The structural, metamorphic and magmatic evolution of Mesoproterozoic orogens

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1. Introduction

The Mesoproterozoic (1600 to 1000 Ma) is an Era of Earth history that has been defined in the literature as being quiescent in terms of both tectonics and the evolution of the biosphere and atmosphere (Holland, 2006; Piper, 2013b; Young, 2013). The 'boring billion' is an informal term that is given to a time period overlapping the Mesoproterozoic period, extending from 1.85 to 0.85 Ga (Holland, 2006). Orogenesis was not absent from this period however, with various continents featuring active accretionary orogenesis along their margins for the entire Mesoproterozoic (see Condie, 2013; Roberts, 2013), and others featuring major continental collisional orogenesis that relates to the formation of the supercontinent Rodinia towards the end of the Mesoproterozoic. Looking at it another way, this period followed the formation of perhaps the first long-lived supercontinent , Columbia (a.k.a. Nuna), and then it prepared the ground for the momentous geological and biological events in the Neoproterozoic that paved the way for the Cambrian explosion of life. As such it is a very important period of Earth history to understand better.

Do orogens formed in the Mesoproterozoic differ from those formed in the recent past, or those formed in early Earth history, and if so in what way? Do orogens in the Mesoproterozoic have distinct structural, metamorphic or magmatic characteristics? How are Mesoproterozoic orogens related geodynamically and kinematically? These are overarching questions that this collection of sixteen research papers aims to address. This introduction presents a brief discussion of the contribution of these papers to these questions and topics.

2. Mesoproterozoic history

The Mesoproterozoic Era is dominated geologically by the break-up of the Columbia supercontinent (also known as Nuna), and the formation of the Rodinia supercontinent at the end of the Mesoproterozoic into the Neoproterozoic. Columbia is perhaps the first true supercontinent (Senshu et al., 2009) and formed between 2.0 and 1.7 Ga (Rogers & Santosh, 2002, 2009; Meert, 2012). Maximum assembly of the continents based on the ages of collisional events is inferred to be around 1.9-1.85 Ga (Rogers & Santosh, 2009). Collisional orogenesis down to 1.6-1.5 Ga may also reflect continued formation of this supercontinent (Cutts et al., 2011). The palaeogeography of Columbia has been described by several workers, largely based on geological fit (i.e. orogenic belts and dyke swarms) and palaeomagnetism (e.g. Zhao et al., 2002; Rogers & Santosh, 2002; Zhang et al., 2012; Pisarevsky et al., 2014). The lack of key palaeopoles for all the continents at regular time intervals, however, precludes any current consensus. For example, Amazonia has been traditionally placed adjacent to Baltica for the entire Mesoproterozoic (e.g. Zhao et al., 2002; Pesonen et al., 2003; Johansson, 2009), but has recently been placed on the other side of Laurentia, and replaced by India (Pisarvesky et al., 2013); such different views highlight the lack of certainty of the global arrangement of continents. With continued effort towards dating mafic intrusions and constructing palaeopoles, the future will no doubt reveal a better constrained supercontinent history prior to the Neoproterozoic (see Evans, 2013; Pisarevsky et al., 2014).

The hypothesis of the supercontinent cycle (see Worsley et al., 1984; Nance & Murphy 2013) implies that Columbia would break-up, continents would disperse, and then they would re-amalgamate to form the next supercontinent (i.e. Rodinia). However, the break-up of Columbia is debated. Some authors infer break-up based on the numerous mafic dyke swarms and other intrusive rocks of various ages that are found across several continents (e.g. Hou et al., 2008; Zhang et al., 2009; Fan et al., 2013). As discussed by Roberts (2013), however, these generally only provide evidence for localised extension, and not necessarily a full rift to drift transition. Both Piper (2013a) and Roberts (2013) suggest that Columbia may have been more akin to a continental lid (i.e. single continental landmass), reforming from Columbia to Rodinia without true dispersal.

The supercontinent Rodinia lacks well-constrained palaeogeographic details for some of its constituent continents (see Evans, 2013), but also features well-documented correlations that have been consistently advocated for decades, for example, the link between Laurentia and Baltica (NENA; Gower et al., 1990; Karlstrom et al., 2001). Rodinia formed around ca. 1.0 Ga, with its collisional orogenesis probably beginning ca. 1.1 Ga and continuing to ca. 0.9 Ga (see Li et al., 2008; Evans, 2009). The evidence of continental collisional orogenesis is found on many cratons (e.g. Laurentia, Baltica, Amazonia, Australia, Antarctica, India, Kalahari). Some of these have been extensively studied for decades, such as Laurentia, whereas others are much less exposed and only have minor evidence of orogenesis at this age (e.g. South China, Li et al., 2002; Song et al., 2012); for others the evidence is debated (e.g. Baltica, Slagstad et al., 2013a, b; Möller et al., 2013). As with Columbia, the increasing palaeomagnetic database, along with refined geological knowledge, will enable a better understanding of the exact history of Rodinia in the future.

2.1. A note on terminology

At this point, it is relevant to make a note on some of the variable use of terminology associated with the Mesoproterozoic. The Grenville Orogen (e.g. Rivers, 1997) is based on geological evidence found in the Grenville Province of Laurentia (eastern Canada and eastern and southern Unites States). Some orogens have been directly correlated with the Grenville, for example the Sveconorwegian in Baltica along strike (e.g. Bingen et al., 2008; Möller et al., in press), and the colliding Amazonia craton (e.g. Tohver et al., 2006; Ibanez-Mejia et al., 2011). These are correctly termed the Sveconorwegian and Sunsas-Putamayo Orogens, respectively, and are equivalent in *age* and other first order features to the Grenville Orogen. Many authors refer to Grenvillian orogenesis in other regions, for example Australia, China, South Africa etc. However, although these may be equivalent in age, they display no evidence that they were directly part of the same contiguous orogen as that of the Grenville Province, and thus the term Grenvillian is misleading. We advocate the use of Rodinia-forming orogen, for collisional orogens that can be linked to the formation of this supercontinent, regardless of their geographical location. But otherwise, temporal associations are best kept to those defined by the geological timescale, e.g. late Mesoproterozoic or Tonian, and spatial associations are best kept to terms that are locally derived, for example, Grenville, Sveconorwegian, Musgrave, Albany-Fraser.

2.2. Accretionary orogens

The term 'boring billion', which encompasses the entire Mesoproterozoic, was defined based on biological and climatic stasis (Holland, 2006). However, there may be an underlying link to tectonics. For example, if there was a clear lack of continental dispersion during the Columbia to Rodinia supercontinent transition, i.e. a long-lived arrangement of continents and oceans, then this in turn may have allowed for prolonged stasis within the hydrosphere and atmosphere (see Roberts, 2013). Palaeomagnetic evidence favours the lack of break-up between some clusters of continents, such as Laurentia, Baltica and Siberia, but indicates that other continents have drifted substantially relative to these and each other (see Meert, 2014; Pisaversky et al., 2014). Regardless of the drift between continents, tectonic activity along the margins of the continents and supercontinents was far from quiescent.

Except for some radial dyke swarms, most geological activity during this Era can be related to events occurring along convergent margins. Many of the continents feature a long-lived history of accretionary activity, namely magmatism in continental and oceanic volcanic arcs, and accretion of these arcs to cratonic margins. Some continents feature a history of long-lived accretionary orogenesis that accounts for large volumes of crustal growth, and which was continuous throughout the Mesoproterozoic. These include Laurentia, Baltica and Amazonia (see Karlstrom et al., 2001; Johansson, 2009). Other cratons are characterised by accretionary orogens of shorter duration, at least in the preserved geological record, for example the North China Craton (Deng et al., 2013), Australia (Betts & Giles, 2006) and India (Dharma Rao et al., 2013). These orogens generally developed around the margin of the Columbia supercontinent, and may have been linked via a single convergent margin, analogous to the Pacific Rim of present day (Great Proterozoic Accretionary Orogen, Condie, 2013; Roberts, 2013).

Orogenesis during the early part of the Mesoproterozoic, before the Rodinia-forming events, can generally be ascribed to arc-collision events. Those that relate to major continental collisions between cratons are rare to non-existent. Even evidence such as high-grade metamorphism does not signify continent-continent collision. For example, the Hallandian orogen of southern Sweden has been postulated as an effect of a Baltica-Amazonia collision (Bogdanova et al., 2001), but has more recently been suggested to relate to an Andean-type orogen (Roberts and Slagstad, 2014; Ulmius et al., this issue).

3. Uniformitarianism

Uniformitarianism is a traditional approach used in Earth Science (Hutton, 1788; Windley, 1993b), but since some physical characteristics of the Earth have changed over time (e.g. mantle temperature; see Fig. 1a, Herzberg et al., 2010), it is now commonly accepted that limitations to this approach will exist. For example, crust-forming processes in the Hadean are generally thought to be quite different to those of today (see Roberts et al., 2015; Kamber, 2015). A question underlying this special issue is therefore how does Mesoproterozoic orogenesis compare to that of the Phanerozoic? Orogenesis today is dominantly a consequence of horizontal plate motions. Some workers suggest modern-day style plate tectonics did not start until the late Neoproterozoic, implying that a different orogenic style may have existed previously (Stern, 2005; Hamilton, 2011; Piper, 2013a). Conversely, many workers advocate plate tectonic characteristics similar to those of the modern day for Meso- to Neoarchaean rock assemblages (see Roberts et al., 2014); this would imply that the younger Mesoproterozoic Era would also be similar. What can be gleaned from the metamorphic record, is that blueschists and ultra-high- pressure rocks are features limited to orogens younger than ~600 Ma, but that high temperature and high pressure rocks have been formed and preserved for the last ~3000 Ma (see Fig 1b; Brown, 2006; 2014).

The mantle has cooled through time (e.g. Turcotte, 1980; Richter, 1985; Herzberg et al., 2010). This will have an important effect on orogenesis, since the rheology of the mantle and overlying crust is strongly dependent on mantle temperature and water content. Increased mantle temperature will aid melting, and melt weakens the lithosphere (e.g. Rosenberg and Handy, 2005; van Hunen & van den Berg, 2008). Sizova et al. (2014) studied the effects of varying mantle temperatures by numerically modelling Precambrian plate collision scenarios at different mantle temperatures. They showed that Archaean collision would be profoundly different to that of the Phanerozoic, with very large volumes of mantle melting, shallow slab break-off, low topographic elevation, and significant extension in the over-riding and colliding plates (leading to their "truncated hot collisional regime"). The Mesoproterozoic ambient mantle could have been between 80 to 150°C hotter than today's (see Fig. 1a; Herzberg et al. 2010). Under these temperatures, the collisional models of Sizova et al. (2014) are moderately different to those of modern orogens. That model implies that the down-going continental lithosphere undergoes shallow rather than deep slab-breakoff, there is limited formation and no exhumation of UHP blocks, and there is a greater portion of mantle melting and lower topographic elevation. Interestingly, an outcome of these models is that the predicted change from shallow to deep slab break-off occurs at mantle temperatures less than 60°C warmer than today, that is, at the conditions predicted for the late Neoproterozoic, when the exhumation of UHP terranes seen in the rock record began (Sizova at al., 2014; Brown, 2014).

3.1. Style of orogenesis

Comparing orogens is not an easy task, since they vary greatly in spatial and temporal scales, and they evolve through time such that minor collisions may evolve into large hot orogens if there is continued plate convergence. Additionally, old orogens are now deeply eroded, and current orogens are still evolving. Orogens can be classified based on a number of variables. For example, Beaumont et al. (2006) compared orogens based on their magnitude (i.e. extra crustal or lithospheric thickness above standard continental lithosphere) and temperature (i.e. excess heat for this same lithosphere under normal heat production conditions). Different styles of orogenesis can then be described according to these two parameters (see Fig. 1a-c). Arc collisions form small orogens with small amounts of crustal thickening, and small regional temperature increases. The Grenville and Himalaya are described as the type examples of large hot orogens with the greatest areal expanse and crustal thickness. Most collisional orogens fall between these two end-members. Additionally, some orogens exhibit elevated heat flow and will will have been hotter without necessarily having greater crustal thickness, for example those with shortening of back-arc basins (Collins, 2002). One distinct feature of these Temperature-Magnitude (T-M) plots is the interpretation that Archaean orogens would generally be hotter, and thus form a shallower trend to higher temperature with similar magnitudes (see Fig. 2a; Beaumont et al., 2006).

Another classification scheme that is based on similar observations is that of Chardon et al. (2009). These authors use the terms cold orogen, mixed orogen and large hot orogen, which essentially mimic those described by Beaumont et al. (2006). They also define, however, an additional category termed Ultra Hot Orogen, which is based on observations from Archaean terranes such as those exposed in the Dharwar craton (Chardon et al., 2008). The distinctive features of these UHO orogens are distributed strain, thin upper crust and thin lithosphere, limited excess topography and very high crustal temperatures. These orogens would fall to the high temperature side of the T-M diagram (see Fig. 2a), and this characteristic is reliant on long-duration and mantle-heating in factors of their development.

On Figure 2c, the Mesoproterozoic orogens that are described within this special issue are loosely placed. The Natal-Namaqua Orogen (NNO) features a history defined by distinct arc-accretion and collision events (e.g. Colliston et al., this issue). The geological exposures are of deformed arc terranes accreted to a largely unaffected Archean craton. A major colliding plate is inferred but not recorded in the exposed rock record. High-temperatures and moderate pressure granulite-facies have been reached in many areas, but this was not accompanied by excessive crustal thickening. Isobaric cooling is evident from some P-T estimates, which is inferred to result from transpressional and transtensional displacements (Spencer et al., this issue and references therein). As such, the NNO appears to be a small to moderate-sized mixed orogen with an elevated geotherm (see Fig. 2c).

The Albany-Fraser and Musgrave orogens formed during the overall amalgamation of the North, South and West Australian cratons in the mid to late Mesoproterozoic, although some contention over the exact nature of their development still exists. The Musgrave, for example, is postulated by some to result from intracontinental reworking of a slightly earlier orogenic belt (Mount West Orogeny; see Howard et al., 2015 and references therein), whilst others suggest it results from true continental collision between the South and West Australian cratons (see Smits et al., 2014 and references therein). The Albany-Fraser and Musgrave broadly occur along strike relative to the craton margins, have overlapping ages, but formed on distinctly different basement (see Kirkland et al., this issue). These authors show that the Albany-Fraser involved reworking of the Archaean cratonic margin, whereas the Musgrave involved reworking of younger (<2.0 Ga) juvenile crust. A distinct feature of the Musgrave is the very high temperature that was apparently attained for a long duration (e.g. Walsh et al., 2014; Gorczyk et al., 2015), although recently it has been suggested that ultra-high temperatures were only achieved in a shorter thermal pulse (Tucker et al., 2015). The cause of the excessive heat flow is suggested to be mantle heating of a thinned crust, and one that contained high radiogenic heat-producing components (see Howard et al., 2015; Kirkland et al., this issue). The Albany-Fraser orogen was affected by transpression, and this is inferred to be the cause of rapid exhumation of crust after peak metamorphism was reached (Scibiorski et al., this issue). The Albany-Fraser fits in regular T-M space as a moderate-sized mixed orogen (Fig. 2c). The Musgrave on the other hand, with its long duration, hot temperatures and lack of excess crustal thickening is tending towards the field of Ultra Hot Orogens (Fig. 2c).

The Sveconorwegian Province displays a range of tectonic styles across the orogen (see Roberts & Slagstad, 2014). The eastern part in SW Sweden and SE Norway is characterised by large-scale thrusting, crustal imbrications, high-pressure metamorphism and subsequent extensional collapse (Viola and Henderson, 2010; Viola et al., 2011; Möller et al., in press; Piñán Llamas et al., this issue; Scheiber et al., this issue), whereas the western part in SW Norway is characterised by voluminous granitic and anorthositic magmatism and UHT metamorphism (Slagstad et al., 2013a; Drüppel et al., 2013; Coint et al., this issue). A heterogeneous tectonic style across the orogen was pointed out more than 30 years ago (Falkum and Petersen, 1980), but has received little attention since. Reconciling these across-strike differences in a tectonic model that accounts for the metamorphic, magmatic and structural evolution in both time and space remains challenging. The Sveconorwegian orogen as a whole fits somewhere in the middle of the T-M plot (Fig. 2c), whether it be a large Cordilleran orogen (Slagstad et al., 2013a) or a moderate-sized continental collisional orogen (Möller et al., 2013).

The Grenville orogen is not a main focus of this special issue, but has been one of the most intensely studied Mesoproterozoic orogens in the past. The Grenville Province in eastern Canada is characterised by orogen-wide, high-grade metamorphism and deformation (1090 -1020 Ma Ottawan phase, Hynes &

Rivers, 2010; Rivers, 2012 and references therein), interpreted as the main Grenvillian collision. This phase was followed at 1020–980 Ma by the Rigolet phase, characterised by deformation and metamorphism interpreted to reflect post-convergent gravitational spreading (Rivers, 2012). Gravitationally driven extension may have started as early as ca. 1060 Ma at high crustal levels in the Grenville, although most workers assume that convergence lasted until ca. 1020 Ma and that gravitationally driven orogenic extension continued until ca. 980 Ma (Hynes & Rivers 2010; Rivers 2012). Eclogites in various states of preservation are common in the SW Grenville Province (Marsh & Culshaw, 2014) and formed at ca. 1090 Ma, i.e., very early on in the collision. Convergence in the Grenville orogen appears to have been sustained for more than 60 Myr after initial collision (Jamieson et al., 2010), not unlike the Himalaya, making it of significant magnitude to be classified as a large hot orogen (Fig. 2a; Beaumont et al., 2006). However, the orogenesis was not accompanied by significant magmatism and did not feature an excessive geotherm. As such, the Grenville does not conform to an Ultra Hot Orogen. In addition, it lacks steep ductile structures typically associated with Archaean hot orogens, and probably featured elevated topography (see Rivers, 2008, 2009; Jamieson et al., 2010).

The 1.47-1.38 Ga Hallandian orogen has generally been poorly understood due to later overprinting by the Sveconorwegain orogeny. However, work by Ulmius et al. (this issue) has identified high-temperature metamorphism under a strongly elevated geotherm, coeval with granitic magmatism at c. 1450 Ma. These authors interpret the data to reflect an Andean-type accretionary setting, and this may represent an extension of the c. 1.5 Ga Telemarkian event in S Norway (Bingen et al., 2005; Roberts et al., 2013; Roberts and Slagstad, 2014). Based on the known exposures of the Hallandian orogen, it falls under the category of a small transitional orogen with an elevated geotherm (see Fig. 2c).

3.2 Summary of the discussed orogens

Mesoproterozoic orogens clearly exhibit wide variation in their spatial and temporal scales, not dissimilar to orogens of more recent Earth history. Mesoproterozoic orogens do not fall on a distinct trend of magnitude vs. temperature , although many feature anomalous heat flow. In terms of large hot orogens, the Grenville is the only well-documented example comparable in magnitude to the Eocene to present-day Himalayan Orogen. These two orogens display many similarities in the structure we can observe today, although this does not necessarily imply similar mechanisms of crustal deformation during their evolution (see Rivers, 2008; Jamieson et al., 2010). The Musgrave is thus the only example included here that conforms to several of the definitions of an Ultra Hot Orogen, and to our knowledge, lacks a more recent analogue.

‘Transitional’ or ‘Mixed’ orogens (see Fig. 1) are often just that - they have a mixture of processes. The Sveconorwegian Orogen for example, features a bivergent structure in its core, with crustal subduction of two separate lithotectonic units (plates?), perhaps with similarities to the modern Alpine Orogen. Its western part, in contrast, features voluminous magmatism, possibly continuous oceanic subduction, and has similarities to the American Cordillera. When viewed as whole, the Sveconorwegian Orogen appears to be a complex, long-lived hot orogen. But as we start to disentangle this orogenic province, the individual and localized nature of complex collisional, accretionary and magmatic events will become clearer (see Roberts & Slagstad, 2014).

3.3. Magmatism

Magmatism related to orogenesis includes syn-collisional anatectic melting, either on a small-scale (i.e. migmatisation), or on a large-scale whereby melts have coalesced to form plutons. These are variably evident in all Mesoproterozoic orogens. For example, extensive migmatite complexes in the middle crust of the Grenville orogen (Slagstad et al., 2005), syn-tectonic leucosomes formed during extrusion of eclogitic lower crust of the Sveconorwegian Eastern Segment (Piñán-Lamas et al., this issue), and similar observations from other orogenic belts (e.g. Howard et al., 2015), suggest that crustal anatexis is a common result of orogenesis. The Natal orogen provides an example whereby deformed plutons are ascribed to syn-orogenic magmatism in a transcurrent deformational regime (e.g. Spencer et al., this issue), and presumably the migmatites that sourced the exposed plutons are located at depth. Post-orogenic magmatism is recorded in the waning stages of most Mesoproterozoic orogens, either as voluminous plutons (e.g. Sveconorwegian Hornblende-Biotite Granite suite, see Coint et al., this issue), or as mafic dykes and other minor intrusives (e.g. Sveconorwegian Blekinge-Dalarna dolerites; see Roberts & Slagstad, 2014 and references therein). The reason that one of these may occur and not the other, presumably relates to a number of variables, including the extent of crustal thinning, the strength of the crust and the existence of delaminating roots or slabs.

Two characteristics have been drawn out of the geological record as rather distinctive of the Mesoproterozoic, one is the abundance of ‘anorogenic’ or A-type magmatic intrusions, and the other is the abundance of massif-type Anorthosite-Mangerite-Charnockitic magmatism more specifically (Anderson, 1983; Emslie, 1985; Windley, 1993a; Anderson & Morrison, 2005; Vigneresse, 2005; Ashwal, 2010). These magmatic styles have been discussed for several decades. Most (but not all) recent publications on both A-type magma suites (e.g. Åhäll et al., 2000; Menuge et al., 2002; Slagstad et al., 2009) and anorthosite provinces (e.g. Bybee et al., 2014), now place their formation within the greater context of convergent margin activity, thus weakening or negating their 'anorogenic' classification. Bickford et al. (this issue), in their synthesis of Laurentian examples, suggest that complex interactions between the asthenosphere and lithosphere, subsequent to arc magmatism and accretion, are an underlying cause. It has been shown that in general, these magmas form by partial melting of dry lower crust (either newly underplated or pre-existing), requiring high temperatures, attributable to mantle heating (e.g. Frost & Frost, 2010; Kirkland et al., this issue).

The prevalence of Mesoproterozoic anorthosites has been related to the formation of a stable supercontinent, and associated heat-flow from a thermal blanketing effect (Hoffman, 1989; Vigneresse, 2005). Bédard (2009) in contrast, suggests this occurrence may purely be a result of secular cooling of the Earth, whereby in the Archaean, continental crust is presumed to be too weak to thicken tectonically, and in the Phanerozoic, the mantle was too cool to reach the elevated temperatures needed to form anorthosite parent magmas (see also Cawood & Hawkesworth, 2014).

3.4. Structure and metamorphism

The structural and metamorphic characteristics of Mesoproterozoic orogens are highly varied, and they exhibit a range of styles, magnitudes and peak-temperatures. There is no unique set of characteristics that defines these orogens, and their first-order structural framework and development appears to be comparable to those of orogens formed in the Phanerozoic. The elevated temperatures of some Mesoproterozoic orogens are generally localised and related to elevated heat flow from coeval magmatism and/or mantle heating. Transpressional deformation may have led to isobaric cooling in some orogens (e.g. Natal; Spencer et al., this issue), and rapid exhumation in others (e.g. Albany-Fraser; Scibiorski et al., this issue). High-pressure metamorphic conditions are generally ascribed to processes of burial of crust via shortening and movement along crustal-scale shear zones, generally at low-angle (see Tual et al., this issue; Piñán-Llamas et al., this issue). High temperature metamorphism is ascribed to localized elevated heat flow driven by magmatism (see Coint et al., this issue), and/or more regionally elevated heat flow driven by mantle heating under thinned crust (see Kirkland et al., this issue).

Bivergent structures can be observed in some of the well-exposed orogens such as the Sveconorwegian. In the Namaqua-Natal orogen, a major colliding plate has not been identified. What is observed is only one side of the orogen, with hinterland-dipping thrusts , bringing allochthonous material onto the craton, like the Scandinavian Caledonides in the Phanerozoic. Modern orogens feature regions of orthogonal convergence and adjacent regions of more oblique convergence. They also feature regions of tectonic escape where crust (upper, lower or both), is translated around the motion of an indenter. For example, the large fault zones of SE Asia (Molnar & Tapponier, 1975; Tapponier et al., 1982). The transpression recorded in shear zones in Mesoproterozoic orogens may also relate to such features of tectonic extrusion. However, this has not been discussed in detail in the literature for Mesoproterozoic orogens, perhaps because the obscured relationships between orogenic belts mean these features are not readily apparent. This feature of orogenic evolution is worthy of further study for the Mesoproterozoic.

Another facet of structural evolution is the reactivation of structures (Viola et al., 2009; Mattila and Viola, 2014; Scheiber et al, this issue). Orogens are generally thought to involve first crustal thickening, and then, due to gravitational instability, their collapse. The latter facilitated by reactivation of thrust structures into normal shear zones and faults. Large shear zones in Mesoproterozoic orogens, such as the "Mylonite Zone" and Kristiansand-Porsgrunn-Shear-Zone of the Sveconorwegian orogen, have a long-lived history of reactivation (Mulch et al., 2005; Viola and Henderson, 2010; Viola et al., 2011; Scheiber et al., this issue), and are often suggested to originate as orogenic sutures (e.g. Bingen et al., 2008; Cornell & Austin Hegardt, 2004; Petersson et al., 2015b). The continued re-use of crustal weaknesses through orogenic cycles is clearly a major tenet of Earth's evolution. Gee et al. (this issue) highlight for example how Sveconorwegian structures probably controlled Sveconorwegian extensional collapse and subsequent Neoproterozoic rifting, and were then recycled during the Caledonian orogeny by Scandian shortening and Devonian extensional collapse.

4. Summary and future questions

The orogens discussed in this special issue and introduction only cover a sample of those formed in the Mesoproterozoic Era. However, from this small selection it can be seen that Mesoproterozoic orogens exhibit both a variety of temporal and spatial scales and a variety of thermal conditions, similar to the Phanerozoic record. The Mesoproterozoic orogens lack evidence of subduction and exhumation of UHP crust, but otherwise feature a range of moderate to high pressure metamorphic conditions associated with burial of crust, and a range of temperatures associated with burial, radiogenic heating ± magmatic or mantle heat advection. Many orogens feature evidence of high to ultra-high temperatures, although this sample set is not representative enough to conclude whether this is a trait particular to the Mesoproterozoic and/or older orogens. Numerical modelling does suggest orogenesis at this time (with ΔT >80-100°C) should produce significant amounts of mantle melting, which would fit with the observations of elevated heat flow from, for example, the Musgrave orogen in

Australia. It is suggested that future studies may be directed to the possible role of an elevated heat flow in the Mesoproterozoic. Structurally, the orogens are generally composed of imbricated crustal terranes or nappes translated along low- to moderately dipping shear-zones, and may include flow of middle or lower crust within nappe- or crustal-scale channels through melt-weakening.

The Sveconorwegian orogen provides an example whereby the traditional model for its formation, i.e. continent-continent collision, has been recently questioned (Slagstad et al., 2013a; Coint et al., this issue) and instead suggested to comprise an Andean- or Cordilleran-type orogen. Although the issue is being lively debated, this example highlights a problem with reconstructing the palaeogeography of orogenic belts and cratons. Palaeomagnetism is currently not precise enough to resolve details between adjacent cratons, and certainly does not constrain the individual blocks or terranes that may build an orogen. As such, the spatial origin of accreted crustal terranes and colliding plates, is therefore quite uncertain. Whether orogens such as the Natal-Namaqua belt that features asymmetrically deformed juvenile crustal blocks, accreted on an older craton, resulted from either a collision of a major indenter as currently inferred or instead purely from accretionary orogenesis, is a pertinent question for future studies.

5. Index of the contributions

5.1. Pre-Rodinia Orogenesis

Ulmius et al. (this issue) provide the first P-T constraints along with new geochronology on the Hallandian orogen of southern Sweden. This orogen has lacked well-defined constraints on its origin, but the moderate temperature, low-pressure metamorphism and voluminous magmatism, lead these authors to infer an Andean-type orogenic setting.

5.2. Rodinia-forming Orogenesis

Five papers study different aspects of the Sveconorwegian orogen in Fennoscandia. Gee et al. (this issue) present detrital zircon data from a transect in northern Sweden, that includes units from the authochthon up section through to the upper part of the Middle Allochthon. Sveconorwegian age zircons are voluminous in most units of the section, including the upper Middle Allochthon. Along with the existence of these zircons from other regions to the north and south, the authors conclude that the Sveconorwegian orogen affected the entire Fennoscandian margin up into the high Arctic.

Coint et al. (this issue) present new geochronology, petrology and field constraints to further our understanding of the Sveconorwegian orogen in SW

Norway. These authors provide evidence that at least one phase of high-grade metamorphism was pre-Sveconorwegian, and that Sveconorwegian metamorphism, including UHT, was localised. They show that deformation was also localised, and the voluminous Sveconorwegian Sirdal Magmatic Belt batholiths lacks significant tilting since its emplacement.

Scheiber et al. (this issue) present structural and geochronological data from the bounding shear zone system between the Telemark and Kongsberg terranes of the Sveconorwegian Province. The shear-zone is hosted within and along the margin of a ~1170-1146 Ma magmatic belt, and importantly, does not juxtapose different age lithotectonic units. Deformation occurred in multiple stages, first as thrusting, then transpression, followed by extension.

Tual et al. (this issue) provide new structural and petrographic data on the sequence of deformation events that affected the ~ 4 km thick basal shear zone of an eclogite-bearing nappe in SW Sweden. The nappe was exhumed from eclogite to high-pressure granulite and upper amphibolite facies conditions as a partially-molten, low-viscosity system in the Eastern Segment of the Sveconorwegian orogen. Their results are used to refine existing kinematic models for the exhumation of eclogite-bearing units in collisional orogens.

Piñán-Llamas et al. (this issue) present a detailed structural and geochronological study of syn-kinematic melt formation in the Eastern Segment of SW Sweden, which complements the study of Tual et al. (this issue). They show that the protolith to the studies gneisses is ca. 1.69 Ga crust, and this has been reworked into a leucosome bearing gneiss in the Hallandian orogen at ca. 1.4 Ga. Sveconorwegian deformation evolved during four stages, with melt-formation throughout, and dated at ca. 970 Ma and ca. 958 Ma.

Four papers study the Natal-Namaqua Orogen that formed on the Kalahari craton, two from the Namaqua belt and two from the Natal belt. Colliston et al. (this issue) present new data from a region comprising the Hartbees River Thrust, which is interpreted as a terrane boundary separating the Grunau and Bladgrond terranes of the Namaqua belt. Older granitic magmatism was emplaced at ~1171 Ma and was deformed during prolonged D1, with sheath folding (D2) taking place at ~1154 Ma. Younger magmatism at ~1116 to 1102 Ma brackets late deformation (D4) to be younger than this, and older than a ~1030 Ma suite that cuts D4 deformation.

Cornell et al. (this issue) present age and isotopic data from the Konkiep terrane of the Namaqua belt. Xenocrysts and Hf isotope signatures suggest this region is comprised of Palaeoproterozoic crust that can be thought of as an extension of the Rehoboth Province. Hybrid gabbro-granite magmatism at ~1359 Ma is interpreted as occurring in a rift setting, and features juvenile isotopic signatures. Younger gabbro-granite magmatism at 1230-1200 Ma is interpreted as subduction-related. The timing of collision of this terrane to the craton is inferred to be ~1200 Ma when magmatism ceased.

Mendonidis et al. (this issue) present new geochronology from the Margate terrane of the Natal belt. The age data imply at least four magmatic/thermal events in the Margate terrane, at ~1170, ~1140-1135, ~1093-1082 and ~1050-1025 Ma. These ages are most similar to the Vardeklettane Terrane of East Antarctica, and a palaeogeographic link is made. The oldest ages are seen on the adjacent Tugela Terrane, implying the Margate Terrane is not entirely younger. Younger ages are also seen on the other adjacent Mzumbe terrane.

Spencer et al. (this issue) present new geochronology and isotopic constraints on the Natal Orogen, from all three of the exposed terranes. The Sezela Syenite Suite is dated at ~1085 Ma, much older than previously thought. Isotopic signatures indicate a juvenile island arc origin for the Mzumbe terrane. Granulite-facies metamorphism is dated by monazite, titanite and zircon from different units at ~1040-1030 Ma. The Oribi Gorge Suite intruded at a similar time, with precise ages at ~1049 and ~1034 Ma. The isobaric cooling path of the metamorphism is suggested to be a result of transcurrent movement during oblique collision.

Two papers discuss orogens in Australia, whether they can be described as Rodinia-forming is speculative, since they occur between different Australian cratons, and before the main Rodinia-forming orogens such as the Grenville Orogen of Laurentia. Kirkland et al. (this issue) compare the Musgrave and Albany-Fraser Orogens using isotopic signatures. They show that these orogens of similar age were formed on different crustal substrates, the Albany-Fraser on Archaean Yilgarn cratonic crust, and the Musgrave on younger late Palaeoproterozoic to early Mesoproterozoic juvenile crust. Additionally, these authors attribute the formation of ferroan dry magmatic rocks to lower crustal melting driven by mantle heating.

Scibiorski et al. (this issue) present new cooling age data from the Albany-Fraser Orogen. Using hornblende and mica Ar-Ar geochronology, they show very rapid rates of cooling for this orogen. They relate this to transpressional deformation and resultant exhumation. Via a compilation of orogenic cooling rates through Earth history, they show these rapid rates in the Mesoproterozoic to be rather anomalous, perhaps questioning the representative nature of this current record (see Fig. 1c).

Jacobs et al. (this issue) describe the geochemistry and geochronology of the eastern Dronning Maud Province of East Antarctica. The data highlight a period of mostly intermediate and felsic magmatism that occurred between 1000-900 Ma, and further indicate that this area was structurally reworked and that melt production occurred in the late Neoproterozoic and early Paleozoic. These characteristics allow for correlations between the study area and the SW domain of the Sør Rondane Mountains, and define a relatively large juvenile Neoproterozoic province within East Antarctica.

5.3. Magmatism

Teixeira et al. (this issue) present new baddeleyite geochronology for two mafic intrusions within the Bolivian part of the Amazonian Craton. The overlapping ages of 1110 ± 2 and 1112 ± 2 Ma for a layered ultramafic-mafic complex (Rincón del Tigre) and mafic sill complex (Huanchaca Suite), separated by 500km, lead the authors to suggest they are part of a Large Igneous Province, previously unrecognised. The authors suggest this may correlate with the Keweenawan in central Laurentia, which would indicate proximity of the cratons at this time, and they point out the lack of a correlative in Baltica.

Bickford et al. (this issue) review magmatism across Laurentia that forms the 1.5-1.34 Ga Granite-Rhyolite Province and related A-type granitoid suites. These authors present a compilation of new and published age and isotopic data, which show that magmatism in the 1.5-1.4 Ga interval occurs across the continent, but with a general younging trend to the west, and that younger 1.39-1.34 Ga magmatism is only a major event in the south-central mid-continent. A petrogenetic model of mantle underplating and crustal anatexis is advocated, inboard of an active margin with complex crust-mantle interactions due to arc accretion events.

Petersson et al. (this issue) present new in-situ zircon U-Pb and oxygen isotope data from drillcore samples taken from Ohio, North America. These data are used to determine the age and nature of the crust within this region. Crust formation ages of ~1650 Ma indicate this crust can be considered as part of the Mazatzal Province. Magmatism at ~1450 Ma is part of the Granite-Rhyolite Province and reworked crust formed earlier at ~1650 Ma. Crust of this age was reworked again during Grenvillian orogenesis at ~1050 Ma, with oxygen isotopes indicating this occurred in the presence of heavy $\delta^{18}O$ fluids.

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Figure Captions

1. a) Ambient mantle temperature through time, predicted through the composition of non-arc basalts (after Johnson et al., 2014, which is modified from Herzberg et al., 2010). b) Metamorphic gradients (°C/GPa) through time for well-constrained and dated orogenic belts, categorised by metamorphic facies (after Brown, 2014). c) Orogenic cooling rates (°C/Ma) through time, categorised by class of orogen (after Scibiorski et al., this issue). The blue band shows the timing of the Mesoproterozoic Era (1600-1000 Ma).

2. Temperature vs. Magnitude plots of orogenic classification (modified from Beaumont et al., 2006; Ultra Hot Orogens of Chardon et al., 2009). a) Orogenic styles and classifications; the thick blue arrows show the main trend of orgens, and the thin blue arrow a hypothetical trend of hotter Archaean orogens. b) Classification of some Phanerozoic orogens. c) Classification of some Mesoproterozoic orogens based on those studied in this issue.

References

1. Åhäll, K. I., Connelly, J. N., & Brewer, T. S. (2000). Episodic rapakivi magmatism due to distal orogenesis?: Correlation of 1.69–1.50 Ga orogenic and inboard,"anorogenic" events in the Baltic Shield. *Geology*, *28*(9), 823-826.
2. Anderson, J. L. (1983). Proterozoic anorogenic granite plutonism of North America. *Geological Society of America Memoirs*, *161*, 133-154.
3. Anderson, J. L., & Morrison, J. (2005). Ilmenite, magnetite, and peraluminous Mesoproterozoic anorogenic granites of Laurentia and Baltica. *Lithos*, *80*(1), 45-60.
4. Ashwal, L. D. (2010). The temporality of anorthosites. *The Canadian Mineralogist*, *48*(4), 711-728.
5. Beaumont, C., Nguyen, M. H., Jamieson, R. A., & Ellis, S. (2006). Crustal flow modes in large hot orogens. ,in: R.D. Law, M.P. Searle, L. Godin (Eds.), Channel Flow, Ductile Extrusion and Exhumation in Continental Collision Zones, *Geological Society, London*, *Special Publication*, 268, 9168,a
6. Bédard, J. H. (2009). Parental magmas of Grenville Province massif-type anorthosites, and conjectures about why massif anorthosites are restricted to the Proterozoic. Earth and Environmental Science Transactions of the Royal Society of Edinburgh, 100 (2009), pp. 77tine

7. Betts, P. G., & Giles, D. (2006). The 1800–1100Ma tectonic evolution of Australia. *Precambrian Research*, *144*(1), 92-125.
8. Bickford, M. E., Van Schmus, W. R., Karlstrom, K. E., Mueller, P. A., & Kamenov, G. D. (2014). Mesoproterozoic-trans-Laurentian magmatism: A synthesis of continent-wide age distributions, new SIMS U–Pb ages, zircon saturation temperatures, and Hf and Nd isotopic compositions. *Precambrian Research*. doi.10.1016/j.precamres.2014.11.024.
9. Bingen, B., Andersson, J., Söderlund, U., & Möller, C. (2008). The Mesoproterozoic in the Nordic countries. *Episodes*, *31*(1), 29.
10. Bingen, B., Skår, Ø., Marker, M., Sigmond, E. M., Nordgulen, Ø., Ragnhildstveit, J., Mansfeld, J., Tucker, R. D., & Liégeois, J. P. (2005). Timing of continental building in the Sveconorwegian orogen, SW Scandinavia. *Norwegian Journal of Geology*, *85*(1-2), 87-116.
11. Bogdanova, S. V., Page, L. M., Skridlaite, G., & Taran, L. N. (2001). Proterozoic tectonothermal history in the western part of the East European Craton: 40 Ar/39 Ar geochronological constraints. *Tectonophysics*, *339*(1), 39-66.
12. Brown, M. (2006). Duality of thermal regimes is the distinctive characteristic of plate tectonics since the Neoarchean. *Geology*, *34*(11), 961-964.
13. Brown, M. (2014). The contribution of metamorphic petrology to understanding lithosphere evolution and geodynamics. *Geoscience Frontiers*, *5*(4), 553-569.
14. Bybee, G. M., Ashwal, L. D., Shirey, S. B., Horan, M., Mock, T., & Andersen, T. B. (2014). Pyroxene megacrysts in Proterozoic anorthosites: implications for tectonic setting, magma source and magmatic processes at the Moho. *Earth and Planetary Science Letters*, *389*, 74-85.
15. Deng, X. H., Chen, Y. J., Santosh, M., & Yao, J. M. (2013). Genesis of the 1.76 Ga Zhaiwa Mo–Cu and its link with the Xiong'er volcanics in the North China Craton: implications for accretionary growth along the margin of the Columbia supercontinent. *Precambrian Research*, *227*, 337-348.
16. Cawood, P. A., & Hawkesworth, C. J. (2014). Earth's middle age. *Geology*,*42*(6), 503-506.
17. Chardon, D., Jayananda, M., Chetty, T. R., & Peucat, J. J. (2008). Precambrian continental strain and shear zone patterns: South Indian case. *Journal of Geophysical Research: Solid Earth (1978–2012)*, *113*(B8).
18. Chardon, D., Gapais, D., & Cagnard, F. (2009). Flow of ultra-hot orogens: a view from the Precambrian, clues for the Phanerozoic. *Tectonophysics*, *477*(3), 105-118.
19. Colliston, W. P., Cornell, D. H., Schoch, A. E., & Praekelt, H. E. (2015). Geochronological constraints on the Hartbees River Thrust and Augrabies Nappe: New insights into the assembly of the Mesoproterozoic Namaqua-

Natal Province of Southern Africa. *Precambrian Research*. doi.10.1016/j.precamres.2015.03.008.

20. Cornell, D.H., Austin-Hegardt, E., 2004. When, where and how did the Sveconorwegian Terranes of Sweden meet? GFF 126, 20
21. Cutts, K., Hand, M., & Kelsey, D. E. (2011). Evidence for early Mesoproterozoic (ca. 1590Ma) ultrahigh-temperature metamorphism in southern Australia. *Lithos*, *124*(1), 1-16.
22. Coint, N., Slagstad, T., Roberts, N. M. W., Marker, M., Røhr, T., Sørensen, B. E., (2015). The late Mesoproterozoic Sirdal Magmatic Belt, SW Norway; relationships between magmatism and metamorphism and implications for Sveconorwegian orogenesis. *Precambrian Research*, doi.10.1016/j.precamres.2015.05.002.
23. Collins, W. J. (2002). Hot orogens, tectonic switching, and creation of continental crust. *Geology*, *30*(6), 535-538.
24. Condie, K. C. (2013). Preservation and recycling of crust during accretionary and collisional phases of Proterozoic orogens: A bumpy road from Nuna to Rodinia. *Geosciences*, *3*(2), 240-261.
25. Cornell, D. H., van Schijndel, V., Simonsen, S. L., & Frei, D. (2014). Geochronology of Mesoproterozoic hybrid intrusions in the Konkiep Terrane, Namibia, from passive to active continental margin in the Namaqua-Natal Wilson Cycle. *Precambrian Research*. doi.10.1016/j.precamres.2014.11.028.
26. Deng, X. H., Chen, Y. J., Santosh, M., & Yao, J. M. (2013). Genesis of the 1.76 Ga Zhaiwa Mo–Cu and its link with the Xiong'er volcanics in the North China Craton: implications for accretionary growth along the margin of the Columbia supercontinent. *Precambrian Research*, *227*, 337-348.
27. Dharma Rao, C., Santosh, M., Zhang, Z., & Tsunogae, T. (2013). Mesoproterozoic arc magmatism in SE India: Petrology, zircon U–Pb geochronology and Hf isotopes of the Bopudi felsic suite from Eastern Ghats Belt. *Journal of Asian Earth Sciences*, *75*, 183-201.
28. Drüppel, K., Elsäßer, L., Brandt, S., & Gerdes, A. (2012). Sveconorwegian mid-crustal ultrahigh-temperature metamorphism in Rogaland, Norway: U–Pb LA-ICP-MS geochronology and pseudosections of Sapphirine granulites and associated paragneisses. *Journal of Petrology*, egs070.
29. Emslie, R. F. (1985). Proterozoic anorthosite massifs. In *The deep Proterozoic crust in the North Atlantic provinces* (pp. 39-60). Springer Netherlands.
30. Evans, D. A. D. (2009). The palaeomagnetically viable, long-lived and all-inclusive Rodinia supercontinent reconstruction. *Geological Society, London, Special Publications*, *327*(1), 371-404.
31. Evans, D. A. D. (2013). Reconstructing pre-Pangean supercontinents. *Geological Society of America Bulletin*, *125*(11-12), 1735-1751.

32. Falkum, T., & Petersen, J. S. (1980). The Sveconorwegian orogenic belt, a case of Late-Proterozoic plate-collision. *Geologische Rundschau*, *69*(3), 622-647.
33. Fan, H. P., Zhu, W. G., Li, Z. X., Zhong, H., Bai, Z. J., He, D. F., ... & Cao, C. Y. (2013). Ca. 1.5 Ga mafic magmatism in South China during the break-up of the supercontinent Nuna/Columbia: the Zhuqing Fe–Ti–V oxide ore-bearing mafic intrusions in western Yangtze Block. *Lithos*, *168*, 85-98.
34. Frost, C. D., & Frost, B. R. (2010). On ferroan (A-type) granitoids: their compositional variability and modes of origin. *Journal of Petrology*, egq070.
35. Gee, D. G., Andréasson, P-.G., Lorenz, H., Frei, D., & Majka, J., (2015). Detrital Zircon Signatures of the Balroscandian Margin along the Arctic Circle Caledonides in Sweden: the Sveconorwegian connection. Precambrian Research, accepted.
36. Gorczyk, W., Smithies, H., Korhonen, F., Howard, H., & De Gromard, R. Q. (2015). Ultra-hot Mesoproterozoic evolution of intracontinental central Australia. *Geoscience Frontiers*, *6*(1), 23-37.
37. Gower, C. F., Ryan, A. B., & Rivers, T. (1990). Mid-Proterozoic Laurentia–Baltica: an overview of its geological evolution and a summary of the contributions made by this volume. In: C.F. Gower, T. Rivers, A.B. Ryan (Eds.), *Mid-Proterozoic Laurentia–Baltica, Geological Association of Canada*, 38, 1 38
38. Hamilton, W. B. (2011). Plate tectonics began in Neoproterozoic time, and plumes from deep mantle have never operated. *Lithos*, *123*(1), 1-20.
39. Herzberg, C., Condie, K., & Korenaga, J. (2010). Thermal history of the Earth and its petrological expression. *Earth and Planetary Science Letters*, *292*(1), 79-88.
40. Hoffman, P. F. (1989). Speculations on Laurentia's first gigayear (2.0 to 1.0 Ga). *Geology*, *17*(2), 135-138.
41. Holland, H. D. (2006). The oxygenation of the atmosphere and oceans. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *361*(1470), 903-915.
42. Hou, G., Santosh, M., Qian, X., Lister, G. S., & Li, J. (2008). Tectonic constraints on 1.3∼ 1.2 Ga final breakup of Columbia supercontinent from a giant radiating dyke swarm. *Gondwana Research*, *14*(3), 561-566.
43. Howard, H. M., Smithies, R. H., Kirkland, C. L., Kelsey, D. E., Aitken, A., Wingate, M. T. D., Quentin de Gromard, R., .Spaggiari, C. V., & Maier, W. D. (2015). The burning heart—The Proterozoic geology and geological evolution of the west Musgrave Region, central Australia. *Gondwana Research*, *27*(1), 64-94.
44. Hutton, J. (1788). Theory of the Earth; or an Investigation of the Laws observable in the Composition, Dissolution, and Restoration of Land upon the Globe. *Transactions of the Royal Society of Edinburgh*, *1*(02), 209-304.

45. Hynes, A., & Rivers, T. (2010). Protracted continental collision—evidence from the Grenville Orogen. *Canadian Journal of Earth Sciences*, *47*(5), 591-620.
46. Ibanez-Mejia, M., Ruiz, J., Valencia, V. A., Cardona, A., Gehrels, G. E., & Mora, A. R. (2011). The Putumayo Orogen of Amazonia and its implications for Rodinia reconstructions: New U–Pb geochronological insights into the Proterozoic tectonic evolution of northwestern South America. *Precambrian Research*, *191*(1), 58-77.
47. Jacobs, J., Elburg, M., Laeufer, A., Kleinhanns, I. C., Henjes-Kunst, F., Estrada, S., Rupperl, A., Damaske, D., Montero, P., & Bea, F., (2015). Two distinct Late Mesoproterozoic/Early Neoproterozoic basement provinces in central/eastern Dronning Maud Land, East Antarctica: the missing link, 15-21°E. *Pecambrian Research*, doi.10.1016/j.precamres.2015.05.003.
48. Jamieson, R. A., Beaumont, C., Warren, C. J., & Nguyen, M. H. (2010). The Grenville Orogen explained? Applications and limitations of integrating numerical models with geological and geophysical data. *Canadian Journal of Earth Sciences*, *47*(4), 517-539.
49. Johansson, Å. (2009). Baltica, Amazonia and the SAMBA connection—1000 million years of neighbourhood during the Proterozoic?. *Precambrian Research*, *175*(1), 221-234.
50. Johnson, T. E., Brown, M., Kaus, B. J., & VanTongeren, J. A. (2014). Delamination and recycling of Archaean crust caused by gravitational instabilities. *Nature Geoscience*, *7*(1), 47-52.
51. Kamber, B. S. (2015). The evolving nature of terrestrial crust from the Hadean, through the Archaean, into the Proterozoic. *Precambrian Research*, *258*, 48-82.
52. Karlstrom, K. E., Åhäll, K. I., Harlan, S. S., Williams, M. L., McLelland, J., & Geissman, J. W. (2001). Long-lived (1.8–1.0 Ga) convergent orogen in southern Laurentia, its extensions to Australia and Baltica, and implications for refining Rodinia. *Precambrian Research*, *111*(1), 5-30.
53. Kirkland, C. L., Smithies, R. H., & Spaggiari, C. V. (2014). Foreign contemporaries–Unravelling disparate isotopic signatures from Mesoproterozoic Central and Western Australia. *Precambrian Research*. doi.10.1016/j.precamres.2014.12.01.
54. Li, Z. X., Li, X. H., Zhou, H., & Kinny, P. D. (2002). Grenvillian continental collision in south China: New SHRIMP U-Pb zircon results and implications for the configuration of Rodinia. *Geology*, *30*(2), 163-166.
55. Li, Z. X., Bogdanova, S. V., Collins, A. S., Davidson, A., De Waele, B., Ernst, R. E., Fitzsimons, I. C. W., Fuck, R. A., Gladkochub, D. P., Jacobs, J., Karlstrom, K., Lu, S., Natapov, L. M., Pease, V., Pisarevsky, S. A., Thrane, K., & Vernikovsky, V. (2008). Assembly, configuration, and break-up history of Rodinia: a synthesis. *Precambrian research*, *160*(1), 179-210.

56. Marsh, J. H., & Culshaw, N. G. (2014). Timing and conditions of high-pressure metamorphism in the western Grenville Province: Constraints from accessory mineral composition and phase equilibrium modeling. *Lithos*, *200*, 402-417.
57. Mattila, J. and Viola, G., (2014). New constraints on 1.7 Gyr of brittle tectonic evolution in southwestern Finland derived from a structural study at the site of a potential nuclear waste repository (Olkiluoto Island*). Journal of Structural Geology*, 67, 50-74.
58. Meert, J. G. (2012). What's in a name? The Columbia (Paleopangaea/Nuna) supercontinent. *Gondwana Research*, *21*(4), 987-993.
59. Meert, J. G. (2014). Strange attractors, spiritual interlopers and lonely wanderers: the search for pre-Pangean supercontinents. *Geoscience Frontiers*, *5*(2), 155-166.
60. Mendonidis, P., Thomas, R. J., Grantham, G. H., & Armstrong, R. A. (2015). Geochronology of emplacement and charnockite formation of the Margate Granite Suite, Natal Metamorphic Province, South Africa: Implications for Natal-Maud belt correlations. *Precambrian Research*. doi.10.1016/j.precamres.2015.02.013.
61. Menuge, J. F., Brewer, T. S., & Seeger, C. M. (2002). Petrogenesis of metaluminous A-type rhyolites from the St Francois Mountains, Missouri and the Mesoproterozoic evolution of the southern Laurentian margin. *Precambrian Research*, *113*(3), 269-291.
62. Möller, C., Andersson, J., Dyck, B., & Lundin, I. A. (2014). Exhumation of an eclogite terrane as a hot migmatitic nappe, Sveconorwegian orogen. *Lithos*, doi:10.1016/j.lithos.2014.12.013
63. Möller, C., Bingen, B., Andersson, J., Stephens, M. B., Viola, G., & Scherstén, A. (2013). A non-collisional, accretionary Sveconorwegian orogen–Comment. *Terra Nova*, *25*(2), 165-168.
64. Molnar, P., & Tapponnier, P. (1975). Cenozoic tectonics of Asia: effects of a continental collision. *Science*, *189*(4201), 419-426.
65. Mulch, A., Cosca, M. A., Andresen, A., & Fiebig, J. (2005). Time scales of deformation and exhumation in extensional detachment systems determined by high-spatial resolution in situ UV-laser 40 Ar/39 Ar dating. *Earth and Planetary Science Letters*, *233*(3), 375-390.
66. Nance, R. D., & Murphy, J. B. (2013). Origins of the supercontinent cycle. *Geoscience Frontiers*, *4*(4), 439-448.
67. Pesonen, L. J., Elming, S. Å., Mertanen, S., Pisarevsky, S., D'Agrella-Filho, M. S., Meert, J. G., Abrahamsen, N., & Bylund, G. (2003). Palaeomagnetic configuration of continents during the Proterozoic. *Tectonophysics*, *375*(1), 289-324.
68. Petersson, A., Scherstén, A., Andersson, J., Whitehouse, M. J., & Baranoski, M. T. (2015a). Zircon U-Pb, Hf and O isotope constraints on growth versus

reworking of continental crust in the subsurface Grenville orogen, Ohio, USA. *Precambrian Research*. doi.10.1016/j.precamres.2015.02.016
69. Petersson, A., Scherstén, A., Bingen, B., Gerdes, A., & Whitehouse, M. J. (2015b). Mesoproterozoic continental growth: U–Pb–Hf–O zircon record in the Idefjorden Terrane, Sveconorwegian Orogen. *Precambrian Research*, *261*, 75-95.
70. Piñán-Llamas, A., Andersson, J., Möller, C., Leif, Johansson, & Hansen, E., (2015). Polyphasal foreland-vergent deformation in a deep section of the 1 Ga Sveconorwegian orogen. Precambrian Research, accepted.
71. Piper, J. D. (2013a). A planetary perspective on Earth evolution: lid tectonics before plate tectonics. *Tectonophysics*, *589*, 44-56.
72. Piper, J. D. A. (2013b). Continental velocity through Precambrian times: the link to magmatism, crustal accretion and episodes of global cooling. *Geoscience Frontiers*, *4*(1), 7-36.
73. Pisarevsky, S. A., Biswal, T. K., Wang, X. C., De Waele, B., Ernst, R., Söderlund, U., Tait, J. M., Ratre, K., Kesorjit Singh, Y., & Cleve, M. (2013). Palaeomagnetic, geochronological and geochemical study of Mesoproterozoic Lakhna Dykes in the Bastar Craton, India: Implications for the Mesoproterozoic supercontinent. *Lithos*, *174*, 125-143.
74. Pisarevsky, S. A., Elming, S. Å., Pesonen, L. J., & Li, Z. X. (2014). Mesoproterozoic paleogeography: supercontinent and beyond. *Precambrian Research*, *244*, 207-225.
75. Richter, F. M. (1985). Models for the Archean thermal regime. *Earth and Planetary Science Letters*, *73*(2), 350-360.
76. Rivers, T. (1997). Lithotectonic elements of the Grenville Province: review and tectonic implications. *Precambrian Research*, *86*(3), 117-154.
77. Rivers, T. (2008). Assembly and preservation of lower, mid, and upper orogenic crust in the Grenville Province—Implications for the evolution of large hot long-duration orogens. *Precambrian Research*, *167*(3), 237-259.
78. Rivers, T. (2009). The Grenville Province as a large hot long-duration collisional orogen–insights from the spatial and thermal evolution of its orogenic fronts. In: Murphy, J.B., Keppie, J.D., A.J. Hynes (Eds.), *Ancient Orogens and Modern Analogues. Geological Society of London, Special Publication*, *327*(1), 405-444.
79. Rivers, T. (2012). Upper-crustal orogenic lid and mid-crustal core complexes: signature of a collapsed orogenic plateau in the hinterland of the Grenville Province. *Canadian Journal of Earth Sciences*, 49(1), 1-42.
80. Roberts, N. M. W. (2013). The boring billion?–Lid tectonics, continental growth and environmental change associated with the Columbia supercontinent. *Geoscience Frontiers*, *4*(6), 681-691.
81. Roberts, N. M. W., & Slagstad, T. (2014). Continental growth and reworking on the edge of the Columbia and Rodinia supercontinents; 1.86–0.9 Ga

accretionary orogeny in southwest Fennoscandia. *International Geology Review*, DOI:10.1080/00206814.2014.958579

82. Roberts, N. M. W., Slagstad, T., Parrish, R. R., Norry, M. J., Marker, M., & Horstwood, M. S. A. (2013). Sedimentary recycling in arc magmas: geochemical and U–Pb–Hf–O constraints on the Mesoproterozoic Suldal Arc, SW Norway. *Contributions to Mineralogy and Petrology*, *165*(3), 507-523.
83. Roberts, N. M. W., Van Kranendonk, M., Parman, S., & Clift, P. D., (2015). Continent formation through time. In: Roberts, N. M. W., van Kranendonk, M., Parman, S., Shirey., S., & Clift, P. S. (eds) Continent Formation Through Time. Geological Society, London, Special Publications, 389, 1-16.
84. Rogers, J. J., & Santosh, M. (2002). Configuration of Columbia, a Mesoproterozoic supercontinent. *Gondwana Research*, *5*(1), 5-22.
85. Rogers, J. J., & Santosh, M. (2009). Tectonics and surface effects of the supercontinent Columbia. *Gondwana Research*, *15*(3), 373-380.
86. Rosenberg, C. L., & Handy, M. R. (2005). Experimental deformation of partially melted granite revisited: implications for the continental crust. *Journal of metamorphic Geology*, *23*(1), 19-28.
87. Scheiber, T., Viola, G., Bingen, B., Peters, M., & Solli, A. (2015). Multiple reactivation and strain localization along a Proterozoic orogen-scale deformation zone: The Kongsberg-Telemark boundary in southern Norway revisited. *Precambrian Research*. doi.10.1016/j.precamres.2015.05.009.
88. Scibiorski, E., Tohver, E., & Jourdan, F. (2015). Rapid cooling and exhumation in the western part of the Mesoproterozoic Albany-Fraser Orogen, Western Australia. *Precambrian Research*. doi.10.1016/j.precamres.2015.02.005.
89. Senshu, H., Maruyama, S., Rino, S., & Santosh, M. (2009). Role of tonalite-trodhjemite-granite (TTG) crust subduction on the mechanism of supercontinent breakup. *Gondwana Research*, *15*(3), 433-442.
90. Sizova, E., Gerya, T., & Brown, M. (2014). Contrasting styles of Phanerozoic and Precambrian continental collision. *Gondwana Research*, *25*(2), 522-545.
91. Slagstad, T., Culshaw, N. G., Daly, J. S., & Jamieson, R. A. (2009). Western Grenville Province holds key to midcontinental Granite-Rhyolite Province enigma. *Terra Nova*, *21*(3), 181-187.
92. Slagstad, T., Jamieson, R. A., & Culshaw, N. G. (2005). Formation, crystallization, and migration of melt in the mid-orogenic crust: Muskoka domain migmatites, Grenville Province, Ontario. *Journal of Petrology*, *46*(5), 893-919.
93. Slagstad, T., Roberts, N. M. W., Marker, M., Røhr, T. S., & Schiellerup, H. (2013a). A non-collisional, accretionary Sveconorwegian orogen. *Terra Nova*, *25*(1), 30-37.

94. Slagstad, T., Roberts, N. M. W., Marker, M., Røhr, T. S., & Schiellerup, H. (2013b). A non-collisional, accretionary Sveconorwegian orogen–Reply. *Terra Nova*,*25*(2), 169-171.
95. Smits, R. G., Collins, W. J., Hand, M., Dutch, R., & Payne, J. (2014). A Proterozoic Wilson cycle identified by Hf isotopes in central Australia: Implications for the assembly of Proterozoic Australia and Rodinia. *Geology*,*42*(3), 231-234.
96. Song, S., Su, L., Li, X. H., Niu, Y., & Zhang, L. (2012). Grenville-age orogenesis in the Qaidam-Qilian block: The link between South China and Tarim. *Precambrian Research*, *220*, 9-22.
97. Spencer, C. J., Thomas, R. J., Roberts, N. M. W., Cawood, P. A., Millar, I., & Tapster, S., (2015). Crustal growth during island arc accretion and transcurrent deformation, Natal Metamorphic Province, South Africa: new isotopic constraints. Precambrian Research, accepted.
98. Stern, R. J. (2005). Evidence from ophiolites, blueschists, and ultrahigh-pressure metamorphic terranes that the modern episode of subduction tectonics began in Neoproterozoic time. *Geology*, *33*(7), 557-560.
99. Tapponnier, P., Peltzer, G., Le Dain, A. Y., Armijo, R., & Cobbold, P. (1982). Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine. *Geology*, *10*(12), 611-616.
100. Teixeira, W., Hamilton, M. A., Lima, G. A., Ruiz, A. S., Matos, R., & Ernst, R. E. (2014). Precise ID-TIMS U–Pb baddeleyite ages (1110–1112Ma) for the Rincón del Tigre–Huanchaca large igneous province (LIP) of the Amazonian Craton: Implications for the Rodinia supercontinent. *Precambrian Research*. doi.10.1016/j.precamres.2014.07.006.
101. Tohver, E., Teixeira, W., van der Pluijm, B., Geraldes, M. C., Bettencourt, J. S., & Rizzotto, G. (2006). Restored transect across the exhumed Grenville orogen of Laurentia and Amazonia, with implications for crustal architecture. *Geology*, *34*(8), 669-672.
102. Tual, L., Piñán-Lamas, A., Möller, C., (2015). High-Temperature Deformation in the Basal Shear Zone of an Eclogite-Bearing Fold Nappe, Sveconorwegian Orogen, Sweden. Precambrian Research, accepted.
103. Tucker, N. M., Hand, M., Kelsey, D. E., & Dutch, R. A. (2015). A duality of timescales: Short-lived ultrahigh temperature metamorphism preserving a long-lived monazite growth history in the Grenvillian Musgrave–Albany–Fraser Orogen. *Precambrian Research*.
104. Turcotte, D. L. (1980). On the thermal evolution of the Earth. *Earth and Planetary Science Letters*, *48*(1), 53-58.
105. Ulmius, J., Andersson, J., & Möller, C. (2015). Hallandian 1.45 Ga high-temperature metamorphism in Baltica: P–T evolution and SIMS U–Pb zircon ages of aluminous gneisses, SW Sweden. *Precambrian Research*, doi.10.1016/j.precamres.2015.05.004.

106. van Hunen, J., & van den Berg, A. P. (2008). Plate tectonics on the early Earth: limitations imposed by strength and buoyancy of subducted lithosphere. *Lithos*, *103*(1), 217-235.
107. Vigneresse, J. L. (2005). The specific case of the Mid-Proterozoic rapakivi granites and associated suite within the context of the Columbia supercontinent. *Precambrian Research*, *137*(1), 1-34.
108. Viola, G., Venvik Ganerød G. and Wahlgren, C.-H. (2009). Unravelling 1.5 Gyr of brittle deformation history in the Laxemar-Simpevarp area, SE Sweden: a contribution to the Swedish site investigation study for the disposal of highly radioactive nuclear waste. *Tectonics*, 28, TC5007, doi:10.1029/2009TC002461.
109. Viola, G.and Henderson, I.H.C. (2010). Inclined transpression at the toe of an arcuate thrust: an example from the Precambrian "Mylonite Zone" of the Sveconorwegian orogen, in Law, R.D., Butler, R.W.H., Holdsworth, R.E., Krabbendam, M. & Strachan, R. A. (eds.) *"Continental tectonics and Mountain building: The Legacy of Peach and Horne", Geological Society, London, Special Publications*, 335, 707-727.
110. Viola, G., Henderson, I. H. C., Bingen, B., & Hendriks, B. W. H. (2011). The Grenvillian–Sveconorwegian orogeny in Fennoscandia: Back-thrusting and extensional shearing along the "Mylonite Zone". *Precambrian Research*, *189*(3), 368-388.
111. Walsh, A. K., Kelsey, D. E., Kirkland, C. L., Hand, M., Smithies, R. H., Clark, C., & Howard, H. M. (2014). P–T–t evolution of a large, long-lived, ultrahigh-temperature Grenvillian belt in central Australia. *Gondwana Research*.
112. Windley, B. F. (1993a). Proterozoic anorogenic magmatism and its orogenic connections. *Journal of the Geological Society*, *150*(1), 39-50.
113. Windley, B. F. (1993b). Uniformitarianism today: plate tectonics is the key to the past. *Journal of the Geological Society*, *150*(1), 7-19.
114. Worsley, T. R., Nance, D., & Moody, J. B. (1984). Global tectonics and eustasy for the past 2 billion years. *Marine Geology*, *58*(3), 373-400.
115. Young, G. M. (2013). Precambrian supercontinents, glaciations, atmospheric oxygenation, metazoan evolution and an impact that may have changed the second half of Earth history. *Geoscience Frontiers*, *4*(3), 247-261.
116. Zhang, S., Li, Z. X., Evans, D. A., Wu, H., Li, H., & Dong, J. (2012). Pre-Rodinia supercontinent Nuna shaping up: a global synthesis with new paleomagnetic results from North China. *Earth and Planetary Science Letters*, *353*, 145-155.
117. Zhang, S. H., Zhao, Y., Yang, Z. Y., He, Z. F., & Wu, H. (2009). The 1.35 Ga diabase sills from the northern North China Craton: implications for breakup of the Columbia (Nuna) supercontinent. *Earth and Planetary Science Letters*, *288*(3), 588-600.

118. Zhao, G., Cawood, P. A., Wilde, S. A., & Sun, M. (2002). Review of global 2.1–1.8 Ga orogens: implications for a pre-Rodinia supercontinent. *Earth-Science Reviews*, *59*(1), 125-162.

Figure 1:

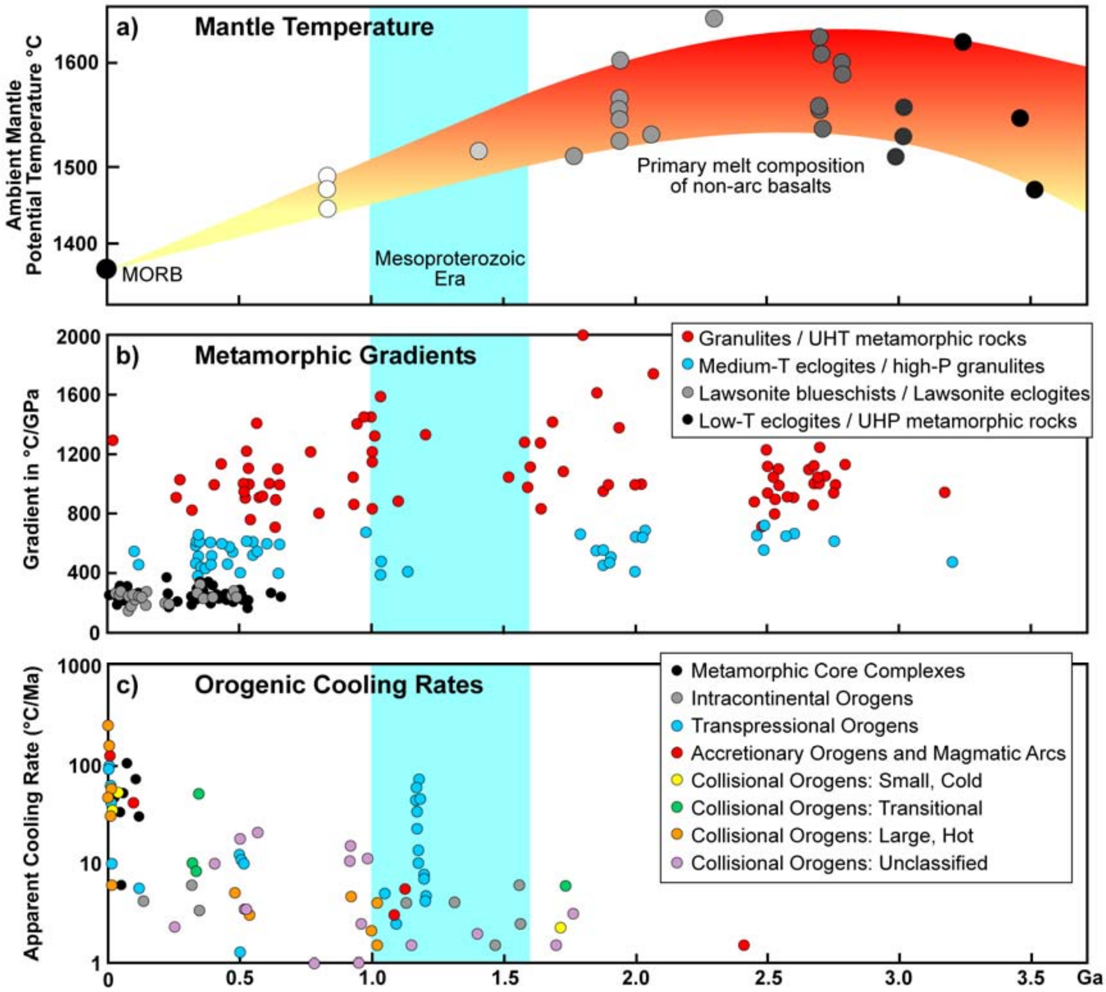
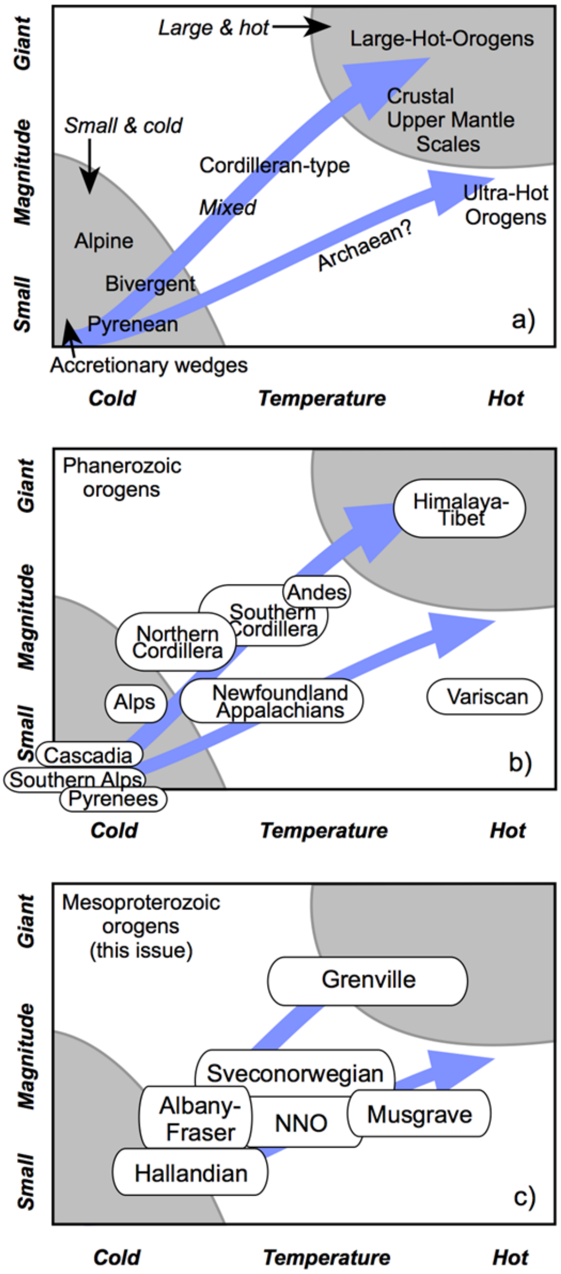

a)
Mantle Temperature
Ambient Mantle Potential Temperature °C
1600
1500
1400
MORB
Mesoproterozoic Era
Primary melt composition of non-arc basalts
b)
Metamorphic Gradients
Gradient in °C/GPa
2000
1600
1200
800
400
0
Granulites / UHT metamorphic rocks
Medium-T eclogites / high-P granulites
Lawsonite blueschists / Lawsonite eclogites
Low-T eclogites / UHP metamorphic rocks
c)
Orogenic Cooling Rates
Apparent Cooling Rate (°C/Ma)
1000
100
10
1
Metamorphic Core Complexes
Intracontinental Orogens
Transpressional Orogens
Accretionary Orogens and Magmatic Arcs
Collisional Orogens: Small, Cold
Collisional Orogens: Transitional
Collisional Orogens: Large, Hot
Collisional Orogens: Unclassified
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Ga

Figure 2:



Large & hot
Large-Hot-Orogens
Crustal
Upper Mantle
Scales
Small & cold
Cordilleran-type
Mixed
Ultra-Hot
Orogens
Archaean?
Alpine
Bivergent
Pyrenean
Accretionary wedges
a)
Giant
Magnitude
Small
Cold
Temperature
Hot
Phanerozoic
orogens
Himalaya-
Tibet
Andes
Southern
Cordillera
Northern
Cordillera
Alps
Newfoundland
Appalachians
Variscan
Cascadia
Southern Alps
Pyrenees
b)
Mesoproterozoic
orogens
(this issue)
Grenville
Sveconorwegian
Albany-
Fraser
NNO
Musgrave
Hallandian
c)