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Contrasting styles of Phanerozoic and Precambrian continental collision

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ABSTRACT

There are differences in the style of collisional orogens between the Phanerozoic and the Precambrian, most notably the appearance of blueschists and ultrahigh pressure metamorphic (UHPM) rocks in the geological record since the late Neoproterozoic, whereas these rocks are absent from older orogens. Understanding collisional orogenesis in the context of present-day values for ambient upper-mantle temperature and radiogenic heat production provides a reference from which to extrapolate back to conditions in the Precambrian. To evaluate differences in the way Phanerozoic and Precambrian collisional orogens develop, a series of experiments was run using a 2-D petrological–thermomechanical numerical model in which the collision of spontaneously moving continental plates was simulated for values of ambient upper-mantle temperature and radiogenic heat production increasing from those appropriate to the present-day. Thus, models of modern collisional orogens involving different modes of exhumation of UHPM rocks were extrapolated back to conditions appropriate for the Precambrian. Based on these experiments an increase of the ambient upper-mantle temperature to >80–100 K above the present-day value leads to two distinct modes of collision that are different from the modern collision regime and for which the terms truncated hot collision regime (strong mafic lower continental crust) and two-sided hot collision regime (weak felsic lower continental crust) are proposed. Some Proterozoic orogens record post-extension thickening to generate counter-clockwise metamorphic *P*–*T* paths followed by slow close-to-isobaric retrograde cooling, such as occurred in the Paleoproterozoic Khondalite belt in the North China craton and the late Mesoproterozoic–early Neoproterozoic Eastern Ghats province, part of the Eastern Ghats belt of peninsular India. These orogens have similarities with the truncated hot collision regime in the numerical models, assuming subsequent shortening and thickening of the resulting hot lithosphere. Other Proterozoic orogens are characterized by clockwise looping metamorphic *P*–*T* paths and extensive granite magmatism derived from diverse crustal and subcontinental lithospheric mantle sources. These orogens have similarities with the two-sided hot collision regime in the numerical models. Both regimes are associated with shallow slab breakoff that precludes the formation of UHPM rocks. The temperature of the ambient upper-mantle where this transition in geodynamic regimes occurs corresponds broadly to the Neoproterozoic Era.

1. Introduction

The relevance of studies of modern collisional orogens to understanding collisional orogenesis in the Precambrian is still an enigmatic issue. For this reason it is common to use a uniform approach based on the plate tectonics paradigm to interpret Precambrian geology and continental reconstructions (e.g. Cawood et al., 2006; Condie and Kröner, 2008; de Kock et al., 2009). Indeed, there are many similarities in rock types between modern and Proterozoic orogens, such as the presence of dismembered ophiolite complexes and eclogites (e.g. Moores, 2002; Brown, 2006, 2007, 2008), as well as a number of changes during the late Archean in the style and chemistry of magmatic rocks (e.g. Valley et al., 2005; Smithies et al., 2007; Condie, 2008; Martin et al., 2010; Keller and Schoene, 2012), the rates of addition of juvenile crust vs. crustal reworking (Dhuime et al., 2012), and the sites of continental growth (Condie and Kröner, 2013) that are consistent with a global plate tectonics regime during the Proterozoic and, perhaps, during the Neoarchean. In addition, seismic reflection and refraction surveys have determined the internal architecture of the continents (e.g. Korja and Heikkinen, 2005; Hammer et al., 2010) and identified dipping structures that displace the Moho (e.g. Calvert et al., 1995; Oueity and Clowes, 2010) back to the Neoarchean, features that are consistent with terrane accretion and collisional orogenesis.

These geological, geochemical and geophysical data from Neoarchean and Proterozoic provinces require the elimination of ocean basins by subduction of oceanic lithosphere, consistent with the large lateral displacement of cratons that are recognized based on paleomagnetic data (e.g. Evans and Mitchell, 2011), which has led many researches to the conclusion that a plate tectonics regime similar to that on modern Earth operated in the Precambrian, perhaps from as early as the late Mesoarchean (e.g. Condie and Pease, 2008; Condie and O'Neill, 2010;

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Gerya, 2014). However, there are no examples of blueschists or evidence of the deep subduction of continental crust in the form of exhumed ultrahigh pressure metamorphic rocks in the geological record before the Neoproterozoic (e.g. Brown, 2006, 2007). Since these features are characteristic of the Phanerozoic style of plate tectonics and collisional orogenesis, some researchers have concluded that the modern plate tectonics regime began only during the Proterozoic (e.g. Hamilton, 1998), possibly as late as the Neoproterozoic (e.g. Stern, 2005; Hamilton, 2011). Thus, a purely uniformitarian approach to collisional orogenesis in the Precambrian may be inappropriate. Indeed, there is a growing body of research pointing to a distinct style of deformation and metamorphism in Neoarchean and Paleoproterozoic orogens (e.g. Choukroune et al., 1995; Rey et al., 2003; Cagnard et al., 2006; Rey and Houseman, 2006; Cagnard et al., 2007; Chardon et al., 2009; Cagnard et al., 2011).

It is only recently that parameterized numerical modeling and analog experiments have been used to investigate the stabilization of cratons and major transitions in tectonic regime with secular evolution on Earth (e.g. Rey and Houseman, 2006; Burov and Yamato, 2008; van Hunen and van den Berg, 2008; Gapais et al., 2009; Gray and Pysklywec, 2010; Rey and Coltice, 2010; Sizova et al., 2010; Moyen and van Hunen, 2011; van Hunen and Allen, 2011; Maierova et al., 2014; Vogt and Gerya, 2014). These studies support a mobile lid regime based on lateral displacement of lithospheric plates and elimination of ocean basins by subduction since the Mesoarchean–Neoarchean (e.g. van Hunen and van den Berg, 2008; Sizova et al., 2010; Moyen and van Hunen, 2011). To resolve some of the issues related to the first appearance of blueschists and ultrahigh pressure metamorphic rocks in the geological record during the Neoproterozoic (e.g., Stern, 2005; Brown, 2006, 2007), we have undertaken a systematic investigation of the effects of a warmer ambient upper-mantle, higher crustal radiogenic heat production, changes in thickness and chemical buoyancy of the continental lithosphere, and differences in lower crustal composition and rheology on the style of collisional orogenesis. In particular, we are interested in what conditions earlier in Earth history prevented blueschists and UHPM rocks from developing on Earth prior to the Neoproterozoic.

1.1. Phanerozoic vs. Precambrian orogens

Phanerozoic collisional orogenic systems generally produce characteristic clockwise metamorphic pressure–temperature (*P*–*T*) paths (e.g. Brown, 1993, 2001) and may generate extreme ultrahigh-pressure metamorphism (UHPM) of subducted continental crust (Ernst, 2001; Liou et al., 2004), which may melt during exhumation (Auzanneau et al., 2006), or if subducted past the “point of no return” may be transported into the deep mantle (e.g., Irifune et al., 1994; Domanik and Holloway, 2000; Searle et al., 2001; Dobrzhinetskaya and Green, 2005; Liu et al., 2007; Wu et al., 2009; Faryad et al., 2013). Continental rocks are subjected to ultrahigh-pressure metamorphism (UHPM) at temperatures from ~700 to 950 °C and pressures >2.8 up to 6.0 GPa, corresponding to depths of ~100 to >200 km (e.g. Liou et al., 2004). These UHPM units are subsequently exhumed to middle crustal depths while erosion or younger tectonic events are responsible for final exhumation to the surface.

More than twenty UHPM terranes have been documented all over the world; with two exceptions at 660–655 Ma (John et al., 2004) and 620 Ma (Jahn et al., 2001), all of them are of Phanerozoic age (Brown, 2007). They lie within major continental collision belts and extend for several hundred kilometers along strike; most are in Eurasia, with rare examples in Africa, Central America and Antarctica. Many of the exhumed UHPM rocks exposed at the surface occur as subhorizontal sheets 1–5 km in thickness, bounded by normal faults on the top and reverse faults on the bottom, sandwiched between high-pressure or lower-grade metamorphic units (Kaneko et al., 2000; Ernst, 2001; Liou et al., 2004). Typically, the UHPM rocks now form the cores of antiformal nappe stacks that define structural domes 5–50 km across (Faure et al., 2003; Xu et al., 2006; Epard and Steck, 2008). The upper levels of many HPM–UHPM terranes are dominated by extensional structures formed during and/or after initial exhumation from UHPM conditions (Andersen and Jamtveit, 1990; Ratschbacher et al., 2000; Avigad et al., 2003).

As discussed above, the appearance of UHPM complexes in the geological record during the Neoproterozoic raises an important question about a different style of orogenesis earlier in Earth history. It is widely accepted that the Earth has been cooling since its formation due to the decline in radiogenic heat production (e.g. Abbott et al., 1994; Labrosse and Jaupart, 2007), although the process may not have been monotonic (e.g. Sleep, 2007). The greater rate of production of continental crust prior to 3.0 Ga (Dhuime et al., 2012) and the occurrence of tonalites–trondhjemites–granodiorites and komatiites, which are largely restricted to the Archean (Goodwin, 1991), are consistent with a hotter Earth. Ambient mantle potential temperatures are inferred to have been significantly higher than the present day, which would have led to the production of a greater volume of primary melts with higher MgO (McKenzie and Bickle, 1988; Nisbet et al., 1993; Herzberg et al., 2007, 2010).

Although there is no debate about a hotter ambient upper-mantle in the past, there is considerable uncertainty in the estimate of how much hotter it might have been. Based on Labrosse and Jaupart (2007) and Herzberg et al. (2010), the ambient upper-mantle temperature from the Paleoarchean to the Paleoproterozoic might have been 250–150 K higher than the present day. Even at 1.0 Ga the ambient upper-mantle temperature was probably ~100 K warmer than at present, and it was probably ~60 K warmer at the dawn of the Phanerozoic. However, field observations of the Archean sediment record and experimental determination of phase relations in hydrous komatiitic melts have shown that the upper mantle liquidus temperatures could not have been much hotter than today (<100 °C; Galer, 1991; Campbell and Griffiths, 1992; Grove et al., 1994; Parman et al., 1997). Higher ambient upper-mantle temperatures are likely to affect the rheology and tectonics of the lithosphere (e.g. Davies, 1992; de Wit, 1998; Burov and Yamato, 2008; van Hunen and van den Berg, 2008; Sizova et al., 2010).

Archean and Paleoproterozoic orogens in particular commonly comprise large areas of monotonous high-temperature, low-to-moderate pressure metamorphic rocks with extensive magmatism that has contributed significantly to crustal growth (e.g. Brown, 2007; Ahäll and Connelly, 2008; Gapais et al., 2009; Kukkonen and Lauri, 2009; Smithies et al., 2011; Dhuime et al., 2012; Percival et al., 2012). These orogens formed above warmer mantle than modern orogens, and remained hot and mechanically extremely weak during deformation over protracted periods of time; Chardon et al. (2009) referred to these as ultra-hot orogens. Rey and Houseman (2006) and Gapais et al. (2009) argued that convergence involving warm and rather weak, buoyant lithosphere in the Precambrian would result in more homogeneous lithospheric deformation that would be reflected in the distributed patterns of strain, lower topographic relief and lower exhumation rates characteristic of these orogens. Even at the end of the Proterozoic Era, granulite and ultrahigh temperature metamorphism occurs in most of the orogenic belts that suture the cratonic elements of Gondwana (Cawood and Buchan, 2007).

Brun (2002) proposed that the fundamental difference between ultra-hot orogens and cold orogens is the Moho temperature, which determines the strength of the upper mantle, and Burov and Yamato (2008) used numerical experiments to investigate the importance of Moho temperature in controlling the style of collisional orogenesis. Burov and Yamato (2008) identified that continental subduction is possible only in the case of strong mantle lithosphere characterized by Moho temperatures below $T_m<500$ °C; thus, the formation and exhumation of UHPM rocks can only occur in this regime. Increasing Moho temperature leads to lithospheric folding at $500\ °C<T_m<650\ °C$ or pure shear thickening at $550\ °C<T_m<650\ °C$, and finally to Rayleigh–Taylor instabilities at $T_m>650$ °C. Subsequently, Gray and Pysklywec (2010) used numerical experiments to investigate the behavior of continental lithosphere during Neoarchean collision taking into