Paleo- to Mesoarchean polymetamorphism in the Barberton Granite-Greenstone Belt, South Africa: Constraints from U-Pb monazite and Lu-Hf garnet geochronology on the tectonic processes that shaped the belt: Discussion

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INTRODUCTION

Cutts et al. (2014) combined thermodynamic modeling of compositional change in metamorphic garnet with metamorphic peak and retrograde pressure-temperature (*P-T*) data derived from quantitative *P-T* pseudosections to determine clockwise *P-T* paths for several samples from the Tjakastad schist belt. The Tjakastad schist belt is located in the central portion of the Stolzburg domain[1] at the southwestern end of the Barberton Granite-Greenstone Belt (BGGB). The Stolzburg domain is part of the older southern terrane in the BGGB, which lies south of the Saddleback-Inyoka fault system—an inferred suture (de Ronde and de Wit, 1994). The Stolzburg domain is bounded on the west by the Inyoni shear zone, to the north by the Komati fault, on the east by the Motjane schist belt, and to the south by the younger Mpululzi batholith (see Cutts et al., 2014, their figure 1).

Cutts et al. (2014) correlated *P-T* paths determined for samples from the Tjakastad schist belt with those established by Moyen et al. (2006) for samples from the Inyoni shear zone <15 km to the west (see Cutts et al., 2014, their figure 1). These authors confirmed an earlier observation by Diener et al. (2005) that there is a trend of increasing peak pressure away from the Komati fault, which they interpreted to indicate that the Stolzburg domain represents an exhumed orogenic core. Cutts et al. (2014) concluded that their results are more consistent with the late Paleoarchean regional metamorphism being the result of subduction-accretion processes rather than due to gravitational redistribution by sagduction[2] of the greenstone belt cover and doming of the tonalite-trondhjemite-granodiorite (TTG) basement. By contrast, the gravitational redistribution interpretation, as proposed by Van Kranendonk (2011), was emphasized in a recent article by Van Kranendonk et al. (2014) published after the Cutts et al. (2014) article had appeared in print.

These contrasting views of the evolution of the BGGB are typical of differences in the interpretation of the geology and inferences about the tectonics of Archean granite-greenstone terrains worldwide. Therefore, it is important to discuss the evidence in this case and evaluate it against predictions from each of the models, particularly because the BGGB is one of the type localities for Archaean granite-greenstone tectonics. In principle, the quantitative *P-T* paths determined by Cutts et al. (2014) for several samples from the Tjakastad schist belt represent data that might permit discrimination between the alternative tectonic scenarios and allow an independent assessment of each model. However, although the general sense of d*T*/d*P* with time for sample paths is likely to be correct, the *P-T* paths themselves are subject to intrinsic uncertainties, as discussed later. Thus, in practice it is unclear whether *P-T* paths are diagnostic of one particular geodynamic driver over another as the cause of burial and exhumation of supracrustal rocks.

Over and above this problem, there is inherent doubt about the geodynamics of the lithosphere-asthenosphere system during the Archean Eon due to secular change, as discussed below. For this reason alone, all models for the evolution of Archean lithosphere, whether based on uniformitarian principles or not, must be considered suspect and should be subjected to rigorous testing of predictions against observations.

In the commentary that follows, I review briefly Archean geodynamics. Then, I use the full range of data available from the published literature to argue that the results given by Cutts et al. (2014) are not only compatible with gravitational redistribution, but also on a warmer Earth, may be better explained by such a model rather than by uniformitarian plate boundary processes.

The following is a list of points of contention:

(1) That the Saddleback-Inyoka fault system and its extension along the Inyoni shear zone is a suture resulting from the tectonic juxtaposition of two separate tectonic blocks—the northern and southern BGGB terranes—by plate boundary processes.

(2) That the age of intrusion of the TTG plutons in the Stolzburg domain of ca. 3.50–3.45 Ga is a significant obstacle to an interpretation that the dome-and-keel architecture was the result of greenstones sinking between rising domes of TTG crust at ca. 3.23 Ga, coeval with the regional metamorphism.

[1]"Terrane" has been used in the literature for the BGGB as a whole, for the northern and southern parts of the BGGB across the Saddleback-Inyoka fault system, and for the Stolzburg area south of the Komati fault. Therefore, to avoid ambiguity in this discussion, "terrane" will be used for the northern and southern parts of the BGGB, and "domain" for the area south of the Komati fault (the Stolzburg "terrane" of Cutts et al. [2014]). The southern part of the BGGB including the area south of the Komati fault is equivalent to the "Stolzburg and Steynsdorp terrane" of Schoene et al. (2009).

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[2]Today, sagduction refers generally to the gravitationally-driven sinking of more dense overlying lithologies into less dense, and commonly less viscous, underlying lithologies. In the original usage, I believe, Goodwin and Smith suggested "that sagging of a pile of Archean lavas would follow the accumulation of a critical thickness of flows and that interaction of the lower part of such a pile with the underlying mantle could result in a geochemically modified source capable of yielding basaltic and intermediate calc-alkaline magmas. We suggest the term sag-duction for this process." (Goodwin and Smith, 1980, p. 309).

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(3) That a model of partial convective overturn is inconsistent with the regional distribution of rocks with similar clockwise *P-T* paths.

(4) That the model of exhumation of the core of the 3230 Ma orogen "as a coherent block of relatively rigid, buoyant crust" is "clearly more consistent with the subduction-accretion model, with the formation of the BGGB being a result of modern-style plate-tectonic processes" (Cutts et al., 2014, p. 268).

(5) That the apparent thermal gradients reflected by the peak *P-T* conditions are anomalous for the Archean and may reflect a low abundance of radiogenic elements within the ca. 3455 Ma TTG plutons.

ARCHEAN GEODYNAMICS

On Earth at present, regional metamorphism is associated principally with subduction and collisional orogenesis at convergent plate boundary zones. Moreover, the plate tectonics paradigm has provided a context to understand different types of metamorphism and their relationship to plate boundary processes at least as far back as the dawn of the Phanerozoic Eon (Brown, 2006, 2007; Stern, 2005), and possibly back to the beginning of the Paleoproterozoic Era (Brown, 2008; Sizova et al., 2014). However, geodynamics on the Archean Earth may have been different (Van Hunen and Van den Berg, 2008; Sizova et al., 2010; Arndt and Davaille, 2013; Johnson et al., 2014; O'Neill et al., 2014). Furthermore, a strong case has been made by some authors for an early Archean stagnant-lid rather than mobile-lid plate tectonics regime (Debaille et al., 2013; Griffin et al., 2014; O'Neill et al., 2013).

Differences in geodynamic behavior are controlled principally by Earth's thermal evolution and mechanism of heat loss (Korenaga, 2006; Labrosse and Jaupart, 2007). Petrological data and generalizations from thermal history models indicate that ambient mantle temperatures in the Archean Eon were significantly hotter than at present (Herzberg et al., 2007, 2010; Van Hunen and Moyen, 2012). Higher Moho temperatures may have allowed lithosphere foundering by Rayleigh-Taylor instabilities (Toussaint et al., 2004), particularly on the early Archean Earth (Johnson et al., 2014). As a result, lower crustal dripping instabilities and gravitational redistribution of material within the lithosphere may have been more important on the early Earth than on contemporary Earth (Jull and Kelemen, 2001; Robin and Bailey, 2009; Johnson et al., 2014).

In turn, these differences in geodynamics may translate to dissimilarities in crustal tectonics (Mareschal and West, 1980; Collins et al., 1998; Sandiford et al., 2004; Bodorkos and Sandiford, 2006; Perchuk and Gerya, 2011; Gerya, 2014; François et al., 2014). Certainly, there are significant differences between the geology of Archean cratons and that of post-Archean orogenic belts, such as the dominance of TTGs, high-MgO basalts, and komatiites in the former, and the characteristic dome-and-keel structural pattern of cratons (Goodwin, 1991; Choukroune et al., 1995), features that are generally absent from younger orogenic belts.

A characteristic feature of subduction plate boundary zones is the development of dual thermal environments (Oxburgh and Turcotte, 1970, 1971), representing the subduction zone or collisional suture (cooler) and the arc-backarc system or orogenic hinterland (warmer). This feature is the hallmark of asymmetric or one-sided subduction on contemporary Earth (Brown, 2006). It results in the development of two contemporaneous but contrasting types of metamorphic belts (Miyashiro, 1961). Outboard, on the trench side, there is a metamorphic belt characterized by lower d*T*/d*P*, whereas inboard, well away from the trench, there is a metamorphic belt characterized by higher d*T*/d*P*. Paired metamorphic belts are a typical feature of subduction-accretion orogens during the Phanerozoic Eon.

Brown (2009, 2010, 2014) has argued that this feature may be recognized in the geological record back to the beginning of the Neoarchean Era. However, to the author's knowledge, this pattern of paired metamorphism is not seen in any individual Archean greenstone belt. On the contrary, greenstone belts in general comprise low- to medium-grade metamorphic rocks (prehnite-pumpellyite facies to amphibolite facies) that commonly yield moderate temperatures at relatively low pressures. Although apparent thermal gradients registered by rocks in greenstone belts tend to be high, they decrease systematically as pressure increases (e.g., Cloete, 1999; Dalstra et al., 1999), reflecting the strongly curved nature of geotherms close to Earth's surface.

With this background in mind, let us move on to the points of contention raised by the Cutts et al. (2014) article.

ELEMENTS OF THE REGIONAL STRUCTURE

Archean Dome-and-Keel Architecture

Although domes will become progressively more subdued with depth as their amplitude declines, a dome-and-keel architecture is the archetypal structural pattern of Archean cratons. This structural pattern appears to be absent from younger crust (Marshak, 1999). Whether this architecture was a simple result of gravitational instability and partial convective overturn, involved a component of crustal-scale extension, or was due to synchronous vertical and horizontal displacements is unclear (e.g., Bouhallier et al., 1995; Marshak et al., 1997; Marshak, 1999; Collins et al., 1998; Lin, 2005). In centrifuged models of sagduction, strain within the subsiding belts is dominated by strong horizontal shortening and vertical extension, although flow also may converge toward points of maximum subsidence, producing local areas of constrictional strain (Dixon and Summers, 1983). Continued horizontal shortening tends to rotate shallow structures into steeper attitudes. There are many documented natural examples of strain patterns similar to those in the models. Examples include the Dharwar craton in peninsula India (Bouhallier et al., 1995; Chardon et al., 1996), the East Pilbara terrane in Western Australia (Collins et al., 1998; Collins and Van Kranendonk, 1999; Van Kranendonk et al., 2007), and the western Superior craton in southern Canada (Lin, 2005; Parmenter et al., 2006; Lin and Beakhouse, 2013).

The Saddleback-Inyoka Fault System and Its Extension Along the Inyoni Shear Zone

Whether the Saddleback-Inyoka fault system and its extension to the Inyoni shear zone to the southwest represent a suture along the line of a former subduction zone remains a speculative proposal in need of more evidentiary support. The regional tectonic subdivision into two blocks, an older terrane in the southeast and a younger terrane in the northwest, separated by the Saddleback-Inyoka fault system, stems from the seminal paper on the tectonic history of the BGGB by de Ronde and de Wit (1994) supported by the extensive geochronological data set of Kamo and Davis (1994). There are certainly differences in the sedimentary facies environments of the Fig Tree Group (Eriksson, 1980) across the Saddleback-Inyoka fault system as well as a contrast in ages of the TTGs between the two terranes (Kamo and Davis, 1994). Whether these features alone are sufficient to identify the Saddleback-Inyoka fault system as a suture associated with a subducted ocean plate is an open question. However, they might be permissive of a terrane boundary defined by a fault with predominantly lateral displacement.

Further to the southwest, the Inyoni shear zone represents the western boundary of the Stolzburg domain, part of the older southern terrane. Based on the presence of rocks with a high-pressure history, Moyen et al. (2006, their figure 4) proposed that this zone might represent the southwesterly extension of the suture proposed by de Ronde and de Wit (1994). Since the publication of Cutts et al. (2014), an extensive structural analysis of the Inyoni shear zone has been provided by Van Kranendonk et al. (2014). In particular, Van Kranendonk et al. (2014) noted the close association of high-pressure garnet-bearing amphibolites with vertical sheath folds (D3 in their structural sequence). Based on the maximum concentration of poles to foliation in figure 2b of Moyen et al. (2006) and fabric orientation data in figure 8 of Van Kranendonk et al. (2014), the Inyoni shear zone dips steeply to the east-southeast with a moderate to steep down-dip lineation. This geometry of fabric elements is common in highly strained greenstone belts (e.g., Lin, 2005; Lin and Beakhouse, 2013). Furthermore, in its present NNE–SSW orientation the Inyoni shear zone appears inconsistent with the interpretation of northwest-dipping subduction as proposed by Cutts et al. (2014). Thus, in contrast to the subduction model of Moyen et al. (2006), Van Kranendonk et al. (2014, abstract) concluded that the Inyoni shear zone represents "just another drip of relatively cool, relatively rigid greenstones into hot, ductile granitic gneisses."

Fabrics in the Stolzburg Domain

Van Kranendonk (2011) argued that the radial foliation pattern and steep lineations in the BGGB should be interpreted in terms of dome-and-keel architecture produced by partial convective overturn. In the Stolzburg domain, the main composite tectonite fabric in the Tjakastad schist belt and across the Stolzburg schist belt to the Komati fault to the north is steeply oriented with a strong, generally south- to east-southeast–plunging mineral elongation lineation (Kisters et al., 2003; Diener et al., 2005; Van Kranendonk et al., 2009). In the schists, strong amphibolite facies prolate fabrics that record high constrictional strain are overprinted to the north by greenschist facies fabrics that are generally close to plane strain. C′-S relations in these mylonitic rocks record consistent kinematics that indicate dextral oblique-slip displacement. As a result, the Tjakastad schist belt and the Theespruit pluton to the east have been displaced down relative to the Stolzburg pluton, and the main BGGB to the north of the Komati fault has been displaced down relative to the Stolzburg domain (Kisters et al., 2003; Diener et al. 2005; Van Kranendonk et al., 2009). Overall, it seems that whatever the mechanism that formed the dome-and-keel architecture of the BGGB, it was a polyphase process rather than simply subsidence of inter-diapir synclines.

COULD THE TTG CRUST HAVE BEEN ABOVE THE SOLIDUS AT ca. 3.23 Ga?

One critical factor in relation to the architecture of the BGGB is the rheology of the TTG basement during the late Mesoarchean events (Cutts et al., 2014), specifically whether it could have been close to or above the solidus when the dome-and-keel architecture was imposed. This issue may be addressed by reference to the calculations of West and Mareschal (1979), Mareschal and West (1980), Mareschal and Jaupart (2006), and Bodorkos and Sandiford (2006). Given the higher heat production of TTG crust and the higher mantle heat flux in the Archean Eon, the geotherm was hotter and the crust was weaker at any given depth than on contemporary Earth (West and Mareschal, 1979; Mareschal and Jaupart, 2006). How hot and how weak depend on the concentration of the heat-producing elements and their distribution with depth, the depth of burial of the TTG crust, and whether or not the solidus was exceeded. Fortunately, it is possible to make some general statements.

From the work of Mareschal and Jaupart (2006), a conservative estimate is that a hotter geotherm could have reached the fluid-present solidus at a depth of ~25 km and the fluid-absent solidus for hornblende-bearing TTG crust at ~35–40 km. Then, from the work of Mareschal and West (1980), we know that the difference in temperature between the center of a rising dome of TTGs and the center of sagducting greenstones would be on the order of 300–470 °C at depths of 7–28 km. The maximum difference in temperature occurs at ~15 km. Rocks at the center of the dome deeper than ~9 km could be above the fluid-present solidus, and those deeper than ~14 km above the fluid-absent solidus. Finally, from the work of Bodorkos and Sandiford (2006) we know that shallow burial of low-heat-producing TTG crust underlying high-heat-producing felsic crust by a greenstone cover would result in a ΔT of only ~65 °C at 18 km depth after ~65 m.y. and ~100 °C after ~165 m.y. The resulting temperatures would be well below the solidus. However, burial of the same TTG-felsic crust to 31 km depth, approximately equivalent to 9 kbar load pressure, would yield temperatures at the wet solidus after 165 m.y. and well above both the fluid-present and fluid-absent solidi after 215 m.y.

Based on these generalizations, it is plausible that the older TTGs in the Stolzburg domain (Stolzburg and Theespruit plutons) could have been close to or above the wet solidus at the current erosion level and well above the fluid-absent solidus at depth. Evidence to support suprasolidus crust beneath the Stolzburg domain at the time of the ca. 3.23 Ga tectonic event is provided by contemporaneous granitoids (discussed below). Furthermore, strongly deformed migmatites along the contacts between the TTG gneisses and the greenstone remnants (Dziggel et al., 2002) could include a leucosome component produced by fluid-present melting of the TTG gneisses fluxed by H_2O derived from prograde subsolidus dehydration reactions occurring in the greenstones as they sank through the rising TTG crust. Although melting is speculative at present, this postulate should be investigated.

GEOCHRONOLOGY OF THE ca. 3.23 Ga TECTONIC EVENT

De Ronde and de Wit (1994) proposed that the Saddleback-Inyoka fault system in the west-central part of the BGGB represents the present-day surface expression of a collisional suture between two contrasting crustal blocks—the northern and southern BGGB terranes. De Ronde and Kamo (2000) proposed that the putative arc collision occurred in the interval ca. 3.29–3.26 Ga. This postulated suturing event immediately predates the regional metamorphism and contemporaneous crustal magmatism in the Stolzburg domain, as well as magmatism to the east-southeast (host gneisses of the Dalmein pluton). In addition, magmatism contemporaneous with metamorphism in the Stolzburg domain occurs to the west-northwest of the Inyoni shear zone (Badplaas domain) and north of the Saddleback-Inyoka fault system (the Nelshoogte and Kaap Valley plutons).

Age information is critical to any discussion comparing and contrasting *P-T* data, apparent thermal gradients, and *P-T* paths, and to any consideration of whether the deep crust could have been partially molten contemporaneously with the regional metamorphism. Such data also may have the potential to distinguish between different mechanisms by which the dome-and-keel architecture was imposed on the BGGB, for example by assessing contemporaneity of events across a wide area versus any possible trend in age of events across the area.

About 10 km to the west of the localities studied by Cutts et al. (2014), within the Inyoni shear zone, Dziggel et al. (2005) constrained the timing of metamorphism in a greenstone remnant to ca. 3.23 Ga using zircon (weighted mean $^{207}Pb/^{206}Pb$ age of 3.227 ± 7 Ga) and titanite (U-Pb upper intercept on concordia age of 3229 ± 9 Ga). This is the same as the timing of metamorphism in the Tjakastad schist belt, as constrained by an existing titanite age of 3.229 ± 25 Ga (U-Pb upper intercept on concordia; Diener et al., 2005) and the new garnet (Lu-Hf) and monazite (weighted mean $^{207}Pb/^{206}Pb$) ages of 3.233 ± 17 and 3.191 ± 9 Ga, respectively, provided by Cutts et al. (2014). Furthermore, based on diffusion modeling, Cutts et al. (2014) argued that the metamorphic event was short lived (<50 m.y.). However, this will not be a discriminant, because time scales shorter than 50 m.y. appear to be consistent with both subduction-accretion processes and sagduction (Maresch and Gerya, 2005; François et al., 2014).

Limits on the timing of deformation and metamorphism are also provided by crystallization ages of contemporaneous and post-tectonic granitoids in the terrane south of the proposed BGGB suture. From the Inyoni shear zone, ~10 km to the west of the localities studied by Cutts et al. (2014), Dziggel et al. (2005) reported a zircon age of 3.229 ± 5 Ga (U-Pb upper intercept on concordia) for a late-synkinematic trondhjemite sheet intrusive into migmatites along the contact of a greenstone remnant and trondhjemitic gneisses of the Stolzburg pluton. This age is close to two near-concordant single-zircon $^{207}Pb/^{206}Pb$ ages of ca. 3.237 and ca. 3.255 Ga from a younger phase of the ca. 3.46 Ga Stolzburg pluton reported by Kamo and Davis (1994). Subsequently, Schoene et al. (2008) reported a zircon age of 3.212.5 ± 0.8 Ga (weighted mean $^{207}Pb/^{206}Pb$ age) for a late-synkinematic granite sheet within a greenstone raft in the Stolzburg pluton.

About 20 km to the southwest of the localities studied by Cutts et al. (2014), tonalite gneiss immediately east of the Welverdiend shear zone, which appears to link to the Inyoni shear zone north of the Schapenburg schist belt, has a magmatic age of 3.228 ± 12 Ga (zircon, U-Pb upper intercept on concordia; Westraat et al., 2005). This age is similar to a crystallization age of 3.231 ± 5 Ga (zircon, weighted mean $^{207}Pb/^{206}Pb$ age; Stevens et al., 2002) for a late-synkinematic tonalite gneiss situated ~5 km further to the south within the Schapenburg schist belt. These two ages are identical within error to the age of the late-synkinematic trondhjemite sheet in the Stolzburg domain discussed above.

About 20 km to the southeast of the localities studied by Cutts et al. (2014), Lana et al. (2010b) reported magmatic ages for the Southern Theespruit and Mooihoek gneisses of 3.234 ± 12 and 3.226 ± 9 Ga, respectively (zircon, U-Pb upper intercepts on concordia). The post-tectonic epizonal Dalmein pluton, which cuts the fabrics in the gneisses, yielded a crystallization age of ca. 3.203 ± 7 Ga (zircon, U-Pb upper intercept on concordia; Lana et al., 2010b).

In a wider context, west of the Inyoni shear zone, the Badplas domain contains plutonic units that were emplaced in the interval ca. 3.26–3.23 Ga (zircon, U-Pb upper intercept on concordia ages; Kisters et al., 2010). In addition, there are abundant synkinematic trondhjemites within the shear zone (Moyen et al., 2006; Nédélec et al., 2012). One trondhjemite with a weak D2 fabric from just west of the shear zone has yielded a magmatic age of 3.238.2 ± 0.9 Ga (mean $^{207}Pb/^{206}Pb$ age; Van Kranendonk et al., 2014), which provides an upper limit for the main steeply dipping, north-northeast–striking fabric in the shear zone (D3 in the structural sequence of Van Kranendonk et al. [2014]). Positive initial εHf values for zircons from the trondhjemite are consistent with derivation from older Barberton-type crust (Van Kranendonk et al., 2014).

Late Mesoarchean magmas were also emplaced extensively north of the Saddleback-Inyoka fault system. The older Nelshoogte pluton has yielded zircon crystallization ages of 3.236 ± 1 (U-Pb upper intercept on concordia; de Ronde and Kamo, 2000) and 3.236 ± 0.3 Ga (weighted mean $^{207}Pb/^{206}Pb$ age; Schoene et al., 2008). In addition, the younger Kaap Valley pluton has yielded crystallization ages of ca. 3.227 ± 1 Ga (zircon and titanite combined, U-Pb upper intercept on concordia; Kamo and Davis, 1994) and 3.228 ± 1 and 3.229 ± 1 Ga (zircon, U-Pb upper intercepts on concordia; de Ronde and Kamo, 2000).

Taken together, these data unambiguously demonstrate regional heating of the deep crust to suprasolidus conditions. The data undermine the argument that the age of intrusion of the TTG plutons in the Stolzburg domain is a significant obstacle to greenstones sinking between rising domes of TTG crust at ca. 3.23 Ga, coeval with the regional metamorphism. Furthermore, a low-viscosity substrate, as would have been provided by the suprasolidus lower crust, is a necessary condition for gravitational redistribution (Johnson et al., 2014). Thus, sagduction of the greenstone belt cover and doming of the TTG basement for the BGGB as a whole as proposed by Van Kranendonk (2011) and Van Kranendonk et al. (2014) are permitted by the data.

P-T PATHS AND TECTONICS

Interpretation of the *P-T* Data

Based on the summary *P-T* diagram from Cutts et al. (2014, their figure 11) and taking the *P-T* paths at face value, the samples from the Tjakastad schist belt modeled by these authors achieved maximum pressures of ~7.5–8.5 kbar at temperatures of ~560–590 °C. These results are comparable with earlier work in the belt that yielded a pressure of ~7.4 kbar at a temperature of ~560 °C (Diener et al., 2005). These data suggest an apparent thermal gradient of 71–75 °C/kbar at the peak pressure.

Assuming an initial pressure of 2 kbar at the beginning of the *P-T* paths, as shown in figure 11 of Cutts et al. (2014), the prograde segments of these *P-T* paths are characterized by a large change in pressure of ~5.5–6.5 kbar. Heating during the evolution to peak pressure was limited to 100–120 °C. The pressure peak was followed by slight additional heating during initial decompression (20–40 °C over 1–2 kbar) prior to cooling to the ambient geotherm at around 500 °C and 4 kbar. Thus, these new *P-T* paths determined from the central part of the northern Stolzburg domain have an overall shape at $P > 4$ kbar that is similar to a steeply inclined hairpin. The shallow slope of the retrograde *P-T* path at $P < 4$ kbar is consistent with slow cooling as required by the apatite thermochronology of Schoene et al. (2008).

How reliable are these *P-T* paths? Uncertainties related to phase equilibria modeling include those inherently associated with internally consistent thermodynamic data and activity-composition models (Powell and Holland, 2008), and simplifications necessary to model phase equilibria in more complex natural systems. The overall topology of pseudosections for pelitic compositions is well constrained by information from natural mineral assemblages (White et al., 2007, 2014), although the exact location in *P-T* space of some phase assemblage fields may be less certain owing to minor components and mixed volatile equilibria. Thus, *P-T* paths derived from correspondence between the petrographic observations and mineral assemblage fields in *P-T* pseudosections are generally regarded as acceptable.

It is more difficult to evaluate the reliability of the thermodynamic modeling of the garnet compositions, particularly because a starting *P-T* condition must be assumed for the *P-T* paths modeled. In the Cutts et al. (2014) study, the calculated X_{grs} (where $X_{grs} = Ca/[Fe^{2+} + Mg + Ca + Mn]$) curves for the *P-T* paths modeled produced a close fit to the measured X_{grs} profiles (their figure 10), but the calculated curves for X_{sps}, X_{pyr}, and X_{alm} (where $X_{sps} = Mn/[Fe^{2+} + Mg + Ca + Mn]$, $X_{pyr} = Mg/[Fe^{2+} + Mg + Ca + Mn]$, and $X_{alm} = Fe^{2+}/[Fe^{2+} + Mg + Ca + Mn]$) did not produce acceptable fits to the measured profiles (see their supplementary data). As discussed by Cutts et al. (2014), there are a number of reasons why this may have occurred, including the uncertainty introduced by modification of compositional zoning due to diffusional relaxation. On balance, the overall shape of the *P-T* paths is likely to be reliable even though the absolute pressure and temperature conditions may be open to question.

If the initial *P-T* conditions for the modeled *P-T* paths of ~435 °C (sample BKC-10 in Cutts et al., 2014) and ~500 °C (samples BKC-16 and BKC-23) at 2 kbar are accepted for the purpose of this discussion, then these initial conditions imply apparent thermal gradients of up to 250 °C/kbar. These gradients are broadly consistent with, but somewhat higher than, the apparent thermal gradients of 125–200 °C/kbar derived from the metamorphic field gradient determined by Cloete (1999, his figure 4.33) from the western limb of the Onverwacht anticline, north of the Komati fault. Starting from this high initial thermal gradient, the deduced *P-T* paths indicate that loading of the Tjakastad schists was close to isothermal. These *P-T* paths are unlike particle paths followed by markers in geodynamic models of both Phanerozoic (Warren et al., 2008; Sizova et al., 2012; Burov et al., 2014) and Proterozoic (Sizova et al., 2014) subduction. During subduction, prograde particle paths generally show trends of increasing temperature with pressure, even at low d*T*/d*P*, reflecting the increase in temperature with depth along the subduction zone. Exceptions may occur at very low temperatures, as shown by some low-grade blocks in the Caribbean serpentinite-hosted subduction channels (Krebs et al., 2011; Escuder-Viruete and Pérez-Estaún, 2013), but those steeply inclined hairpin *P-T* paths start from much lower apparent thermal gradients than do the *P-T* paths for the Tjakastad schist belt. Furthermore, the Tjakastad schists do not display any of the typical lithological or structural features expected in a typical serpentinite-type subduction zone (Guillot et al., 2009; Krebs et al., 2011).

Making the simplifications that there is no component of tectonic overpressure and that metamorphic pressure (i.e., mean stress) is approximately equivalent to the imposed load, and assuming a constant density of 2900 kg/m^3 for the greenstone belt lithologies, the steeply inclined hairpin *P-T* paths determined by Cutts et al. (2014) imply burial from ~7 km to ~26–30 km depth. The absence of any significant rise in temperature at the pressure peak before unloading returned the rocks to mid-crustal depths of 19–14 km indicates that there was no opportunity for conductive relaxation and implies a rapid evolution. This is a similar evolution to that predicted by Collins and Van Kranendonk (1999) for sagduction of a 10-km-thick greenstone unit during partial convective overturn of the underlying TTG crust. Furthermore, the prograde segments of the *P-T* paths from the Tjakastad schists are similar to the burial *P-T* paths for particles initially located at the interface between greenstone and TTG crust in numerical models of sagduction (François et al., 2014). During sagduction, the contrast in temperature at the contact between the sinking crust and the doming granitoids is negligible (Collins and Van Kranendonk, 1999), and, given the fast rates of burial and exhumation associated with sagduction (François et al., 2014), there is only limited time for heating. Thus, steeply inclined hairpin *P-T* paths are to be expected. On balance, the *P-T* paths from the Tjakastad schists appear more likely to have been generated by sagduction than subduction.

Cutts et al. (2014) correlated the *P-T* paths from the Tjakastad schists with the peak-to-retrograde *P-T* paths derived from the high-pressure garnet amphibolites in the Inyoni shear zone by Moyen et al. (2006; see also Diener et al., 2006, their sample SL1-6, and Nédélec et al., 2012). The Inyoni samples could have achieved peak *P-T* conditions of >10–12 kbar at 650–700 °C based on results from the average *P-T* protocol in THERMOCALC software (Moyen et al., 2006) and *P-T* pseudosections (Diener et al., 2006; Nédélec et al., 2012). Within uncertainty, these *P-T* conditions are similar to those for samples from a greenstone raft apparently within a shear zone in the central Stolzburg domain (Diener et al., 2006), where *P-T* was estimated to be ~10 kbar at ~670 °C (by conventional thermobarometry; Dziggel et al., 2002). In addition, in the Steynsdorp area, ~24 km to the southeast of Tjakastad (see Cutts et al., 2014, their figure 1), Lana et al. (2010a) estimated peak *P-T* conditions of >10 kbar at >640 °C using the average *P-T* protocol in THERMOCALC. Regrettably, the prograde paths are undefined at all three localities. Thus, whether the prograde paths have similarly low d*T*/d*P* to those in the Tjakastad schists is unknown. Based on these *P-T* data, the apparent thermal gradients are: ~80 °C/kbar on the north side of the Stolzburg pluton (Kisters et al., 2003); 64–67 °C/kbar for the greenstone remnants in the central Stolzburg domain (Dziggel et al., 2002) and for the amphibolites in the Steynsdorp area (Lana et al., 2010a); and, ~54–58 °C/kbar for the Inyoni shear zone (Diener et al., 2006; Moyen et al., 2006).

Implications for the Stolzburg Domain

One prediction of the subduction-accretion model is the development of contrasting metamorphic belts—one of low-d*T*/d*P* type associated with subduction and another of high-d*T*/d*P* type developed in the overriding plate—separated by a fault zone that may represent a suture, albeit commonly associated with lateral displacement, as found in many Phanerozoic orogenic belts (Miyashiro, 1961). This paired arrangement of metamorphic belts registers the unidirectional asymmetry of the contemporaneous thermal structure caused by subduction of the ocean plate. Thus, if the BGGB was formed by subduction-accretion processes, contrasting types of metamorphism associated with the amalgamation of the southern and northern terranes along the Saddleback-Inyoka fault system and the Inyoni shear zone would be expected. Is there evidence of contrasts in metamorphism associated with these two structures or to the northwest or southeast?

About 25 km to the southwest along the Inyoni shear zone, the Schapenburg schist belt contains metasedimentary rocks assigned to the Fig Tree Group—an unusual occurrence because rocks of this group are generally confined to the area north of the Komati fault in the central BGGB. Furthermore, the metamorphism of these rocks, which is inferred to have occurred at 3.23 Ga, is of high d*T*/d*P* type with *P-T* conditions of ~5 kbar and ~640 °C (Stevens et al., 2002), yielding an apparent thermal gradient of ~128 °C/kbar. Based on the correlation with the Fig Tree Group, the Schapenburg schist belt represents a shallower structural level within the Inyoni shear zone than the high-pressure garnet amphibolites some 25 km to the north (Moyen et al., 2006; Nédélec et al., 2012; Van Kranendonk et al., 2014).

In addition, ~50 km to the northeast, north of the Saddleback-Inyoka fault system, at the northern margin of the Jamestown schist belt, gneisses and associated supracrustal rocks record *P-T* conditions of ~5.5 kbar and ~650 °C (Dziggel et al., 2006), yielding an apparent thermal gradient of ~118 °C/kbar. The age of this metamorphism is likely between 3.26 Ga and 3.23 Ga (Dziggel et al., 2010). In the same belt, around the New Consort gold mine, the structurally lower Onverwacht Group records *P-T* conditions of ~7 kbar and ~650 °C whereas the structurally higher Fig Tree Group records *P-T* conditions of ~4.5 kbar and ~550 °C for the 3.23 Ga event (Otto et al., 2007). These results yield apparent thermal gradients of ~93 and ~122 °C/kbar, respectively.

Worldwide, high-temperature and high-pressure metamorphic rocks of Neoarchean to Neoproterozoic age exhibit two contrasting types of metamorphism with different apparent thermal gradients, one with mean d*T*/d*P* of ~110 °C/kbar and another with mean d*T*/d*P* of ~55 °C/kbar (Brown, 2014). To ensure a robust result, in compiling the data Brown (2014) used a minimum *T* of 700 °C at *P* < 1 GPa for high-d*T*/d*P* metamorphism (granulite–ultrahigh temperature metamorphism) and a minimum *P* of 1 GPa at *T* < 700 °C for low-d*T*/d*P* metamorphism (eclogite–high-pressure granulite metamorphism). This discrimination increases the likelihood of an equilibrated peak mineral assemblage and, at low pressures, avoids the issue of including rocks that yield artificially high apparent thermal gradients that are simply an artifact of the curvature and flattening of the geotherm close to the Earth's surface. Thus, these apparent thermal gradients are taken as typical for Neoarchean to Neoproterozoic metamorphism.

The apparent thermal gradients registered in the Stolzburg domain are similar to the low-d*T*/d*P* type of metamorphism, consistent with the style of subduction that operated from the Neoarchean to the Neoproterozoic. However, the apparent thermal gradients retrieved from the Schapenburg and Jamestown schist belts are higher. This is also true for rocks of the Komati Formation to the north of the Komati fault (Cloete, 1999). These differences in apparent thermal gradient may be related to structural position within the BGGB, deeper versus shallower, rather than related to contrasting types of metamorphism generated in different thermal regimes. If this interpretation is correct, then these differences do not require a convergent plate boundary tectonic setting.

In a regional context, Cutts et al. (2014) emphasized the trend, which was previously noted by Diener et al. (2005), for peak pressure to increase away from the Komati fault. These authors interpreted this trend to indicate that the Stolzburg domain represents an exhumed orogenic core, consistent with the core complex model proposed by Kisters et al. (2003) and emphasized by Lana et al. (2010b). This begs the question of the trigger mechanism for formation of the dome-and-keel architecture for the BGGB as a whole. It is plausible that the regional distribution of rocks with similar clockwise *P-T* paths was due to partial convective overturn followed by differential exhumation increasing away from the Komati fault. Certainly, it seems that the extensional structures in the footwall rocks of the Komati fault would allow for this mechanism (Van Kranendonk, 2011). There is evidence from geodynamic modeling that other explanations are plausible for these types of clockwise *P-T* paths from greenstone belts (François et al., 2014). In addition, it is unclear why the core of the orogen is inferred to have been exhumed "as a coherent block of relatively rigid, buoyant crust" or why this is "clearly more consistent with the subduction–accretion model, with the formation of the BGGB being a result of modern-style plate-tectonic processes" (Cutts et al., 2014, p. 268). These statements need further clarification.

There remains the question of whether the apparent thermal gradients retrieved from south of the Komati fault (summarized above) are anomalous for the Archean. Apparent thermal gradients of 35–75 °C/kbar are common from the beginning of the Neoarchean (Brown, 2006, 2007, 2014), but at present there are insufficient data to judge whether such gradients are unusual in the late Mesoarchean. Notably, apparent thermal gradients for the full range of *P-T* paths derived from the numerical model of sagduction by François et al. (2014) are in the range 45–80 °C/kbar. By contrast, apparent thermal gradients for the full range of *P-T* paths determined from the Caribbean subduction-accretionary complex by Krebs et al. (2011) and Escuder-Viruete and Pérez-Estaún (2013) are in the range 22–33 °C/kbar, much lower than those in the Stolzburg domain. These low gradients are typical for Phanerozoic oceanic subduction, for which the mean d*T*/d*P* derived from lawsonite blueschists and lawsonite eclogites is ~24 °C/kbar (Brown, 2014).

CONCLUDING REMARKS

Notwithstanding the uncertainties discussed above, Cutts et al. (2014) are to be commended for providing *P-T* data and *P-T* paths for which both the prograde and retrograde segments are based on quantitative thermodynamic modeling. Their results demonstrate that the prograde and early retrograde segments of these *P-T* paths within the Stolzburg terrane are characterized by high d*P*/d*T* ratios suggestive of rapid burial and rapid initial decompression. However, there is no evidence in the Stolzburg domain or across either the Saddleback-Inyoka fault system or the Inyoni shear zone of the hallmark of subduction-accretion, which is a unidirectional asymmetry in the thermal structure as has been registered by paired metamorphism in many Phanerozoic metamorphic belts. It has been argued here that the *P-T* paths determined by Cutts et al. (2014) are more consistent with sagduction than with subduction-accretion processes. As a result, the non-uniformitarian partial convective overturn model of Van Kranendonk (2011) is preferred over the uniformitarian mobile-lid plate tectonic interpretation of Cutts et al. (2014). However, this preference is indicative rather than definitive, and more data from various subdisciplines in geology are required before any authoritative interpretation will be possible.

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REFERENCES CITED

Arndt, N., and Davaille, A., 2013, Episodic Earth evolution: Tectonophysics, v. 609, p. 661–674, doi:10.1016/j.tecto.2013.07.002.

Bodorkos, S., and Sandiford, M., 2006, Thermal and mechanical controls on the evolution of Archean crustal deformation: Examples from Western Australia, *in* Benn, K., Mareschal, J.-C., and Condie, K.C., eds., Archean Geodynamics and Environments: American Geophysical Union Geophysical Monograph 164, p. 131–147, doi:10.1029/164GM10.

Bouhallier, H., Chardon, D., and Choukroune, P., 1995, Strain patterns in Archean dome-and-basin structures: The Dharwar craton (Karnataka, south India): Earth and Planetary Science Letters, v. 135, p. 57–75, doi:10.1016/0012-821X(95)00144-2.

Brown, M., 2006, Duality of thermal regimes is the distinctive characteristic of plate tectonics since the Neoarchean: Geology, v. 34, p. 961–964, doi:10.1130/G22853A.1.

Brown, M., 2007, Metamorphic conditions in orogenic belts: A record of secular change: International Geology Review, v. 49, p. 193–234, doi:10.2747/0020-6814.49.3.193.

Brown, M., 2008, Characteristic thermal regimes of plate tectonics and their metamorphic imprint throughout Earth history: When did Earth first adopt a plate tectonics mode of behavior?, *in* Condie, K.C., and Pease, V., eds., When Did Plate Tectonics Begin on Planet Earth?: Geological Society of America Special Paper 440, p. 97–128, doi:10.1130/2008.2440(05).

Brown, M., 2009, Metamorphic patterns in orogenic systems and the geological record, *in* Cawood, P.A., and Kröner, A., eds., Earth Accretionary Systems in Space and Time: Geological Society of London Special Publication 318, p. 37–74, doi:10.1144/SP318.2.

Brown, M., 2010, Paired metamorphic belts revisited: Gondwana Research, v. 18, p. 46–59, doi:10.1016/j.gr.2009.11.004.

Brown, M., 2014, The contribution of metamorphic petrology to understanding lithosphere evolution and geodynamics: Geoscience Frontiers, v. 5, p. 553–569, doi:10.1016/j.gsf.2014.02.005.

Burov, E., Francois, T., Yamato, P., and Wolf, S., 2014, Mechanisms of continental subduction and exhumation of HP and UHP rocks: Gondwana Research, v. 25, p. 464–493, doi:10.1016/j.gr.2012.09.010.

Chardon, D., Choukroune, P., and Jayananda, M., 1996, Strain patterns, decollement and incipient sagducted greenstone terrains in the Archaean Dharwar craton (south India): Journal of Structural Geology, v. 18, p. 991–1004.

Choukroune, P., Bouhallier, H., and Arndt, N.T., 1995, Soft lithosphere during periods of Archaean crustal growth or crustal reworking, *in* Coward, M.E., and Ries, A.C., eds., Early Precambrian Processes: Geological Society of London Special Publication 95, p. 67–86, doi:10.1144/GSL.SP.1995.095.01.05.

Cloete, M., 1999, Aspects of Volcanism and Metamorphism of the Onverwacht Group Lavas in the Southwestern Portion of the Barberton Greenstone Belt: Geological Survey of South Africa Memoir 84, 232 p.

Collins, W.J., and Van Kranendonk, M.J., 1999, Model for the development of kyanite during partial convective overturn of Archean granite-greenstone terranes: The Pilbara Craton, Australia: Journal of Metamorphic Geology, v. 17, p. 145–156, doi:10.1046/j.1525-1314.1999.00187.x.

Collins, W.J., Van Kranendonk, M.J., and Teyssier, C., 1998, Partial convective overturn of Archaean crust in the east Pilbara Craton, Western Australia: Driving mechanisms and tectonic implications: Journal of Structural Geology, v. 20, p. 1405–1424, doi:10.1016/S0191-8141(98)00073-X.

Cutts, K.A., Stevens, G., Hoffmann, J.E., Buick, I.S., Frei, D., and Münker, C., 2014, Paleo- to Mesoarchean polymetamorphism in the Barberton Granite-Greenstone Belt, South Africa: Constraints from U-Pb monazite and Lu-Hf garnet geochronology on the tectonic processes that shaped the belt: Geological Society of America Bulletin, v. 126, p. 251–270, doi:10.1130/B30807.1.

Dalstra, H.J., Ridley, J.R., Bloem, E.J.M., and Groves, D.I., 1999, Metamorphic evolution of the central Southern Cross Province, Yilgarn Craton, Western Australia: Australian Journal of Earth Sciences, v. 46, p. 765–784, doi:10.1046/j.1440-0952.1999.00744.x.

Debaille, V., O'Neill, C., Brandon, A.D., Haenecour, P., Yin, Q.Z., Mattielli, N., and Treiman, A.H., 2013, Stagnant-lid tectonics in early Earth revealed by ^{142}Nd variations in late Archean rocks: Earth and Planetary Science Letters, v. 373, p. 83–92, doi:10.1016/j.epsl.2013.04.016.

de Ronde, C.E.J., and de Wit, M., 1994, The tectonic history of the Barberton greenstone belt, South Africa: 490 million years of Archean crustal evolution: Tectonics, v. 13, p. 983–1005, doi:10.1029/94TC00353.

de Ronde, C.E.J., and Kamo, S., 2000, An Archean arc-arc collisional event: A short-lived (ca. 3 Myr) episode, Weltevreden area, Barberton greenstone belt, South Africa: Journal of African Earth Sciences, v. 30, p. 219–248, doi:10.1016/S0899-5362(00)00017-8.

Diener, J.F.A., Stevens, G., Kisters, A.F.M., and Poujol, M., 2005, Metamorphism and exhumation of the basal parts of the Barberton greenstone belt, South Africa: Constraining the rates of Mesoarchean tectonism: Precambrian Research, v. 143, p. 87–112, doi:10.1016/j.precamres.2005.10.001.

Diener, J.F.A., Stevens, G., and Kisters, A.F.M., 2006, High-pressure intermediate-temperature metamorphism in the southern Barberton granitoid–greenstone terrain, South Africa: A consequence of subduction-driven overthickening and collapse of Mid-Archean continental crust, *in* Benn, K., Mareschal, J.-C., and Condie, K., eds., Archean Geodynamics and Environments: American Geophysical Union Geophysical Monograph 164, p. 239–254, doi:10.1029/164GM15.

Dixon, J.M., and Summers, J.M., 1983, Patterns of total and incremental strain in subsiding troughs: Experimental centrifuged models of inter-diapir synclines: Canadian Journal of Earth Sciences, v. 20, p. 1843–1861, doi:10.1139/e83-175.

Dziggel, A., Stevens, G., Poujol, M., Anhaeusser, C.R., and Armstrong, R.A., 2002, Metamorphism of the granite–greenstone terrane south of the Barberton greenstone belt, South Africa: An insight into the tectono-thermal evolution of the 'lower' portions of the Onverwacht Group: Precambrian Research, v. 114, p. 221–247, doi:10.1016/S0301-9268(01)00225-X.

Dziggel, A., Armstrong, R.A., Stevens, G., and Nasdala, L., 2005, Growth of zircon and titanite during metamorphism in the granitoid-gneiss terrane south of the Barberton greenstone belt, South Africa: Mineralogical Magazine, v. 69, p. 1019–1036, doi:10.1180/0026461056960305.

Dziggel, A., Knipfer, S., Kisters, A.F.M., and Meyer, F.M., 2006, *P–T* and structural evolution during exhumation of high-*T*, medium-*P* basement rocks in the Barberton Mountain Land, South Africa: Journal of Metamorphic Geology, v. 24, p. 535–551, doi:10.1111/j.1525-1314.2006.00653.x.

Dziggel, A., Poujol, M., Otto, A., Kisters, A.F.M., Trieloff, M., Schwarz, W.H., and Meyer, F.M., 2010, New U-Pb and ^{40}Ar/^{39}Ar ages from the northern margin of the Barberton greenstone belt, South Africa: Implications for the formation of Mesoarchaean gold deposits: Precambrian Research, v. 179, p. 206–220, doi:10.1016/j.precamres.2010.03.006.

Eriksson, K.A., 1980, Transitional sedimentation styles in the Moodies and Fig Tree groups, Barberton Mountain Land, South Africa: Evidence favouring an Archean continental margin: Precambrian Research, v. 12, p. 141–160, doi:10.1016/0301-9268(80)90027-3.

Escuder-Viruete, J., and Pérez-Estaún, A., 2013, Contrasting exhumation *P–T* paths followed by high-*P* rocks in the northern Caribbean subduction-accretionary complex: Insights from the structural geology, microtextures and equilibrium assemblage diagrams: Lithos, v. 160–161, p. 117–144, doi:10.1016/j.lithos.2012.11.028.

François, C., Philippot, P., Rey, P., and Rubatto, D., 2014, Burial and exhumation during Archean sagduction in the East Pilbara Granite-Greenstone Terrane: Earth and Planetary Science Letters, v. 396, p. 235–251, doi:10.1016/j.epsl.2014.04.025.

Gerya, T., 2014, Precambrian geodynamics: Concepts and models: Gondwana Research, v. 25, p. 442–463, doi:10.1016/j.gr.2012.11.008.

Goodwin, A., 1991, Precambrian Geology: The Dynamic Evolution of the Continental Crust: London, Academic Press, 651 p.

Goodwin, A.M., and Smith, I.E.M., 1980, Chemical discontinuities in Archean metavolcanic terrains and the development of Archean crust: Precambrian Research, v. 10, p. 301–311.

Griffin, W.L., Belousova, E.A., O'Neill, C., Reilly, S.Y., Malkovets, V., Pearson, N.J., Spetsius, S., and Wilde, S.A., 2014, The World Turns Over: Hadean–Archean crust-mantle evolution: Lithos, v. 189, p. 2–15, doi:10.1016/j.lithos.2013.08.018.

Guillot, S., Hattori, K., Agard, P., Schwartz, S., and Vidal, O., 2009, Exhumation processes in oceanic and continental subduction contexts: A review, *in* Lallemand, S., and Funiciello, F., eds., Subduction Zone Geodynamics: Berlin-Heidelberg, Springer Verlag, p. 175–205.

Herzberg, C., Asimow, P.D., Arndt, N., Niu, Y., Lesher, C.M., Fitton, J.G., Cheadle, M.J., and Saunders, A.D., 2007, Temperatures in ambient mantle and plumes: Constraints from basalts, picrites and komatiites: Geochemistry Geophysics Geosystems, v. 8, Q02006, doi:10.1029/2006GC001390.

Herzberg, C., Condie, K., and Korenaga, J., 2010, Thermal history of the Earth and its petrological expression: Earth and Planetary Science Letters, v. 292, p. 79–88, doi:10.1016/j.epsl.2010.01.022.

Johnson, T.E., Brown, M., Kaus, B., and VanTongeren, J.A., 2014, Delamination and recycling of Archaean crust caused by gravitational instabilities: Nature Geoscience, v. 7, p. 47–52, doi:10.1038/ngeo2019.

Jull, M., and Kelemen, P.B., 2001, On the conditions for lower crustal convective instability: Journal of Geophysical Research, v. 106, p. 6423–6446, doi:10.1029/2000JB900357.

Kamo, S.L., and Davis, D.W., 1994, Reassessment of Archean crustal development in the Barberton Mountain Land, South Africa, based on U-Pb dating: Tectonics, v. 13, p. 167–192, doi:10.1029/93TC02254.

Kisters, A.F.M., Stevens, G., Dziggel, A., and Armstrong, R.A., 2003, Extensional detachment faulting and core-complex formation in the southern Barberton granite–greenstone terrain, South Africa: Evidence for a 3.2 Ga orogenic collapse: Precambrian Research, v. 127, p. 355–378, doi:10.1016/j.precamres.2003.08.002.

Kisters, A.F.M., Belcher, R.W., Poujol, M., and Dziggel, A., 2010, Continental growth and convergence-related arc plutonism in the Mesoarchaean: Evidence from the Barberton granitoid-greenstone terrain, South Africa: Precambrian Research, v. 178, p. 15–26, doi:10.1016/j.precamres.2010.01.002.

Korenaga, J., 2006, Archean geodynamics and the thermal evolution of Earth, *in* Benn, K., Mareschal, J.-C., and Condie, K.C., eds., Archean Geodynamics and Environments: American Geophysical Union Geophysical Monograph 164, p. 7–32, doi:10.1029/164GM03.

Krebs, M., Schertl, H.-P., Maresch, W.V., and Draper, G., 2011, Mass flow in serpentinite-hosted subduction channels: *P–T–t* path patterns of metamorphic blocks in the Rio San Juan mélange (Dominican Republic): Journal of Asian Earth Sciences, v. 42, p. 569–595, doi:10.1016/j.jseaes.2011.01.011.

Labrosse, S., and Jaupart, C., 2007, Thermal evolution of the Earth: Secular changes and fluctuations of plate characteristics: Earth and Planetary Science Letters, v. 260, p. 465–481, doi:10.1016/j.epsl.2007.05.046.

Lana, C., Kisters, A.F.M., and Stevens, G., 2010a, Exhumation of Mesoarchean TTG gneisses from the middle crust: Insights from the Steynsdorp core complex, Barberton granitoid-greenstone terrain, South Africa: Geological Society of America Bulletin, v. 122, p. 183–197, doi:10.1130/B26580.1.

Lana, C., Tohver, E., and Cawood, P., 2010b, Quantifying rates of dome-and-keel formation in the Barberton granitoid-greenstone belt, South Africa: Precambrian Research, v. 177, p. 199–211, doi:10.1016/j.precamres.2009.12.001.

Lin, S., 2005, Synchronous vertical and horizontal tectonism in the Neoarchean: Kinematic evidence from a synclinal keel in the northwestern Superior craton, Canada: Precambrian Research, v. 139, p. 181–194, doi:10.1016/j.precamres.2005.07.001.

Lin, S., and Beakhouse, G.P., 2013, Synchronous vertical and horizontal tectonism at late stages of Archean cratonization and genesis of Hemlo gold deposit, Superior craton, Ontario, Canada: Geology, v. 41, p. 359–362, doi:10.1130/G33887.1.

Maresch, W.V., and Gerya, T.V., 2005, Blueschists and blue amphiboles: How much subduction do they need?: International Geology Review, v. 47, p. 688–702, doi:10.2747/0020-6814.47.7.688.

Mareschal, J.C., and Jaupart, C., 2006, Archean thermal regime and stabilization of the cratons, *in* Benn, K., Mareschal, J.-C., and Condie, K.C., eds., Archean Geodynamics and Environments: American Geophysical Union Geophysical Monograph 164, p. 61–74.

Mareschal, J.C., and West, G.F., 1980, A model for Archean tectonism. Part 2. Numerical models of vertical tectonism in greenstone belts: Canadian Journal of Earth Sciences, v. 17, p. 60–71, doi:10.1139/e80-006.

Marshak, S., 1999, Deformation style way back when: Thoughts on the contrasts between Archean/Paleoproterozoic and contemporary orogens: Journal of Structural Geology, v. 21, p. 1175–1182, doi:10.1016/S0191-8141(99)00057-7.

Marshak, S., Tinkham, D., Alkmim, F., Brueckner, H., and Bornhorst, T., 1997, Dome-and-keel provinces formed during Paleoproterozoic orogenic collapse—Core complexes, diapirs, or neither? Examples from the Quadrilátero Ferrífero and the Penokean orogen: Geology, v. 25, p. 415–418, doi:10.1130/0091-7613(1997)025<0415:DAKPFD>2.3.CO;2.

Miyashiro, A., 1961, Evolution of metamorphic belts: Journal of Petrology, v. 2, p. 277–311, doi:10.1093/petrology/2.3.277.

Moyen, J.-F., Stevens, G., and Kisters, A.F.M., 2006, Record of mid-Archean subduction from metamorphism in the Barberton terrain, South Africa: Nature, v. 442, p. 559–562, doi:10.1038/nature04972.

Nédélec, A., Chevrel, M.O., Moyen, J.F., Ganne, J., and Fabre, S., 2012, TTGs in the making: Natural evidence from the Inyoni shear zone (Barberton, South Africa): Lithos, v. 153, p. 25–38, doi:10.1016/j.lithos.2012.05.029.

O'Neill, C., Debaille, V., and Griffin, W., 2013, Deep earth recycling in the Hadean and constraints on surface tectonics: American Journal of Science, v. 313, p. 912–932, doi:10.2475/09.2013.04.

O'Neill, C., Lenardic, A., and Condie, K.C., 2014, Earth's punctuated tectonic evolution: Cause and effect, *in* Roberts, N.M.W., Van Kranendonk, M., Parman, S., Shirey, S., and Clift, P.D., eds., Continent Formation Through Time: Geological Society of London Special Publication 389, doi:10.1144/SP389.4 (in press).

Otto, A., Dziggel, A., Kisters, A.F.M., and Meyer, F.M., 2007, The New Consort Gold Mine, Barberton greenstone belt, South Africa: Orogenic gold mineralization in a condensed metamorphic profile: Mineralium Deposita, v. 42, p. 715–735, doi:10.1007/s00126-007-0135-5.

Oxburgh, E.R., and Turcotte, D.L., 1970, Thermal structure of island arcs: Geological Society of America Bulletin, v. 81, p. 1665–1688, doi:10.1130/0016-7606(1970)81[1665:TSOIA]2.0.CO;2.

Oxburgh, E.R., and Turcotte, D.L., 1971, Origin of paired metamorphic belts and crustal dilation in island arc regions: Journal of Geophysical Research, v. 76, p. 1315–1327, doi:10.1029/JB076i005p01315.

Parmenter, A.C., Lin, S., and Corkery, M.T., 2006, Structural evolution of the Cross Lake greenstone belt in the northwestern Superior Province, Manitoba: Implications for relationship between vertical and horizontal tectonism: Canadian Journal of Earth Sciences, v. 43, p. 767–787, doi:10.1139/e06-006.

Perchuk, L.L., and Gerya, T.V., 2011, Formation and evolution of Precambrian granulite terranes: A gravitational redistribution model, *in* van Reenen, D.D., Kramers, J.D., McCourt, S., and Perchuk, L.L., eds., Origin and Evolution of Precambrian High-Grade Gneiss Terranes, with Special Emphasis on the Limpopo Complex of Southern Africa: Geological Society of

America Memoir 207, p. 289–310, doi:10.1130/2011.1207(15).

Powell, R., and Holland, T.J.B., 2008, On thermobarometry: Journal of Metamorphic Geology, v. 26, p. 155–179, doi:10.1111/j.1525-1314.2007.00756.x.

Robin, C.M.I., and Bailey, R.C., 2009, Simultaneous generation of Archean crust and subcratonic roots by vertical tectonics: Geology, v. 37, p. 523–526, doi:10.1130/G25519A.1.

Sandiford, M., Van Kranendonk, M.J., and Bodorkos, S., 2004, Conductive incubation and the origin of dome-and-keel structure in Archean granite-greenstone terrains: A model based on the eastern Pilbara Craton, Western Australia: Tectonics, v. 23, TC1009, doi:10.1029/2002TC001452.

Schoene, B., de Wit, M.J., and Bowring, S.A., 2008, Mesoarchean assembly and stabilization of the eastern Kaapvaal craton: A structural-thermochronological perspective: Tectonics, v. 27, TC5010, doi:10.1029/2008TC002267.

Schoene, B., Dudas, F.O.L., Bowring, S.A., and de Wit, M., 2009, Sm–Nd isotopic mapping of lithospheric growth and stabilization in the eastern Kaapvaal craton: Terra Nova, v. 21, p. 219–228.

Sizova, E., Gerya, T., Brown, M., and Perchuk, L., 2010, Subduction styles in the Precambrian: Insight from numerical experiments: Lithos, v. 116, p. 209–229, doi:10.1016/j.lithos.2009.05.028.

Sizova, E., Gerya, T., and Brown, M., 2012, Exhumation mechanisms of melt-bearing ultrahigh pressure crustal rocks during collision of spontaneously moving plates: Journal of Metamorphic Geology, v. 30, p. 927–955, doi:10.1111/j.1525-1314.2012.01004.x.

Sizova, E., Gerya, T., and Brown, M., 2014, Contrasting styles of Phanerozoic and Precambrian continental collision: Gondwana Research, v. 25, p. 522–545, doi:10.1016/j.gr.2012.12.011.

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, v. 33, p. 557–560, doi:10.1130/G21365.1.

Stevens, G., Droop, G.T.R., Armstrong, R.A., and Anhaeusser, C.R., 2002, Amphibolite facies metamorphism in the Schapenburg schist belt: A record of the mid-crustal response to ~3.23 Ga terrane accretion in the Barberton greenstone belt: South African Journal of Geology, v. 105, p. 271–284, doi:10.2113/1050271.

Toussaint, G., Burov, E., and Jolivet, L., 2004, Continental plate collision: Unstable vs. stable slab dynamics: Geology, v. 32, p. 33–36, doi:10.1130/G19883.1.

Van Hunen, J., and Moyen, J.-F., 2012, Archean subduction: Fact or fiction?: Annual Review of Earth and Planetary Sciences, v. 40, p. 195–219, doi:10.1146/annurev-earth-042711-105255.

Van Hunen, J., and Van den Berg, A.P., 2008, Plate tectonics on the early Earth: Limitations imposed by strength and buoyancy of subducted lithosphere: Lithos, v. 103, p. 217–235, doi:10.1016/j.lithos.2007.09.016.

Van Kranendonk, M.J., 2011, Cool greenstone drips and the role of partial convective overturn in Barberton greenstone belt evolution: Journal of African Earth Sciences, v. 60, p. 346–352, doi:10.1016/j.jafrearsci.2011.03.012.

Van Kranendonk, M.J., Smithies, R.H., Hickman, A.H., and Champion, D.C., 2007, Review: Secular tectonic evolution of Archean continental crust: Interplay between horizontal and vertical processes in the formation of the Pilbara Craton, Australia: Terra Nova, v. 19, p. 1–38, doi:10.1111/j.1365-3121.2006.00723.x.

Van Kranendonk, M.J., Kröner, A., Hegner, E., and Connelly, J., 2009, Age, lithology and structural evolution of the c. 3.53 Ga Theespruit Formation in the Tjakastad area, southwestern Barberton Greenstone Belt, South Africa, with implications for Archean tectonics: Chemical Geology, v. 261, p. 115–139, doi:10.1016/j.chemgeo.2008.11.006.

Van Kranendonk, M.J., Kröner, A., Hoffman, E.J., Nagel, T., and Anhaeusser, C.R., 2014, Just another drip: Reanalysis of a proposed Mesoarchean suture from the Barberton Mountain Land, South Africa: Precambrian Research, v. 254, p. 19–35, doi:10.1016/j.precamres.2014.07.022.

Warren, C.J., Beaumont, C., and Jamieson, R.A., 2008, Modelling tectonic styles and ultra-high pressure (UHP) rock exhumation during the transition from oceanic subduction to continental collision: Earth and Planetary Science Letters, v. 267, p. 129–145, doi:10.1016/j.epsl.2007.11.025.

West, G.F., and Mareschal, J.C., 1979, Model for Archean tectonism. Part 1. Thermal conditions: Canadian Journal of Earth Sciences, v. 16, p. 1942–1950.

Westraat, J.D., Kisters, A.F.M., Poujol, M., and Stevens, G., 2005, Transcurrent shearing, granite sheeting and the incremental construction of the tabular 3.1 Ga Mpuluzi batholith, Barberton granite-greenstone terrane, South Africa: Journal of the Geological Society, v. 162, p. 373–388, doi:10.1144/0016-764904-026.

White, R.W., Powell, R., and Holland, T.J.B., 2007, Progress relating to calculation of partial melting equilibria for metapelites: Journal of Metamorphic Geology, v. 25, p. 511–527, doi:10.1111/j.1525-1314.2007.00711.x.

White, R.W., Powell, R., Holland, T.J.B., Johnson, T.E., and Green, E.C.R., 2014, New mineral activity-composition relations for thermodynamic calculations in metapelitic systems: Journal of Metamorphic Geology, v. 32, p. 261–286, doi:10.1111/jmg.12071.

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