petrological–thermomechanical numerical model of oceanic–continental subduction (Fig. 5) and systematically investigated the dependence of tectono-metamorphic and magmatic regimes at an active plate margin on; upper-mantle temperature, crustal radiogenic heat production and degree of lithospheric weakening by fluids and melts. From these experiments, the authors identified a first-order transition from a "no-subduction" tectonic regime to a "pre-subduction" tectonic regime and finally to the modern style of subduction (Fig. 5). The first transition is gradual and occurs at upper-mantle temperatures between 250 and 200 °C above the present-day values, whereas the second transition is more abrupt and occurs at 175–160 °C. The link between geological observations and model results suggests that the transition to the modern plate tectonic regime might have occurred during the Mesoarchean–Neoarchean time (ca. 3.2–2.5 Ga). In the case of the "pre-subduction" tectonic regime (upper-mantle temperature 175–250 °C above the present), the plates are weakened by intense percolation of melts derived from the underlying hot melt-bearing sub-lithospheric mantle. In such cases, convergence does not produce self-sustaining one-sided subduction, but rather results in two-sided lithospheric downwellings and shallow underthrusting of the oceanic plate under the continental plate (Fig. 5b). A further increase in the upper-mantle temperature (>250 °C above the present) causes a transition to a "no-subduction" regime, where horizontal movements of small deformable plate fragments (Fig. 5a) are accommodated by internal strain, where even shallow underthrusts do not form under the imposed convergence. Thus, based on the results of the numerical modeling, it was suggested that the crucial parameter controlling the tectonic regime is the degree of lithospheric weakening induced by emplacement of sub-lithospheric melts into the lithosphere. A lower melt flux at upper-mantle temperatures <175–160 °C results in a smaller amount of melt-related weakening and stronger plates, which stabilizes the modern subduction style, even at high mantle temperatures (Sizova et al., 2010).

A major issue concerning both modern and Precambrian subduction is that the subduction initiation process remains largely enigmatic (e.g., Gerya, 2011) and numerical studies often use ad hoc assumptions in order to initiate and stabilize subduction in models, e.g. via prescribed plate velocity and prescribed pre-existing weak zones. Consequently, numerical investigation of Precambrian plate tectonic styles is intimately linked to understanding and modeling of spontaneous subduction initiation processes. Ueda et al. (2008) examined subduction initiation related to thermochemical plumes (Fig. 6), which has implications to Archean tectonics. Numerical testing of this hypothesis has been conducted using a 2D thermomechanical model accounting for phase transitions and a viscoplastic representation of a thin oceanic lithosphere, impacted by a partially molten thermochemical, or purely thermal plume. It was demonstrated that a mantle plume can break the lithosphere and initiate self-sustaining subduction, provided the plume causes a critical local weakening of the lithospheric material above it, due to percolation of melts extracted from the plume toward the surface. The intensity

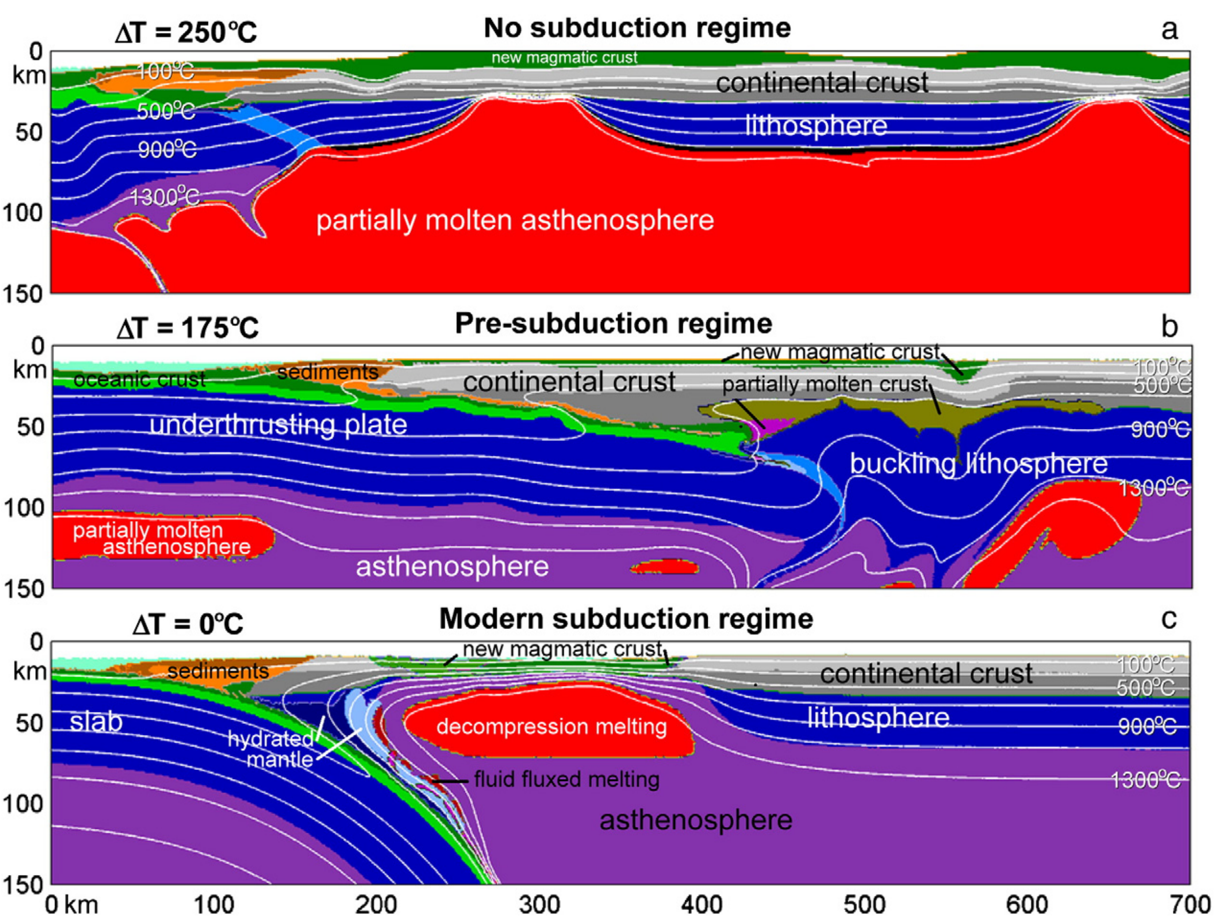

Fig. 5. High-resolution numerical models of an active continental margin evolution for various mantle temperature difference (ΔT) above present day values (Sizova et al., 2010). Models predict a first-order transition from a "no-subduction" tectonic regime (a) through a "pre-subduction" tectonic regime (b) to the modern style of subduction (c).

of the required weakening depends on the plume volume, plume buoyancy and the thickness of the lithosphere. The weakening is greatest for the least buoyant, purely thermal plumes. Another necessary condition is the presence of high-pressure fluids at the slabs' upper interface, which reduces the effective friction coefficient to very low values. Based on numerical results, it was suggested that sheet-like instabilities during Archean mantle convection could have initiated subduction on Earth where an ocean was already present in less stable tectonic settings, provided that mantle plumes (sheets) at that time were rich in water and melt, thereby drastically reducing the effective friction coefficient in the lithosphere above the plume (Ueda et al., 2008). Indeed, frequent slab breakoff was observed in these experiments (Fig. 6, 1.0 Myr), pointing toward the unstable and episodic nature associated with subducting rheologically weak plates (e.g., Van Hunen and van den Berg, 2008; Moyen and van Hunen, 2012). Recently, Burov and Cloetingh (2010) demonstrated numerically that the plume–lithosphere interaction can also trigger delamination and subduction of the continental mantle lithosphere, inducing spontaneous downthrusting to depths of 300–500 km upon plume impingement of the lithosphere. The subsequent evolution of the slab is governed by phase changes and its interactions with the surrounding mantle (Burov and Cloetingh, 2010). This scenario can indeed be relevant for the Precambrian where (proto-) continental mantle lithosphere was rheologically weaker than the present day (e.g., Cooper et al., 2006).

Nikolaeva et al. (2010) numerically investigated the spontaneous, passive continental margin collapse driven by the geometry of the margin, in which models employed a relatively thick (20–35 km) low density continental/arc crust that was bounded laterally by significantly more dense oceanic lithosphere. They used self-consistent 2D thermomechanical visco-elasto-plastic models with experimentally calibrated flow laws to investigate processes at a continental margin driven solely by these lateral buoyancy variations (Fig. 7). During the margin evolution, when the forces generated from this lateral density contrast become large enough to overcome the continental/arc crust strength, the continental crust starts to creep over the oceanic crust (Fig. 7, 0.3 Myr). This process causes deflection of the oceanic lithosphere (Fig. 7, 0.3 Myr) and may actually lead to its delamination from the continental/arc lithosphere (Fig. 7, 0.3–1.9 Myr), thus triggering a retreating subduction process (Fig. 7, 1.9–3.2 Myr). Using 2D models, Nikolaeva et al. (2010) investigated the factors controlling a passive margins' stability and showed that three subsequent tectonic regimes can develop at a passive margin: (1) stable margin, (2) overthrusting, and (3) subduction. The transition from a stable margin to the overthrusting regime is mainly controlled by the ductile strength of the lower continental crust. The transition from overthrusting to the subduction regime is governed by the ductile strength of the sub-continental lithospheric mantle and the compositional density contrast with the sub-oceanic lithospheric mantle. Nikolaeva et al. (2010) demonstrated that favorable conditions for subduction initiation correspond to passive margins with chemically buoyant (depleted) thin and hot (Moho temperature >660 °C) continental lithosphere. At present day conditions, this situation can only arise when external processes such as rifting and/or thermochemical plume activity (e.g., Van der Lee et al., 2008) are imposed on the region of future subduction initiation. Such situations

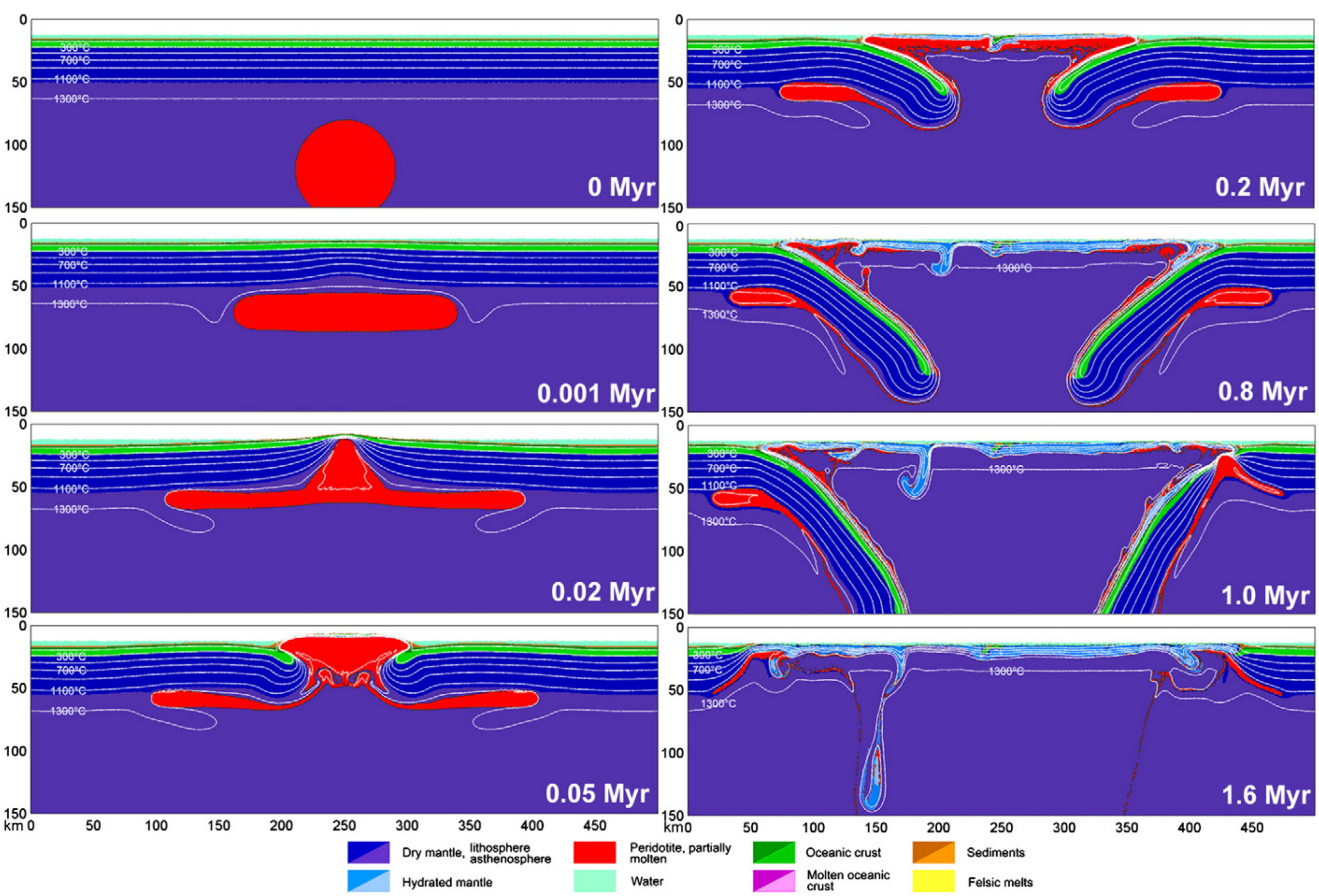

Fig. 6. 2D numerical model of subduction initiation by chemical plume interaction with young (10 Ma) oceanic lithosphere (Ueda et al., 2008). Plume is modeled as a circular volume of hydrated partially molten rocks in the mantle.

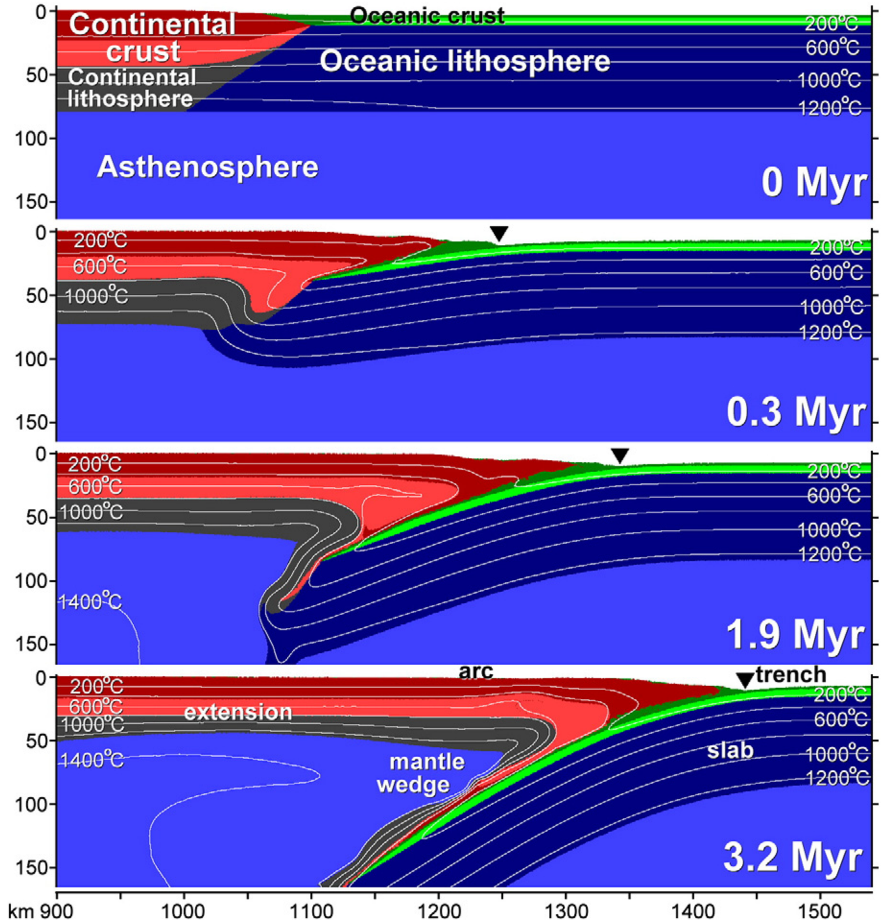

Fig. 7. 2D numerical model of subduction initiation by spontaneous passive margin collapse (Nikolaeva et al., 2010).

could definitely be more common in the Precambrian due to the elevated mantle temperature, more vigorous convection and enhanced plume activity (e.g., Condie, 2003; Davies, 2006; Moyen and van Hunen, 2012).

The critical role of continental margins for the onset of global plate tectonics was recently investigated by Rolf and Tackley (2011) based on 3D spherical mantle convection models with self-consistent plate tectonics and mobile, rheologically strong continents (Fig. 8). It was found that stable cratons affect the convective regime by thermally blanketing and stress focusing at the continental margins. The focusing facilitates the formation of subduction zones by increasing convective stresses at the margins, which allows for plate tectonics to occur at a higher yield strength and thus leads to better agreement with the yield strength inferred from laboratory experiments. The resulting convective regime depends on the lateral extent of the craton and the thickness ratio of continental and oceanic lithosphere. For a given yield strength, a larger ratio favors plate-like behavior, while intermediate ratios tend towards episodic behavior and small ratios leads to a stagnant lid regime (Rolf and Tackley, 2011). An obvious inference from this numerical study is that the establishment of thick, rheologically strong cratonic roots in the Archean could have critically contributed to the onset of global plate tectonics. In contrast, earlier stages with thinner continental plates could have been characterized by episodic plate tectonics. This inference is in apparent contradiction to the numerical results of Nikolaeva et al. (2010) which require relatively thin and hot continental lithosphere at the continental margins for the spontaneous subduction initiation. This contradiction can be in part relaxed by geological data which suggests the widespread occurrence of rheologically weak mobile belts, which often surround Archean cratons (e.g., Ring, 1994; Vauchez et al., 1997; Lenardic et al., 2000, 2003; Yoshida, 2012). Indeed, further high-resolution numerical experiments with free surface boundary conditions and realistic rock rheologies (e.g., Nikolaeva et al., 2010; Crameri et al., 2012) are needed on both global and regional scales to reconcile predictions from different types of models with natural data.

3. Collision and orogeny

Similarly to subduction and plate tectonics, the Precambrian collision and orogeny is an enigmatic and unresolved problem. Different tectonic styles of orogeny in the Precambrian compared to modern Earth are suggested by interpretations of geological, petrological and geochemical observations from Proterozoic and Archean orogenic belts (e.g. Taylor and McLennan, 1985, 1995; Windley, 1995; Condie, 1998, 2007; Brown, 2007, 2008). Two types of Precamrian orogens are distinguished (e.g., Windley, 1992; Condie, 2007; Chardon et al., 2009 and references therein), accretionary and collisional. Accretionary orogens form along active continental margins where oceanic crust is subducted (Condie, 2007 and references therein). Precambrian accretionary orogens contribute strongly to continental growth, owing to their high production rates of juvenile crust compared to Phanerozoic accretionary orogens (Condie, 2007). Many post-Archean accretionary orogens terminate by continent-continent collision during supercontinent assembly (Condie, 2007). The average terrain lifespan is typically 70–700 Myr during the Archean, 50–100 Myr in pre-1 Ga Proterozoic and 100–200 Myr in younger orogens (Condie, 2007). Collisional orogens form by continent–continent collision; they started to develop in the Proterozoic, however contributed little to continental growth (Windley, 1992; Chardon et al., 2009 and references therein). The

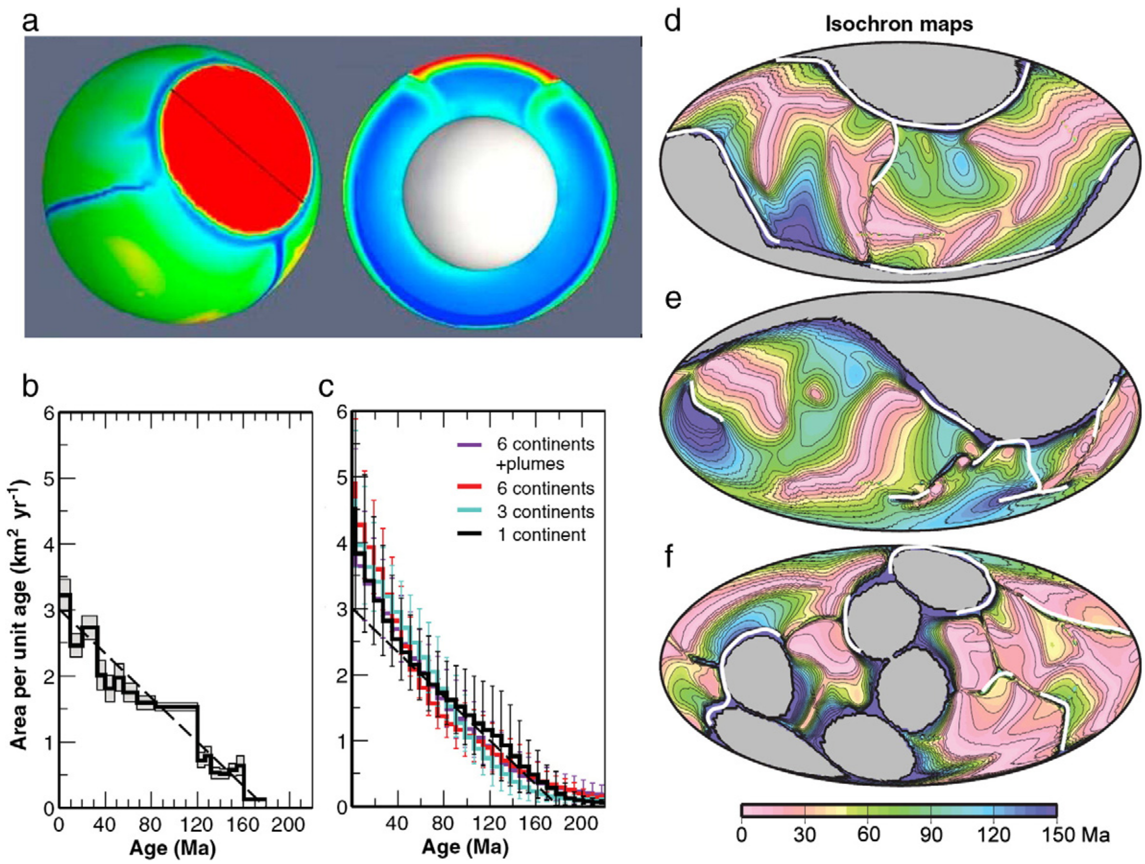

Fig. 8. Results of 3D numerical models of global mantle convection with self-consistent plate tectonics and mobile, rheologically strong continents (Rolf and Tackley, 2011; Coltice et al., 2012). (a) Viscosity field for the model with one continent; red color represents highly viscous, blue color weaker material. (b) Distribution of area versus age of the ocean floor on the present-day Earth. (c) Time-averaged distribution computed in 3D spherical simulations implementing continents (their cumulative area is 30% of the total) and plate-like behavior. (d),(e),(f) Maps of the distribution of the age of the ocean floor for 3D spherical convection models with various continent configurations; the gray areas on the maps represent the continents, the white lines are the positions of subduction zones, and the age contours are plotted at 10-My intervals.

relevance of studies of modern collisional orogens to the Precambrian currently remains uncertain given the warmer continental crust and upper mantle affecting the geodynamic regime earlier in Earth history (van Hunen and Allen, 2011; Sizova et al., 2014-this volume). Phanerozoic collisional orogenic systems generally produce characteristic clockwise metamorphic P–T paths and may generate and exhume extreme ultrahigh-pressure (UHP) metamorphic rock complexes. Approximately 20 high-pressure (HP)-UHP metamorphic terrains have been documented all over the world; most of them are of Phanerozoic ages, although one is Neoproterozoic and another is Neoarchean to Paleoproterozoic (e.g., Liou et al., 2004; Perchuk and Morgunova, 2014-this volume). The scarcity of UHP metamorphic complexes in the Precambrian geological record suggests a different style of orogenesis was prevalent earlier in Earth's history (e.g., Brown, 2007, 2008).

Field observations of Precambrian orogens show significant differences with modern orogens. In particular, Precambrian orogenesis involved major contributions to crustal growth and magmatism at high apparent geothermal gradients (Taylor and McLennan, 1995; Windley, 1995; Brown, 2007; Condie, 2007). Precambrian collisional belts represent large areas of monotonous high-temperature-low-pressure metamorphic rocks with extensive magmatism at moderate depths, often less than 25 km (e.g. Ehlers et al., 1993; Nironen, 1997; Bedard, 2003). Such orogens, which formed atop of hot mantle, remained hot and therefore extremely mechanically weak over protracted periods of deformation (e.g., Cagnard et al., 2006a, b; Chardon et al., 2009). Chardon et al. (2009) and Cagnard et al. (2011) have recently made an attempt to classify Precambrian accretionary orogens based on their first-order structural and metamorphic characteristics, reflecting the state of the continental lithosphere in these convergent settings involving massive juvenile magmatism. Four different types of orogens were proposed (Fig. 9): ultra-hot orogens (UHO); hot orogens (HO); mixed hot orogens (MHO) and cold orogens (CO). UHO is the most extreme and distinct class of Precambrian accretionary orogens, in which the weakest type of lithosphere on Earth is deformed. UHO are characterized by (i) massive juvenile magmatism, (ii) distributed shortening and orogen-scale flow combining vertical and horizontal longitudinal advection, under long-lasting convergence, (iii) homogeneous thickening by combined downward movements of supracrustal units and three-dimensional mass redistribution in the viscous lower crust, and (iv) steady-state, negligible topography and relief leveled by syn-shortening erosion and near-field sedimentation. In between the UHO and the modern cold orogens (CO), developed by shortening of lithosphere bearing a stiff upper mantle, two classes of orogens are further defined (Fig. 9a). Hot orogens (HO, representative of Cordilleran and wide mature collisional belts) share flow pattern characteristics with UHO, but involve a less intense magmatic activity and develop high topographies driving their collapse. Mixed-hot orogens (MHO, representative of magmatic arcs and Proterozoic collisional belts) are orogens made of UHO-type juvenile crust and display CO-like structure and kinematics. This classification points to a fundamental link between the presence of a stiff lithospheric mantle and strain localization along major thrusts in convergent settings. A high Moho temperature (>900 °C), implying thinning of the lithospheric mantle, enhances three-dimensional flow of the lithosphere in response to convergence. Also, this classification of Precambrian orogens emphasizes the space and time variability of uppermost mantle temperature in controlling

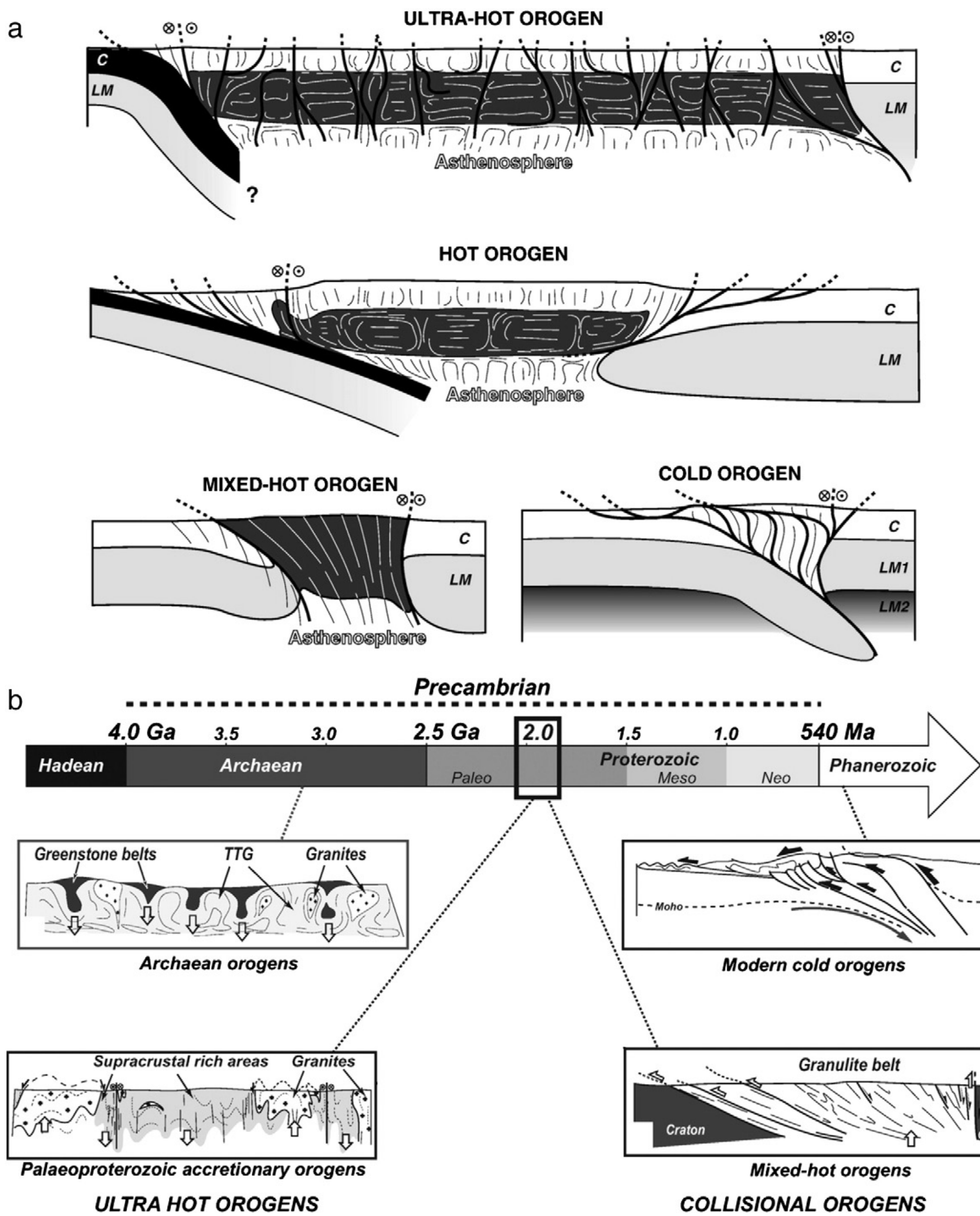

Fig. 9. Classifications of Precambrian orogens suggested by Chardon et al. (2009) (a) and Cagnard et al. (2011) (b). (a) Schematic orogen building scenarios (Chardon et al., 2009): C = crust; LM = lithospheric mantle; LM1 = stiff upper mantle lithosphere; LM2 = ductile, lower viscosity, lower lithospheric mantle. (b) Schematic orogenic cross sections illustrating different orogenic styles developed through time (Cagnard et al., 2011).

plate interactions and continental growth (Chardon et al., 2009), which points toward the necessity for further development of self-consistent, thermomechanical models for Precambrian orogenic styles (van Hunen and Allen, 2011; Sizova et al., 2014-this volume).

During the last decade, numerical modeling and analogue experiments were actively used to investigate Precambrian orogeny (e.g., Gerya et al., 2000, 2004; Cagnard et al., 2006a, b; Rey and Houseman, 2006; Cooper et al., 2006; Chardon et al., 2009; Gapais et al., 2009; Gray and Pysklywec, 2010; Perchuk and Gerya, 2011; Sizova et al., 2014-this volume). In addition, a number of recent numerical modeling studies of continental collision (e.g., Burov and Yamato, 2008; Faccenda et al., 2009; Duretz et al., 2011, 2012; van Hunen and Allen, 2011; Gray and Pysklywec, 2012; Sizova et al., 2012; Ueda et al., 2012) have implications for the early Earth orogenic processes. Cagnard et al. (2006a, b) presented a series of analogue models dedicated to compression of weak Precambrian-type lithospheres characterized by a thin upper brittle crust, overlying a weak ductile crust and a ductile sub-Moho mantle. An original mode of lithospheric thickening (Fig. 10) was identified in these experiments showing that (i) deformation is controlled by the ductile layers that undergo distributed thickening by vertical pure shear with the envelopes of the Earth's surface, Moho and lithosphere base remaining close to horizontal, (ii) thrusting is limited to the upper brittle crust and induces burial and stacking of upper crust "pop-down" units.

Moreover, the models showed that such thrusting-induced sinking of supracrustal units does not require inverse density profiles but can be simply driven by compression. The results of modeling compares well with internal structures of many ancient deformation belts, especially of Archean and Palaeoproterozoic age (Fig. 9b). These belts show large areas marked by primary flat-lying fabrics associated with rather monotonous metamorphic conditions of high-temperature-low-pressure type and affected by steep transpressive zones involving vertical stretch. These features do not support strain localization along large-scale thrusts and (or) extensional detachments, as common in modern orogens. Instead, they are consistent with hot and weak lithospheres where gravity-driven horizontal flow may compete with distributed thickening from early stages of collisional processes. These belts are also characterized by the juxtaposition, at the same structural level, of buried supracrustals and basement-dominated domains. Supracrustals may be dominated by dense rocks, as in Archaean greenstones, but also by metasediments, as observed in some Proterozoic belts (Cagnard et al., 2006a, b and references therein).

Numerical modeling work of Rey and Houseman (2006) agrees well with the analogue models (Cagnard et al., 2006a, b) and demonstrates that the convergence involving warm and buoyant lithospheres would result in more homogeneous lithospheric deformation, distributed over broad regions and also less topographic relief. In the Archaean, the combination of warmer continental geotherm with a lighter sub-continental lithospheric mantle suggests that gravitational forces played a more significant role in continental lithospheric deformation. Rey and Houseman (2006) compared numerically the evolution of the deformation and the regional state of stress in 'Archaean-like' and 'Phanerozoic-like' lithospheres, submitted to the same boundary conditions in a triaxial stress-field with imposed convergence in one direction. For plausible physical parameters, thickening of normal to cold Phanerozoic lithospheres produces relatively weak buoyancy forces (extensional or compressional). In contrast, for Archaean continental lithospheres, or for anomalously warm Phanerozoic lithospheres, lateral gravitationally-driven flow prevents significant thickening. It was argued that conclusions based on numerical models are consistent with: (1) the relative homogeneity of the erosional level now exposed at the surface of Archaean cratons, (2) the sub-aerial conditions that prevailed during the emplacement of up to 20 km of greenstone cover, (3) the relatively rare occurrence in the Archaean record of voluminous detrital sediments, (4) the near absence of significant tectonic, metamorphic and magmatic age gradients across Archaean cratons, (5) the relative homogeneity of strain across large areas, and (6) the ubiquitous presence of crustal-scale strike slip faults in many Late Archaean cratons (Rey and Houseman, 2006).

Burov and Yamato (2008) using 2D numerical thermomechanical experiments investigated the importance of Moho temperature (T_m), lower crustal rheology and convergence rates for collisional orogenesis and UHP rocks exhumation. They proposed that lithospheric deformation mechanisms and respectively continental convergence scenarios can be represented as a superposition of (1) simple shear (subduction), (2) pure shear (collision), (3) folding and (4) Rayleigh–Taylor instability (unstable subduction). It appears that stable subduction may occur in the case of cold lithospheres (T_m<550 °C) and relatively high convergence rates (>3–5 cm/yr). Depending on the lower-crustal rheology (strong or weak), either the entire (upper and lower) crust or only the lower crust can be involved in subduction.

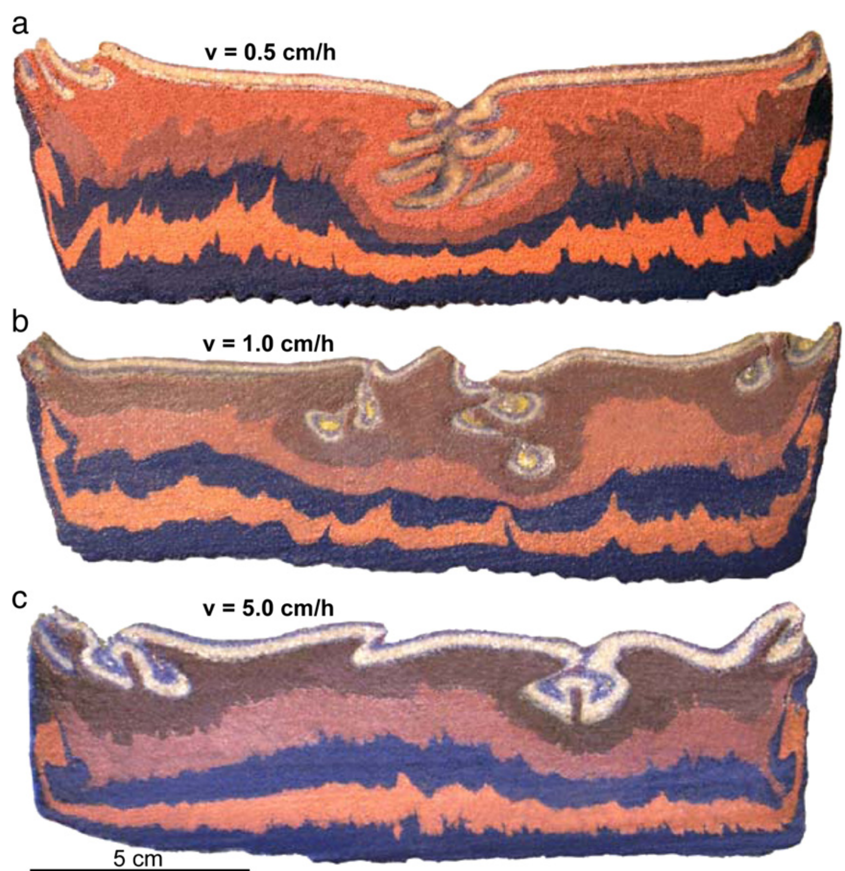

Fig. 10. Results from analogue models of shortening of weak Precambrian-type lithospheres with a thin upper brittle crust overlying a weak ductile crust and a ductile sub-Moho mantle (Cagnard et al., 2006b). Sections across the central part of three different models performed at different shortening velocities are shown: (a) = 0.5 cm/h (a), (b) = 1 cm/h, (c) = 5 cm/h (c). Top of the uppermost blue layer corresponds to the Moho.

Pure shear becomes a dominant mechanism when $T_m > 550$ °C, or when convergence rates are lower than 3 cm/yr. Large-scale folding is favored in case of $T_m = 500–650$ °C and is more effective in the case of mechanical coupling between crust and mantle (e.g., strong lower crust). Gravitational (Rayleigh–Taylor) instabilities (unstable subduction) overcome other mechanisms for very high values of $T_m > 800$ °C and may lead to the development of subvertical "cold spots" (Burov and Yamato, 2008). Although this numerical modeling study was not aimed at the Precambrian orogeny, it indeed suggests that the decrease of Moho temperature since the Archean should have resulted in a transition (Fig. 9b) from gravitational dominated tectonics, toward modern subduction-collision orogenic settings.

Useful insights into the structure and evolution of Precambrian accretionary orogens can also be extracted from the recent numerical modeling studies of lithospheric delamination processes in continental collision zones (Faccenda et al., 2009; Gray and Pysklywec, 2010; Ueda et al., 2012). Two distinct delamination modes are identified (Ueda et al., 2012), in which orogens undergo mantle delamination (i) concurrently (Faccenda et al., 2009; Gray and Pysklywec, 2010) or (ii) after collision (Fig. 11). Delamination propagates along the Moho of the subducted plate, together with the retreating trench, provided that slab pull is sufficient and that the meta-stability of the crust–lithospheric mantle interface is overcome (Faccenda et al., 2009; Gray and Pysklywec, 2010; Ueda et al., 2012). Topography is an instantaneous response to delamination and migrates with the focused and localized separation between crust and lithospheric mantle (delamination front, Fig. 11) (Faccenda et al., 2009; Ueda et al., 2012). Early exhumation of high-pressure rocks is followed by exhumation of high-temperature, partially molten rocks (Fig. 11). The following inferences from the study of Ueda et al. (2012) are important for understanding Precambrian accretionary orogens:

- Delamination can be triggered by increasing the Moho temperature to 700–800 °C, which results from enhanced lower crustal radiogenic heat production (Fig. 11d-h). These characteristics should be common in the Precambrian (e.g., Gray and Pysklywec, 2010).
- Delamination does not require a strong lithospheric mantle and can last for hundreds of millions years, being driven by multiple episodes of lithospheric drip-off (Fig. 11g–j), rather than subduction of the coherent subcontinental lithosphere. This is consistent with the extremely long (up to 700 Myr) life span of some of the Precambrian accretionary orogens (Condie, 2007).
- Convective stabilization of delamination outlasts slab break-offs (lithospheric drip-offs) and impedes renewed build-up of mechanically strong lithospheric mantle under the orogeny by static cooling (Fig. 11g–j). This may explain the long life span of high-temperature–low-pressure conditions in Precambrian orogens (Chardon et al., 2009; Cagnard et al., 2011).
- Similarly to slab break-off episodes, geochemical signatures of drip-off episodes in the hot Precambrian mantle may explain the frequent alternation of "arc" and "plume" affinities in Archean TTGs (Moyen and van Hunen, 2012).

It should be noted that the numerical experiments of Ueda et al. (2012) were performed at present-day mantle temperatures and the above inferences still need to be verified for Precambrian-like mantle and crustal conditions.

Perchuk and Gerya (2011) reviewed the significance of crustal gravitational redistribution processes for the geometry and structure of Precambrian high-grade terrains exposing large volumes of high-temperaure granulite facies rocks. A gravitational redistribution model was initially proposed for the formation and exhumation of Precambrian granulite complexes (Perchuk, 1989, 1991) and was later extended for some of the modern granulite terrains (e.g., Gerya et al., 2004; Maerova, this volume and references therein). This model considers the Earth's crust as a multilayered system comprised of layers of different density which are metastable in the gravity field under relatively low temperature conditions, due to their overall high effective viscosity (e.g., Ramberg, 1981). This viscosity, however, is exponentially lowered with increasing temperature, so that under high-grade metamorphic conditions (characteristic for Precambrian), crustal gravitational redistribution (Fig. 12a) is triggered in the inherently unstable crustal configuration (e.g. Gerya et al., 2000, 2004; Perchuk and Gerya, 2011). Subsequent exhumation of high-grade rocks is associated with the subduction (underthrusting) of colder negatively buoyant cratonic crust under a hotter positively buoyant granulite-facies crustal body (Fig. 12a, b). Due to the high ambient temperature and pressure in the lower crust in the Archean and Paleoproterozoic, a significant proportion of subducted cratonic rocks was further transformed into granulite. Large positively buoyant (relatively felsic) fractions of newly formed granulite rose toward the surface, whereas denser rocks, such as garnet-bearing metabasite and metakomatiite, preferentially concentrated in the lower crust at or near the Moho (Fig. 12a, 8.9 Myr). During this process, shear zones developed between the overlying granulite bodies and the upper-crustal cratonic rocks. The reverse-sense displacement and the syntectonic metamorphism (Fig. 12b) inside these shear zones was related to the exhumation of the granulite. Owing that the majority of the Precambrian high-grade granulite terrains are situated in between granite-greenstone belts, an integrated geodynamic scenario (Fig. 12c, cf. with Fig. 13) was proposed by Leonid Perchuk (Perchuk and Gerya, 2011) relating the evolution of the upper mantle and the crust in the Precambrian. According to this scenario, large-scale and long-lived zones (e.g., Torsvik et al., 2010) of partially molten mantle upwellings (plumes) are expected to play a crucial role for the growth and evolution of the hot Precambrian crust. These plumes generated large amounts of mafic and ultramafic magmas which could have initiated growth of the continental crust (e.g., Condie, 2004; Chardon et al., 2009; van Kranendonk, 2011 and references therein), and partially melted the crust producing TTG cupolas (e.g., MacGregor, 1951; Ramberg, 1981; Cagnard et al., 2011). Large amounts of sub-lithospheric melts produced by these plumes contributed to crustal growth and are expected to also notably weaken the Precambrian lithosphere causing distinct tectonics styles with pronounced horizontal movements of deformable plates (Sizova et al., 2010). Plume tectonics should associate with horizontal flows of the rheologically-weakened lithosphere, thus creating areas of assembled cratonic crust located between the long-living mantle upwellings regions (Fig. 12c). Such areas of crustal assembly (where high-grade granulite terrains were subsequently generated) are precursors of modern collision zones, however they are not characterized by intense crustal thickening and high topography, rather they are associated with gentle mantle downwellings in contrast with modern subduction and collision of rigid lithospheric plates (Perchuk and Gerya, 2011).

Duretz et al. (2011, 2012), van Hunen and Allen (2011) and Sizova et al. (2012, 2014-this volume) have recently modeled numerically the dynamics of a subduction-collision system subjected to slab break-off, using fully dynamic 2D and 3D models. Both 2D (Duretz et al., 2011; Sizova et al., 2012, 2014-this volume) and 3D (Van Hunen and Allen, 2011) models indicate that collision after the subduction of old, strong subducting oceanic slab can lead to the onset of slab detachment at 15–25 Myr following the onset of continental collision. Subsequently a slab tear migrates, more or less horizontally, through the slab with a propagation speed of 100–150 mm/yr (Van Hunen and Allen, 2011). Young, weak oceanic slabs commence break-off at 5–10 Myr after continental collision (Duretz et al., 2011; van Hunen and Allen, 2011), and can experience tear migration rates up to 800 mm/yr (Van Hunen and Allen, 2011). A 40-km thick continental crust can be buried to depths greater than 200 km, providing the possibility for the formation and exhumation of UHP rocks driven by a range of processes including slab eduction, crustal-scale stacking, crustal delamination, channel flow, vertical extrusion and diapiric flow (Duretz et al., 2011, 2012; Sizova et al., 2012, 2014-this volume). Van Hunen and Allen (2011) hypothesized that the shallow, early

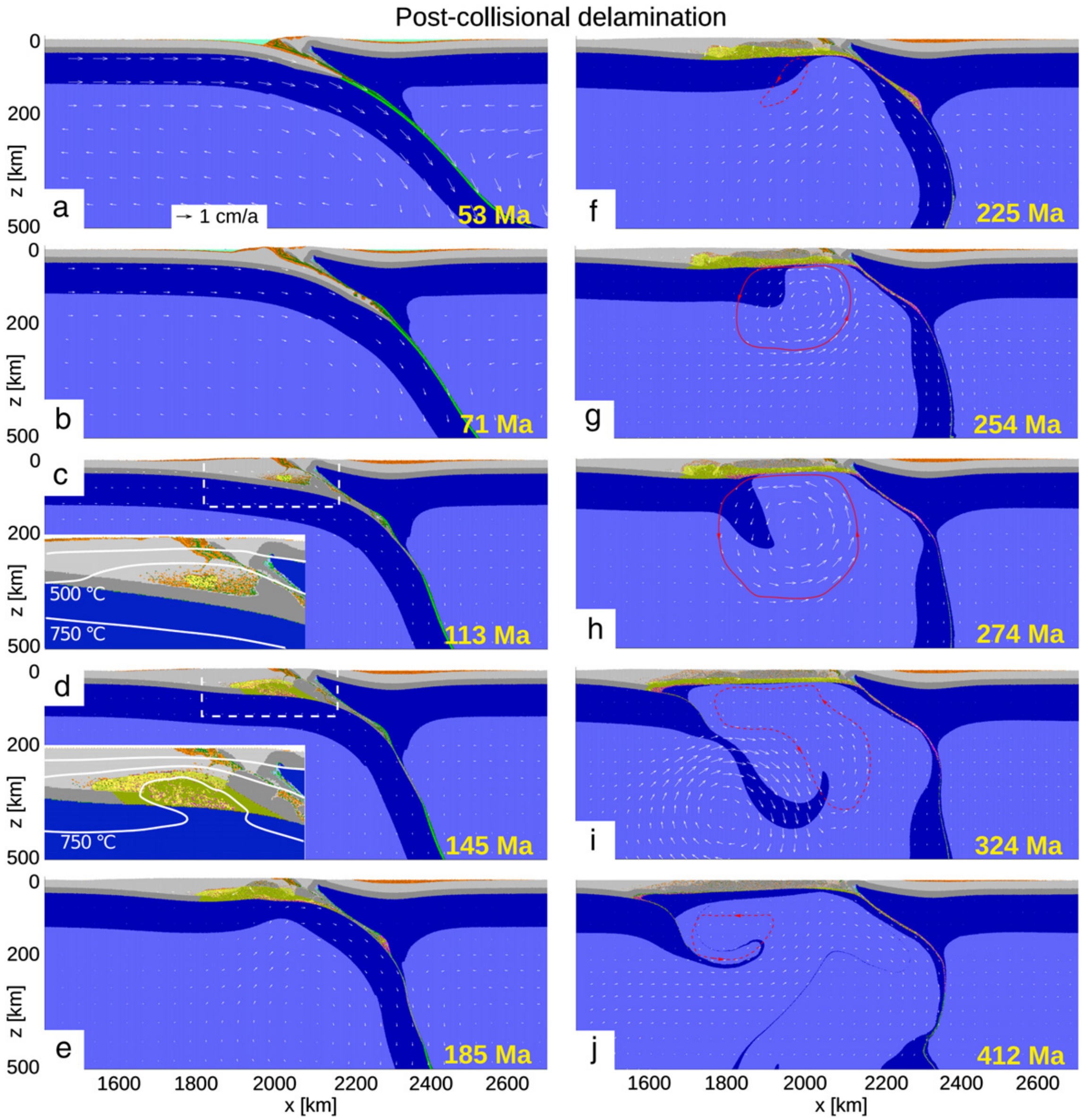

Fig. 11. 2D numerical model of post-collisional delamination within a wide and hot orogen (Ueda et al., 2012). Yellow color chows regions of crustal melting. Red line approximates flow pattern that includes delamination.

break-off of weak slabs after the onset of continental collision provides a viable explanation for the absence of blueschists and UHP metamorphism in the Precambrian geological record (also see van Hunen and van den Berg, 2008). Sizova et al. 2014 (this volume) tested this hypothesis by modeling post-subduction collision of spontaneously moving plates under geodynamic conditions representative of both modern day and a Precambrian Earth. According to these new models, increasing the upper-mantle temperature by 80–100° above the present-day value (which would correspond to Neoproterozoic time at 600–800 Ma), produces distinct hot collision regimes associated with the shallow slab breakoff—thus precluding the formation and exhumation of the UHPM rocks, which agrees well with the scarcity of these rocks in the Precambrian geological record (e.g., Liou et al., 2004; Perchuk and Morgunova, 2014-this volume). From model results, we can refer the transition to the Neoproterozoic (600–800 Ma) (Sizova et al., 2014-this volume). Remarkably, according to both the geological record (e.g., Brown, 2007; Cagnard et al., 2011 and references therein) and numerical experiments (Sizova et al., 2010, 2014-this volume and references therein), modern style collision should become widespread on the Earth much later (Neoproterozoic) than modern style subduction (Neoarchean), which points toward a rather complex and "decoupled" evolution of geodynamics styles for these major plate convergence processes on Earth.

4. Craton formation and stability

Cratons are underlain by thick, cold, and highly melt-depleted peridotitic mantle roots. One of the key questions which is posed for the Archean and, more generally, Precambrian tectonics is (Bailey, 2006): "What geodynamic processes can we reasonably expect to have provided the principal controls on the formation and preservation of Archean lithosphere?" It is widely accepted on the basis of geochemical, petrological and geochronological data (e.g., Beuchert et al., 2010 and references therein) that the Archean cratons are preserved until today, including their more than 200 km thick lithospheric keels, formed at >2.5 Ga, and have remained cold and stable ever since. The mechanisms of cratonic lithosphere formation are not yet fully understood, but generally fall into three major categories suggested on the basis of mainly petrologic/geochemical evidence (Lee, 2006; Gray and Pysklywec, 2010 and references

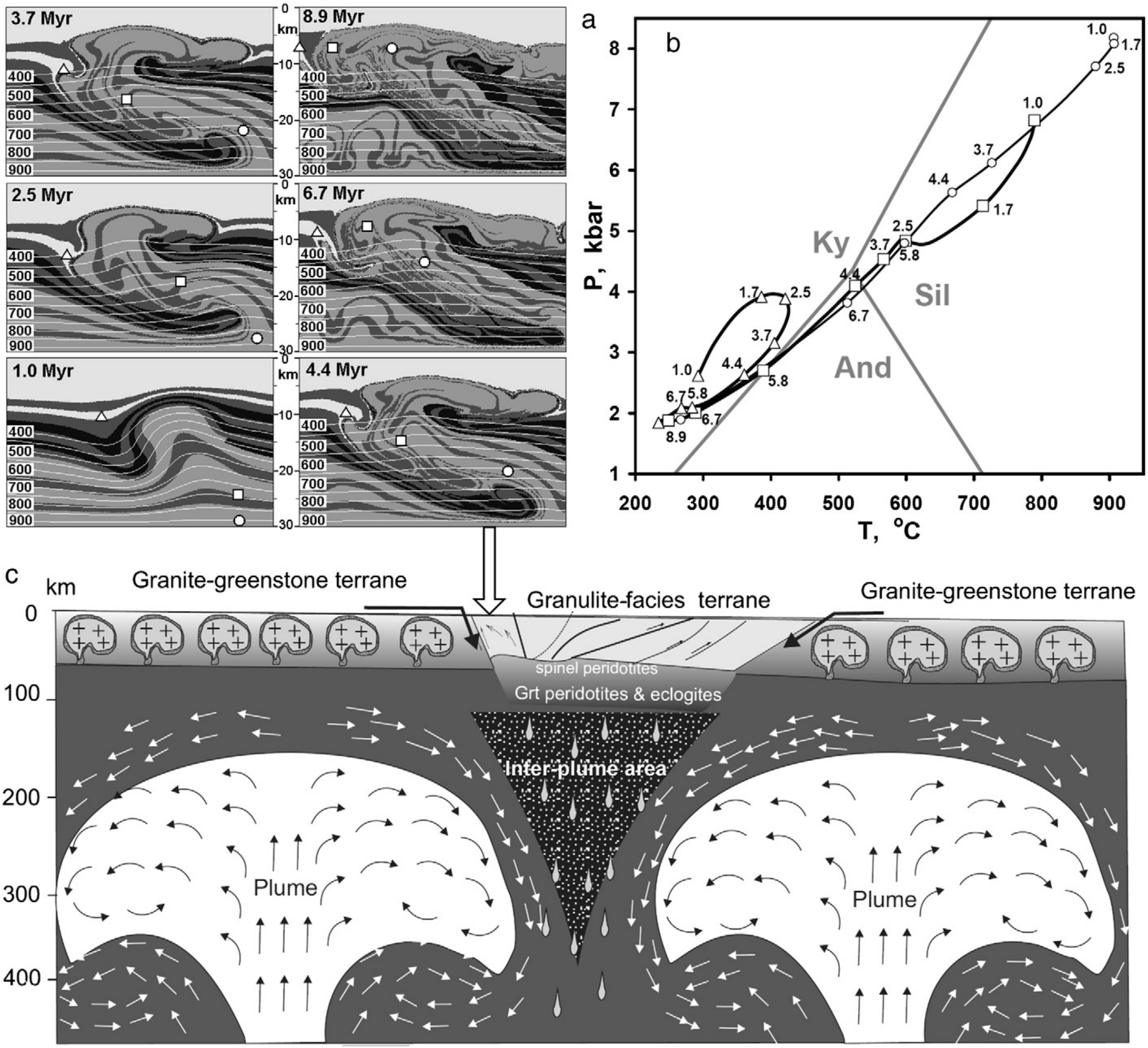

Fig. 12. 2D numerical model of gravitational redistribution in the hot Precambrian crust (a) with representative P–T paths of metamorphic rocks (b) and geodynamic concept for joint evolution of granite-greenstone and granulite terrains (c) (Perchuk and Gerya, 2011).

therein): (1) high-degree melting in a very hot (>1650 °C) plume head, (2) accretion of either oceanic and/or arc lithosphere and (3) continental collision.

The hot plume scenario suggests that subcontinental lithospheric mantle (SCLM) was formed by high degrees of melting in a wide range of pressures (up to 7 GPa). This is apparently not supported by major-element and mildly incompatible trace-element compositions of cratonic peridotite xenoliths, suggesting partial melting occurred at pressures less than their current equilibration pressure (Lee, 2006 and references therein). Refinement of the hot plume scenario has been recently suggested by Arndt et al. (2009) who proposed that the peculiar composition of the SCLM results from two separate processes: melt extraction and gravitational redistribution. According to this concept, the residue of melting in the very hot plume was stratified from fertile peridotite at the plume margins and towards the base of the melting zone, to refractory Fo-rich olivine ± orthopyroxene in the upper parts of the core of the melting zone. The latter material formed stable lithospheric mantle, whilst the denser, more fertile parts of the plume have been ejected by gravitational redistribution. The sorting of Fo-rich olivine and magnesian orthopyroxene from the denser and less viscous components of the fertile peridotite took place during the impingement of subsequent mantle plumes and during the reworking of the accumulated peridotites (Arndt et al., 2009).

The accretion scenario is consistent with the determined relatively shallow conditions of melting of the SCLM. This scenario suggests that mantle melting and melt extraction occurred on average at lower pressures (<~4 GPa), followed by a subsequent transport of the residual peridotites to greater depths (3–7 GPa). However, a lateral tectonic accretion model suggests a greater amount of eclogite in the SCLM than is implied by mantle derived xenoliths (Schulze, 1989; Gray and Pysklywec, 2010). A possible explanation for this discrepancy can be found in the work of Arndt et al. (2009) who proposed and numerically tested gravitational sorting of the accreted

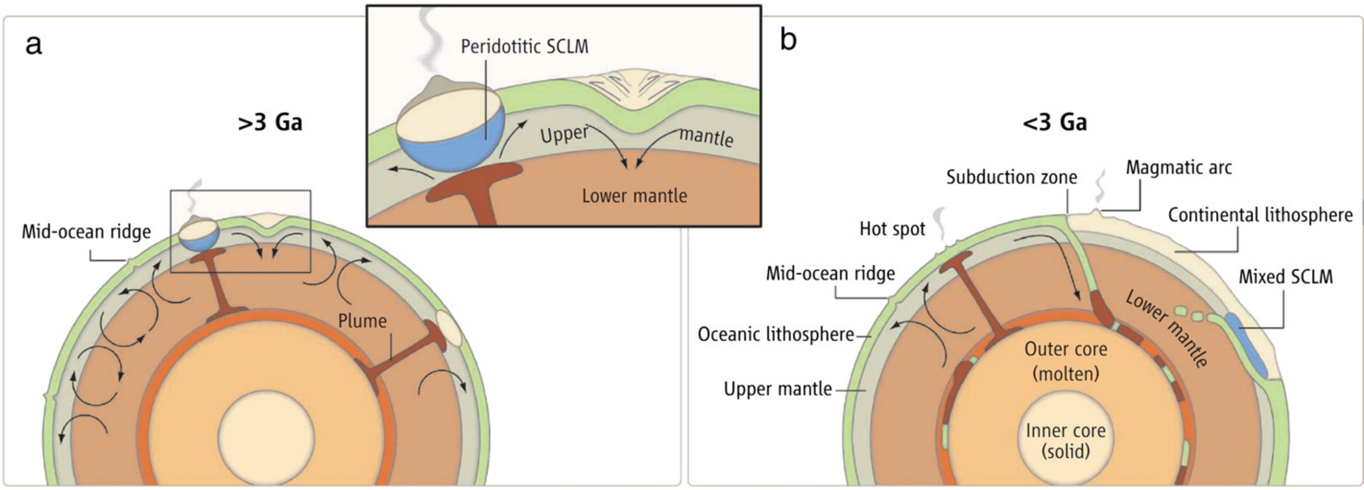

Fig. 13. Conceptual schematic cross sections of (a) early Earth (>3 Ga) and (b) young Earth (<3 Ga), showing different modes of crust formation (van Kranendonk, 2011).

SCLM, which ejected high-density low-viscosity eclogites from the lithospheric roots.

The simultaneous operation of plume and accretion scenarios (Fig. 13) on Precambrian Earth has also been suggested to explain continental growth (Van Kranendonk, 2011). According to this combined scenario, on early Earth (>3 Ga) crust formed in two settings (see enlagement in Fig. 13a, also cf. with Fig. 12c): (i) over an upwelling of hot mantle material, where it formed a thick crust with a depleted keel of peridotitic SCLM; (ii) over areas of down going mantle, where oceanic lithosphere was repeatedly stacked (imbricated) and extensively melted to form high-grade gneiss terrains. Starting from around 3 Ga, on a young Earth with larger plates, whole-mantle convection generated steep subduction zones and the return of oceanic lithosphere to the mantle (Fig. 13b). Crust grew via subduction-generated arc magmatism and at hot spots. Accretion of oceanic lithosphere to the base of continents produced SCLM with mixed peridotitic and eclogitic compositions (Van Kranendonk, 2011). The latter appeared in the SCLM at about 3 Ga, which may imply the onset of the Wilson cycle of plate tectonics (Shirey and Richardson, 2011). SCLM older than 3 Ga was composed entirely of peridotitic composition. Given that some crustal elements of Paleoarchean cratones are as old as 4 Ga, these cratons were assembled by non-plate-tectonics mechanisms (Fig. 13a), such as flow around plumes, oceanic plateau accumulation, delamination, vertical tectonics and slab-free mantle downwellings (Shirey and Richardson, 2011). The onset of the Wilson cycle at 3 Ga would have marked the end of processes which were dominated by crustal growth (Shirey and Richardson, 2011). However, it should be mentioned that the thermomechanical consistency of various proposed plume and accretion scenarios has not yet been systematically investigated and remains as a future challenge for numerical modelers and geodynamists.

According to the collisional scenario, cratons formed from the coalescence of proto-cratonic lithospheric material over a mantle downwelling (Jordan, 1978, 1988; Bostock, 1998; Cooper et al., 2006; Gray and Pysklywec, 2010). This scenario is supported by seismic evidence suggesting that cratonic lithosphere may have formed via thrust stacking of proto-cratonic lithosphere (Cooper et al., 2006 and references therein). In contrast to the plume and accretion concepts which are mainly based on petrologic/geochemical data, collisional scenarios have to some extent been investigated numerically (Cooper et al., 2006; Rey and Houseman, 2006; Gray and Pysklywec, 2010). Cooper et al. (2006) conducted numerical simulations and scaling analysis to test the stacking hypothesis, as well as to elucidate mechanisms for SCLM stabilization. They found that formation of cratonic lithosphere via thrust stacking over convective downwellings (Fig. 14a) is the most viable mechanism for a buoyant and viscous lithosphere which is thin, and/or possesses low effective friction coefficients attributed to the presence of pore fluid. These conditions lead to low integrated yield strength within proto-cratonic lithosphere which allows it to fail in response to convection generated stresses. Specifically, formation via thrust stacking is a viable mechanism for a lithosphere with chemical to thermal buoyancy ratios of 0.75–1.5, viscosity contrasts between the lithosphere and convective mantle of >100, and friction coefficients in the range of 0.05–0.1. On the other hand, further preservation of the SCLM through geological time depends on the balance between the chemical lithosphere's integrated yield strength and convection generated stresses. The physical process of thrust stacking generates a thickened cratonic root. This provides a higher integrated yield strength within cratons, which consequently become stable. Increased friction coefficient and viscosity values (e.g. Peslier et al., 2010 and references therein), due to dehydration, can also provide higher integrated yield stresses within cratons (Cooper et al., 2006). To provide long-term stability, integrated yield stresses must be sufficiently large to offset future mantle convection generated stresses, which can increase with time as the mantle viscosity increases due to cooling (Cooper et al., 2006). Thin or rehydrated cratonic lithosphere may not provide stability against the increasing convective stresses, thus providing an explanation as to why some cratons are not long-lived (Cooper et al., 2006). Indeed, realistic thermomechanical models accounting for self-consistent SCLM formation and long-term stability are yet to be developed.

Gray and Pysklywec (2010) investigated the dynamics of continental lithosphere during collision under Neoarchean-like conditions as a potential process for creating thick SCLM, specifically considering the dynamical interactions between the continental crust and mantle. The numerical experiments illustrate that depending on the composition of the crust and the degree of radioactive heat production in the crust, three dominant modes of mantle lithosphere deformation evolve (Fig. 14b–d): imbrications, underplating and pure-shear thickening. All three modes of deformation result in the thickening and emplacement of plate-like mantle lithosphere to depths between 200 km and 350 km. The imbrication style of deformation (Fig. 14b) occurs in a mantle lithosphere that is overlain by a rheologically weak lower crust while the degree of heat production in the crust is sufficiently low. This allows the strong upper portion of the mantle lithosphere to progressively underthrust adjacent mantle lithosphere along a weak/decoupling crust-mantle interface. The underplating deformation style (Fig. 14c) occurs when the lower crust is rheologically strong and does not decouple from the underlying mantle

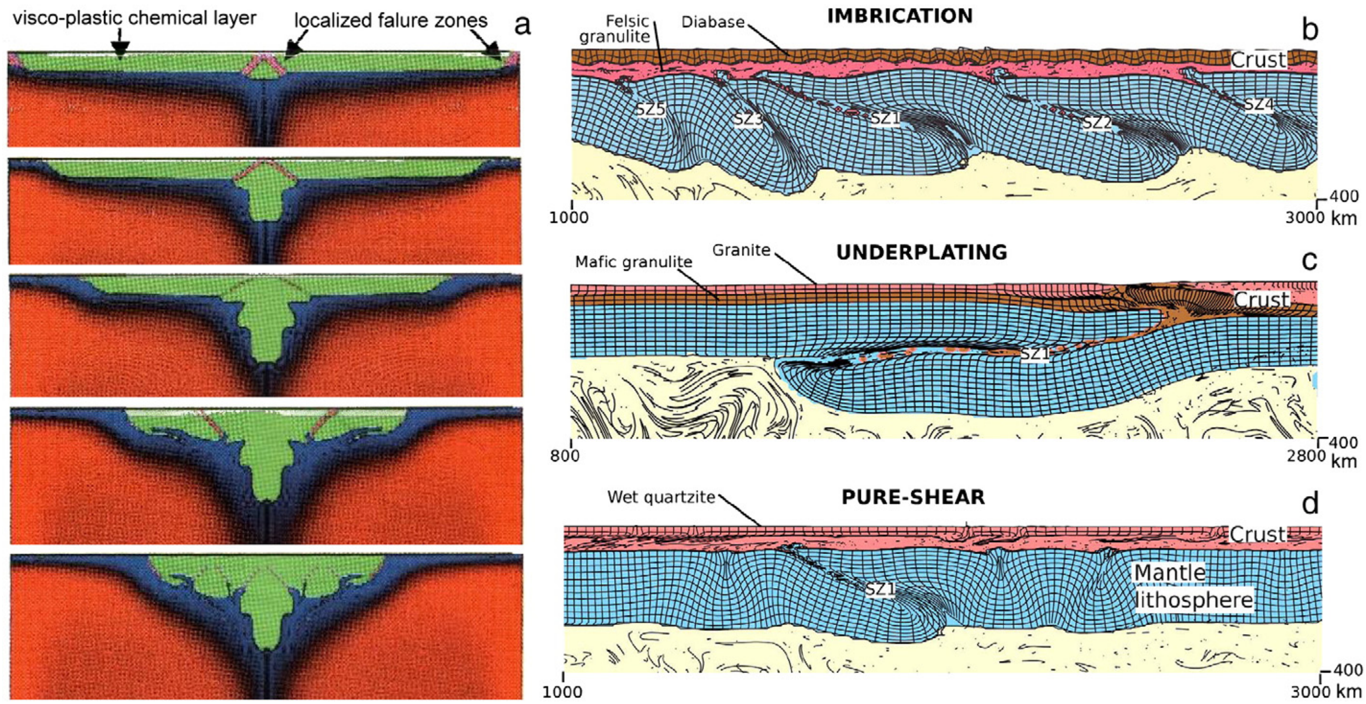

Fig. 14. 2D numerical models of SCLM formation by collisional processes presented by Cooper et al. (2006) (a) and Gray and Pysklywec (2010) (b)–(d). (a) Top to bottom frames representing modeled time sequence (upper part of 1 × 1 models is shown). The green layer is the chemically distinct layer that is emplaced within the upper thermal boundary layer (blue) of a 1 × 1 convecting mantle cell (red). (b)–(d) Three dominant modes of mantle lithosphere deformation during collision under Neoarchean-like conditions (upper central part of 4800 × 600 km models is shown): imbrications (b), underplating (c) and pure-shear thickening (d).

lithosphere. Finally, the pure-shear-thickening style of deformation (Fig. 14d) occurs when the temperature of the lower crust is noticeably elevated by high crustal radiogenic heat production. This leads to a decrease of rheological coupling between the lower crust and the mantle lithosphere, in turn enabling a dominantly ductile distribution of deformation in the mantle lithosphere (Gray and Pysklywec, 2010). Importantly, the authors mentioned that two-dimensional experiments cannot adequately study Archean continental collision because three dimensional warm and buoyant lithosphere will undergo orogeny-parallel ductile flow during orogenesis (Gray and Pysklywec, 2010, also see Rey and Houseman, 2006; Cagnard et al., 2006a, b). Consequently, further progress in understanding of formation of the SCLM will critically depend on developing 3D numerical modeling approaches.

The remarkable long-term stability of cratons has attracted significant attention from the numerical modeling community (Doin et al., 1997; Lenardic and Moresi, 1999; Shapiro et al., 1999; Lenardic et al., 2000, 2003; O'Neill and Moresi, 2003; Sleep, 2003; Cooper et al., 2004, 2006; O'Neill et al., 2008; Beuchert et al., 2010). Whereas some authors (Shapiro et al., 1999; Lenardic et al., 2003; Sleep, 2003; O'Neill et al., 2008; Beuchert et al., 2010) confirmed long-term survival of the cratonic root based on their modeling, several others documented lithospheric instability in their numerical experiments (Doin et al., 1997; Lenardic and Moresi, 1999; Lenardic et al., 2000; O'Neill and Moresi, 2003; Cooper et al., 2004). Also, the inability of some models to reproduce long-term craton stability has been used as an argument to discuss the geodynamic significance of the old ages obtained from inclusions in diamonds (O'Neill and Moresi, 2003), which are broadly used for the interpretation of the styles of Precambrian geodynamics (Shirey and Richardson, 2011; Van Kranendonk, 2011).

One of the earlier numerical studies of Doin et al. (1997) addressed the question of how convective processes control the thicknesses of adjacent oceanic and continental lithospheres using 2D numerical convection model with a temperature and pressure dependent rheology. A repeated plate tectonic cycle was modeled by imposing a time-dependent surface velocity along one part of the surface, representing a persistent continent, which is never subducted. It was demonstrated that the edge driven convection (lateral destabilization) at the continent-ocean boundaries is the main process controlling erosion of the lithospheric continental root. In the numerical experiments conducted, about 200 km of continental lithosphere was eroded in 800 Myr, implying that the borders of continental roots should be offset by > 500 km inside cratons. These results are hardly affected if the continental lithosphere is assumed to be petrologically less dense (due to depletion) than normal mantle. It was concluded, that the calculated lithospheric erosion seems too large to explain the observed close spatial correlation of crustal structures with the variations in lithospheric thickness inside cratons. It was also suggested that somewhat slower destabilization rates may be obtained for higher activation energies of the mantle related to SCLM devolatilization (Doin et al., 1997).

Shapiro et al. (1999) further investigated the long-term stability of the continental lithosphere at an ocean-continent boundary using a 2D thermomechanical finite element models and considered the effects of (i) activation energy used to define the temperature dependence of viscosity, (ii) compositional buoyancy and (iii) linear or non-linear rheology. The main purpose of this numerical study was to understand under which conditions the continental tectosphere would be able to survive for several billion years without undergoing a convective instability (in particular, edge driven instability), despite being both cold and thick. The large lateral thermal gradients required to match the oceanic and continental structures initiate the dominant instability (a "drip") which develops at the side of the continental lithosphere and migrates beneath its center. High activation energies and high background viscosities restrict the amount and rate of entrainment. It was confirmed that the compositional buoyancy of the SCLM does not significantly change the flow pattern. Rather, compositional buoyancy tends to slow the destruction process and reduces the stress within the continental root. With a non-Newtonian rheology, this reduction in stress helps to stiffen the

SCLM. In contrast to the previous study (Doin et al., 1997), Shapiro et al. (1999) found lower rates of SCLM ablation and documented long-term stability of cratons over a broad range of model parameters. They, in particular, concluded that dynamical systems that adequately model the present ocean-continent structures should have an activation energy greater than 180 kJ/mol, which is actually much below the actual estimate of activation energy for olivine (520 kJ mol), which is major component of the SCLM (Shapiro et al., 1999).

A number of further 2D numerical studies focused on the difficulty of preserving the SCLM over Gyr timescales (Lenardic et al., 2000, 2003; O'Neill and Moresi, 2003; Sleep, 2003; Cooper et al., 2004; O'Neill et al., 2008). Specifically, Lenardic et al. (2000, 2003) conducted numerical experiments with a model time up to 100 Myr and concluded that the two most often invoked factors of SCLM preservation, chemical buoyancy and/or high viscosity of cratonic root material, are relatively ineffective if cratons come into contact with a subduction zone. The author found that having a high continental root viscosity can provide stability and longevity of the SCLM, but only within a thick root limit in which the thickness of the chemically distinct, high-viscosity cratonic lithosphere exceeds the thickness of old oceanic lithosphere by at least a factor of 2. It was also concluded that a much higher brittle yield stress for the cratonic lithosphere, compared to oceanic lithosphere, is required for stability and longevity of the SCLM. The variations of yield stress between cratonic and oceanic lithosphere required for stability and longevity can be decreased if the cratons are bordered by a continental lithosphere which has a relatively low yield stress, i.e., mobile belts, which often surround Archean cratons, and can thus buffer them from mantle derived stresses (Lenardic et al., 2000, 2003). However, erosion of the mobile belts on the timescale of few tens of million years was documented in the models (Lenardic et al., 2000, 2003), which question the long-term buffering efficiency of these tectonic features. Recently, Yoshida (2010, 2012) demonstrated numerically in 3D that deformable continents and weak mobile belts might indeed remain mutually stable over timescales (~2000 Myr) which are relevant for the supercontinent cycle (Yoshida and Santosh, 2011). He demonstrated that weak mobile belts plays a primary role in the longevity of cratonic lithosphere, even if the viscosity contrast between the cratonic and oceanic lithospheres is quite high (up to 10^3), whilst the high-viscosity of cratonic lithosphere may only play a secondary role (Yoshida, 2012). O'Neill and Moresi (2003) explored numerically the longevity of the diamond stability field in SCLM for systems with chemically distinct continental crust and a strongly temperature-dependent mantle viscosity. They concluded that, although models frequently produce the temperature conditions needed to form diamonds within the Archean lithosphere, the temperature fluctuations experienced within the modeled mantle lithosphere are generally able to destroy these diamonds within 1 Gyr (O'Neill and Moresi, 2003). This conclusion was somewhat relaxed in the later work by O'Neill et al. (2008), in which they incorporated an endothermic phase change at 670 km, and a depth-dependent viscosity structure consistent with post-glacial rebound and geoid modeling. They found that cratons are unconditionally stable in such systems for a plausible range of viscosity ratios between the root and asthenosphere (50–150), and the root/oceanic lithosphere yield strength ratio (5–30). According to these newer models, realistic mantle viscosity structures have a limited effect on the average background cratonic stress state, but do buffer cratons from extremely high stresses. Under Precambrian mantle conditions, the dominant effect is the drastic viscosity drop which results from the existence of having a hotter mantle conditions in the past. This results in a large decrease in the cratonic stress field, and promotes craton survival under the evolving mantle conditions of the early Earth (O'Neill et al., 2008). It was also proposed that the convectively stable cratonic roots extend the lifetime of the diamond stability field in the SCLM. However, while the residence time of diamonds in the models approached the order of magnitude required (284–852 Myr), extremely fortuitous mantle conditions were still required to explain Archean diamonds (O'Neill et al., 2008).

A recent review by King (2005) summarized the findings of the previous numerical models and concluded that the apparent stability of Archean cratons and cratonic keels for billions of years is a difficult observation for geodynamic modeling to explain. It was pointed out that in numerical studies, strong and buoyant cratonic keels typically survive relatively undeformed for several mantle overturn times (the equivalent of several hundred million years), however extending this result to several billion years remains a challenge. The strength required to stabilize keels in some of these numerical experiments exceeds reasonable estimates of the laboratory measurements of the strength of mantle materials (including both the effects of temperature and melt-depletion). In addition, the most common explanation of keel formation, vertical stacking of subducted plate, requires the keel material to be deformable at the time of formation and soon afterward the keel material must becomes strong enough to resist shearing. It was also concluded that the extent to which cratonic keels interact with and influence the pattern of mantle convection, by nucleating small-scale edge-driven convection, or by coupling plate motions to deeper mantle flow, remains an open question (King, 2005).

New insight into the controversial issue of the SCLM stability has been recently provided by the numerical study of Beuchert et al. (2010), based on 2D viscoelastic mantle convection models in the stagnant lid regime. The author indicated that previous difficulties with reproducing long-term stability of SCLM could be in part caused by choosing ad hoc upper limits for viscosity variations in models. It was demonstrated that the question whether cratons are stable in numerical experiments with Gyr model time depends, for a given craton thickness, both on the Rayleigh number and imposed temperature-dependent viscosity ratio. If the viscosity ratio is fixed at too low value, or too low maximal viscosity cutoff is introduced, cratons do not remain stable over long geological times. In contrast, more realistic higher temperature-dependent viscosity ratios for the Earth's mantle indicated by laboratory experiments ensure stability of cratonic roots. Within the framework of stagnant lid convection, these new numerical modeling results showed that a large temperature-dependent viscosity ratio between cold cratonic lithosphere and the convecting mantle can indeed provide for long term stability of cratonic lithosphere, even for realistically high Rayleigh numbers and without introducing compositionally increased viscosity of the craton (Beuchert et al., 2010).

Long-term stability of cratons has recently been supported by 3D numerical models of global mantle convection with self-consistent plate tectonics and continents (Rolf and Tackley, 2011; Coltice et al., 2012) (Fig. 8). Allowing for very high maximal viscosity of continents (10^{26}–10^{27} Pa s, Tobias Rolf, personal communication) in these models results in their stability on a timescale >5 Ga (Rolf and Tackley, 2011; Coltice et al., 2012). It was also found that the long-term stability of a craton in such a 3D spherical, global mantle convection model can be achieved if the viscosity and yield strength are sufficiently higher than those of the oceanic lithosphere (Fig. 8a), indeed confirming conclusions derived in some previous 2D studies (e.g., Lenardic et al., 2003). Stable cratons facilitate subduction initiation and have a critical influence for global plate dynamics (Fig. 8) (Rolf and Tackley, 2011). In particular, it was demonstrated numerically that the presence of stable cratons explains the observed distribution of seafloor ages (Fig. 8b), suggesting that present-day subduction affects lithosphere of all ages (Coltice et al., 2012). This peculiar terrestrial distribution is at odds with the theory of thermal convection which predicts that subduction should happen once a critical age has been reached. The simulations show that plate-like behavior and the presence of continents are the two necessary ingredients to build a model in which a young seafloor is subducted, as is observed on Earth (Fig. 8c–f). Continents constrain the location and geometry of the downwellings that cool the Earth's mantle. When subduction is confined at an ocean-continent boundary, convection forces the subduction of very young seafloor. Such a situation is favored by continental growth and dispersal (Coltice et al., 2012). Applying similar global spherical models to geodynamic settings relevant for Archean times may strongly contribute to resolving the controversy of craton formation, evolution and long-term stability and remains as a future challenge.

5. Future modeling directions

It is obvious from the overview presented here that numerous key issues of Precambrian geodynamics have not yet been explored systematically and should receive more attention in the near future. Future studies will likely focus on the development of realistic self-consistent high-resolution 2D and 3D models taking into account exogenic and endogenic conditions of the early Earth (e.g., Hansen, 2007; van Hunen and van den Berg, 2008; Rey and Coltice, 2008; Sizova et al., 2010 and references therein). Progress will critically depend on the continued development of self-consistent global mantle convection and plate tectonic models for present day conditions, in which realistic one-sided subduction (Fig. 15), deformable continents (Fig. 16) and thermal–chemical plumes (Torsvik et al., 2010) can spontaneously initiate, and which closely match a suite of available geological and geophysical observations (e.g., Stadler et al., 2010; Torsvik et al., 2010; Yoshida, 2010; Yoshida and Santosh, 2011; Coltice et al., 2012; Crameri et al., 2012). Exploration of these models for Precambrian geodynamic conditions will likely contribute to the development of a successful paradigm of global geodynamics and lithosphere tectonics for this geological time period (Benn et al., 2006).

The following key issues remain as challenges for self-consistent numerical thermomechanical modeling.

1. Formation and evolution of thick and rheologically strong subcontinental lithospheric mantle. On one hand, a relatively weak rheology for SCLM is required to allow for an efficient initial thickening. On the other hand, a strong rheology of SCLM is required to ensure its longevity. Fluids, melts, compositional changes and cooling are proposed to explain this rheological transition, however no self-consistent model comprising both SCLM formation and SCLM evolution has been developed.
2. Long-term stability and dynamics of ultra-hot accretionary Archean orogens. It is not yet entirely clear what are the global and regional

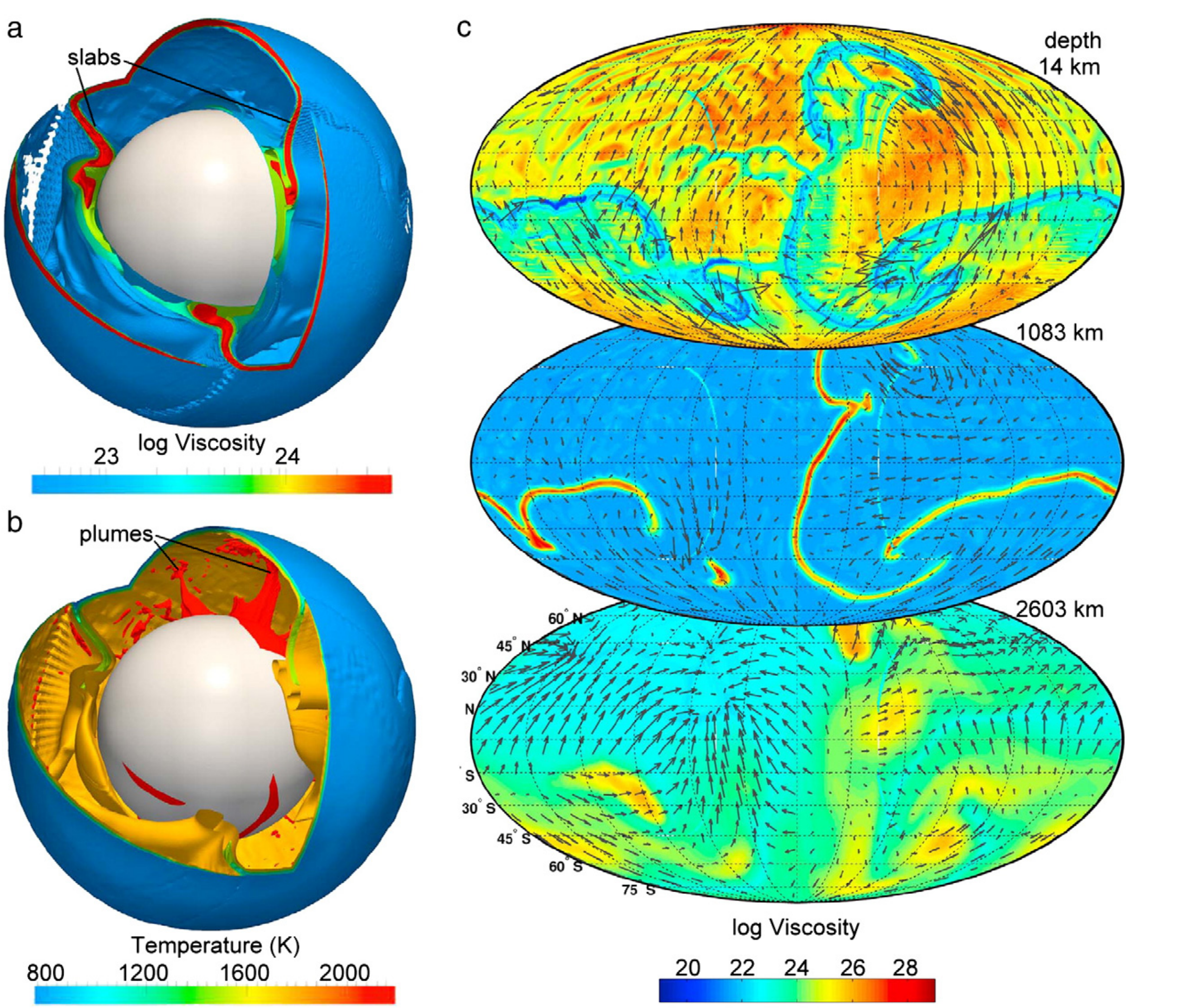

Fig. 15. Example of 3D numerical models of global mantle convection with self-consistent one-sided subduction, mantle plumes and a free surface (Crameri et al., 2012). All plates are oceanic, no continents are prescribed.

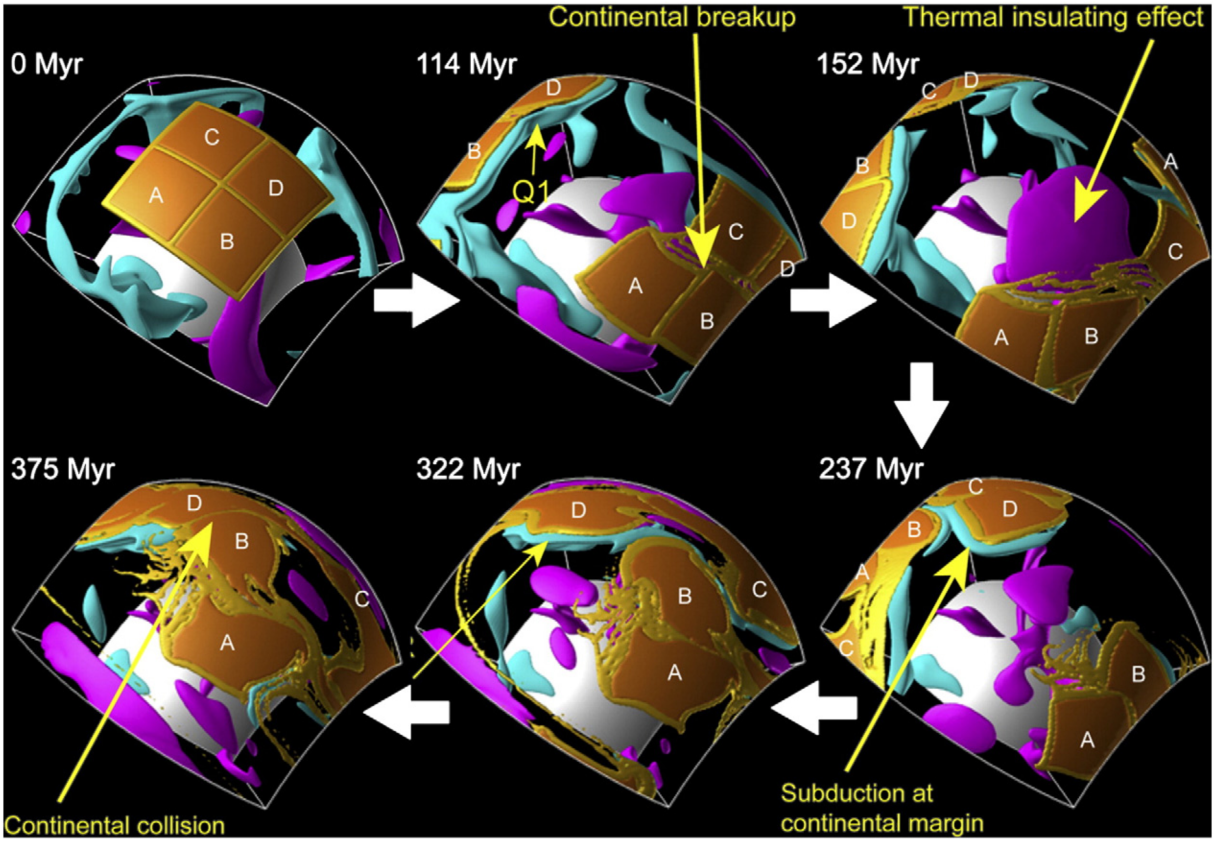

Fig. 16. Time sequence of 3D mantle convection with deformable, mobile continents (Yoshida and Santosh, 2011). The supercontinent is initially composed by the four continental fragments (named 'A' to 'D'), surrounding by the weak (low-viscosity) continental margins (light orange), and it instantaneously imposed on the well developed mantle convection with temperature-dependent rheology (Yoshida, 2010).

styles of coupled, crustal-mantle evolution associated with this type of orogeny. Mantle downwellings and lithospheric delamination processes are proposed for assembling and stabilizing the hot orogens. This issue is strongly related to the rheology and evolution of the SCLM which formed under the orogens. Also, the strong three-dimensionality of the orogenic deformation in the Precambrian is suggested by structural and petrological data, however high-resolution thermomechanical models developed are presently limited to 2D.

3. Growth, assembling and differentiation of the continental crust in the Archean. Several hypotheses were proposed to explain this process: plume tectonics, episodic subduction with arc-like processes, lithospheric accretion and gravitational sorting of proto-oceanic lithospheres, collisions of proto-continental lithospheres and crustal gravitational redistribution. Current numerical models of crustal growth and differentiation are highly simplified and thus arguably quite limited. Geochemical variations remain largely unexplored in the models. This issue is again related to the formation and evolution of the SCLM underneath the crust.
4. Relationship between geodynamic and surface processes in the Precambrian. Low topography in the Precambrian is suggested based on both natural data and theoretical models. To date, no systematic coupled thermomechanical-landscape evolution modeling has been performed and compared with available geological record.
5. Evolution of global mantle convection and lithospheric dynamics in the Precambian. Several transitions in the global style of dynamics were proposed from regional 2D models, however the construction and validation of self-consistent, high-resolution 3D global thermomechanical models remains as a future challenge. The relationship between global lithospheric and plume tectonics for the Precambrian remain unclear.

6. Conclusions

Precambrian geodynamics remains a controversial and thus unresolved barrier in furthering our understanding of the evolution of the Earth. The specific challenge of Precambrian geodynamics is that presently there does not exist an approved paradigm of global geodynamics and lithosphere tectonics for the early Earth, such as exists for modern-day plate tectonics, within which growing observations and analytical data can be employed for validation. In this review, we focused on three critical aspects, namely (i) subduction and plate tectonics, (ii) collision and orogeny and (iii) craton formation and stability. The three key features of Precambrian Earth evolution are outlined based on combining available observations and numerical and analogue models. These are summarized below:

Subduction and plate tectonics. Archean geodynamics was dominated by plume tectonics and lithospheric delamination (dripping-off) processes. Both oceanic-like and continental-like lithospheres were rheologically weak due to the high Moho temperature (>800 °C) and melt percolation from hot partially molten sublithospheric mantle, which precluded development of stable subduction. Wide spread development of modern-style subduction on Earth started during Mesoarchean–Neoarchean at 3.2–2.5 Ga. This is marked by the appearance of paired metamorphic complexes and the oldest eclogite ages in subcontinental lithospheric mantle. Numerical models suggest that the transition occurred at mantle temperatures 175–250 °C higher than present day values been triggered by stabilization of rheologically strong plates of both continental and oceanic type. Due to the hot mantle temperature, slab break-off was more frequent in the Precambrian time causing more episodic subduction compared to present day.

Collision and orogeny. Archean time was characterized by hot accretionary orogens with low topography, three-dimensional deformation and pronounced gravitational tectonics. Mantle downwellings and lithospheric delamination (dripping-off) processes are likely to have played a key role in assembling and stabilizing the hot orogens on a timescale up to hundreds of millions of years. Wide spread development of modern-style (cold) collision on Earth started during Neoproterozoic at 600–800 Ma and is thus decoupled from the onset of modern-style subduction. Cold collision created favorable conditions for generation of ultrahigh-pressure (UHP) metamorphic complexes which become widespread in Phanerozoic orogens. Numerical models suggest that the transition occurred at mantle temperatures 80–150 °C higher than present day values and associated with stabilization of the continental subduction. Frequent shallow slab break-off limited occurrence of UHP rocks in the Precambrian time.

Craton formation and stability. Mechanisms of cratonic lithosphere formation are not yet fully understood, but generally fall into three major categories suggested on the basis of mainly petrologic/geochemical evidence: (1) high-degree melting in a very hot (>1650 °C) plume head, (2) accretion of either oceanic and/or arc lithosphere and (3) continental collision. Numerical models suggest that the long-term stability of cratons sustaining multiple supercontinent cycles can be achieved if their viscosity and yield strength are sufficiently high and weak mobile belts are present along the boundaries of the cratons. Stable cratons facilitate subduction initiation and have a critical influence for global plate dynamics, in particular forcing the subduction of very young seafloor during continental growth and dispersal.

Continued research is required to develop a consensus regarding the geodynamics of the Precambrian era. This challenge requires cross-disciplinary efforts with a special emphasis placed upon quantitative testing of existing geodynamic concepts and applying 2D and 3D thermomechanical models, which have been validated for the modern Earth, to geodynamic settings relevant to the Precambrian period.

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