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Commentary

Comment on "Ultrahigh temperature granulites and magnesian charnockites: Evidence for the Neoarchean accretion along the northern margin of the Kaapvaal craton" by Rajesh et al.

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1. Introduction

Over the years, the Southern Marginal Zone (SMZ) of the Limpopo mobile belt has been intensively studied, as it potentially results from one of the oldest continent-continent collision on Earth. Indeed, the general consensus about the evolution of this terrane is that it underwent a single tectono-metamorphic event at ~2.7 Ga, ascribed to collision between the Kaapvaal and Zimbabwe Cratons (Barton et al., 2006; Eglington and Armstrong, 2004; Kröner et al., 2000; Kreissig et al., 2001; Roering et al., 1992; Rigby et al., 2008; Stevens and van Reenen, 1992a,b; Zeh et al., 2009). The study of the Limpopo belt, and in particular the SMZ, is therefore of primary interest to unravel the tectonic regimes that prevailed back in the late-Archean and their evolution throughout Earth history.

In a recent contribution, Rajesh et al. (2014) proposed a new "*out-of-the-box*" interpretation of the geological record in the SMZ, which would represent a micro-continent accreted to the northern margin of the Kaapvaal Craton during the Neoarchean at 2.72 Ga. The key element on which this interpretation is based is the spatial and temporal association of ultra-high temperature (UHT) granulites and magnesian charnockites, which would be a criterion to identify subduction and collision settings in Precambrian terranes. To demonstrate the occurrence of both rock types in the SMZ, Rajesh et al. (2014) provide (1) new zircon U–Pb ages of 2.72 Ga, obtained from metamorphic zircon overgrowths in proposed UHT metamorphic rocks, and (2) a new interpretation of major-element data from the spatially associated Matok pluton, originally produced by Bohlender (1992), to reflect a magmatic arc setting at the time of intrusion.

This new interpretation, however, is in conflict with previous models and other published data, which strongly support that (1) the SMZ underwent metamorphism at "normal" granulite facies temperatures of 850–875 °C, with the preservation of a substantial volume of peak metamorphic biotite in most rocks; (2) granitoids of the Matok pluton were not generated within an arc setting but rather during the post-collisional stage of the ca. 2.72 Ga orogeny, as testified by both their age (~2.68 Ga) and chemical compositions; (3) the SMZ represent reworked material of the adjacent and overthrusted Pieterburg Block, and thus cannot have been an isolated terrane prior to amalgamation with the Kaapvaal Craton.

2. UHT metamorphism

A detailed comment on the occurrence of UHT metamorphism proposed by Belyanin et al. (2012) and Rajesh et al. (2014) was provided by Nicoli et al. (2014); the reader is referred to this work for further details, only the key points being repeated here. The *P*–*T* estimates suggested by Belyanin et al. (2012) and Rajesh et al. (2014) (i.e. ~1000 °C and ~12 kbar) are inconsistent with both field observations and experimental studies. The detailed metamorphic analysis provided by Taylor et al. (2014) clearly demonstrates that the presence of peak metamorphic biotite in the Bandelierkop formation metapelites is inconsistent with peak metamorphic temperatures in excess of 900 °C. This is in agreement with earlier metamorphic studies (e.g. Stevens and van Reenen, 1992a,b), more recent conclusions from phase equilibrium modelling (Koizumi et al., 2014), as well as a very large body of experimental data on partial melting of biotite-bearing metasediments (e.g. Montel

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and Vielzeuf, 1997; Patiño Douce and Harris, 1998; Patiño Douce and Johnston, 1991; Pickering and Johnston, 1998; Stevens et al., 1997; Vielzeuf and Holloway, 1988) arguing for a temperature peak around fluid-absent biotite breakdown partial melting conditions, i.e. 820–870 °C.

In addition to these considerations about the peak temperature attained by the SMZ, it is important to note that Rajesh et al. (2014) provide no metamorphic analysis for the two dated samples (i.e. DR-19C and DR-20). Therefore, it is not clear whether the obtained metamorphic ages documented by Rajesh et al. (2014) actually reflect peak metamorphism, and if so, if the dated samples underwent the same *P*–*T* conditions as the sample used for the metamorphic study (i.e. DR-19A).

3. Geochemical signature of the Matok pluton

3.1. *Terminology issues*

Rajesh et al. (2014) suggest that the ~2.68 Ga granitoids of the Matok pluton are "magnesian charnockites", a family of rocks supposedly formed in subduction settings (Frost and Frost, 2008; Rajesh, 2012), being compositionally similar to arc magmas. In this context, it must be noted that the "charnockite" appellation used by Rajesh et al. (2014) is incorrect, because it should (strictly speaking) only be used for orthopyroxene-bearing granites (Frost and Frost, 2008). However, the Matok pluton is a composite intrusion, made up of different magmatic rocks having a wide range of silica contents ($SiO_2 = 55–70$ wt.%; Laurent et al., 2014 and Fig. 5f–g of Rajesh et al., 2014), i.e. not only granites. This misuse is confusing, as Bohlender et al. (1992) clearly demonstrated that there are at least two different generations of orthopyroxene-bearing rocks in the SMZ, namely (1) metamorphic charnockites (sensu stricto), in which orthopyroxene is the dominant mafic phase and formed at the expense of biotite, presumably during dehydration melting, for example in the Baviaanskloof TTG gneisses; and (2) a suite of so-called "charnockitic rocks" (jotunites, enderbites and charno-enderbites), restricted to the Matok pluton and igneous in origin. These latter contain orthopyroxene in places, but always much less than clinopyroxene, and both phases are completely absent in the more felsic rocks (Bohlender, 1992; Laurent et al., 2014; Rapopo, 2010). Therefore, it is likely that several, if not most, of the samples plotted by Rajesh et al. (2014) in their discrimination diagrams are not charnockites at all, and probably not even orthopyroxene-bearing.

3.2. *Matok granitoids are not similar to arc magmas*

Apart from the terminology issue, the geochemical arguments used by Rajesh et al. (2014) to discriminate the geodynamic setting of the "Matok charnokites" are also problematic. Indeed, the interpretation of magmatic arc affinity solely relies on the use of a few major-element data. In fact, many previous studies clearly showed that "subduction signatures" are commonly equivocal, even when trace element systematics are considered (e.g. Bédard, 2006; Rollinson, 2009; Willbold et al., 2009). The "magnesian" signature used by Rajesh (2012) and Rajesh et al. (2014) as a smoking gun to reflect a subduction origin is therefore not unambiguous, and could also characterize magmas formed in very different geodynamic environments. To support the magmatic arc setting, Rajesh et al. (2014) argue that the "Matok charnockites" formed by dehydration melting of amphibolites, in a roughly similar process to that proposed for the formation of Archean TTGs (e.g. Moyen and Martin, 2012 and references therein). However, Archean TTGs, although mostly magnesian in character, can be generated in a wide range of geodynamic environments (Fig. 1), not necessarily requiring a convergent plate margin (Moyen, 2011; Moyen and Martin, 2012).

In addition, the magnesian signature of the Matok "charnockites" is not that obvious. It is clear in Fig. 5f of Rajesh et al. (2014) that their samples are richer in Fe than typical charnockites from the Northern Marginal Zone (NMZ), several of them straddling the boundary between magnesian and ferroan groups defined by Frost et al. (2001). Moreover, the diagram presented in Fig. 5h of Rajesh et al. (2014) also shows that the Matok granitoids follow a very distinctive trend with respect to the NMZ ones, characterized by lower Al_2O_3/CaO ratios. These two characteristics (high Fe and low Al contents) have been recently highlighted by Laurent et al. (2014), who conducted a detailed petrogenetic study of the Matok granitoids on the basis of major-, trace element and Sm–Nd isotope geochemistry as well as geochemical modelling. In contrast to the suggestion made by Rajesh et al.

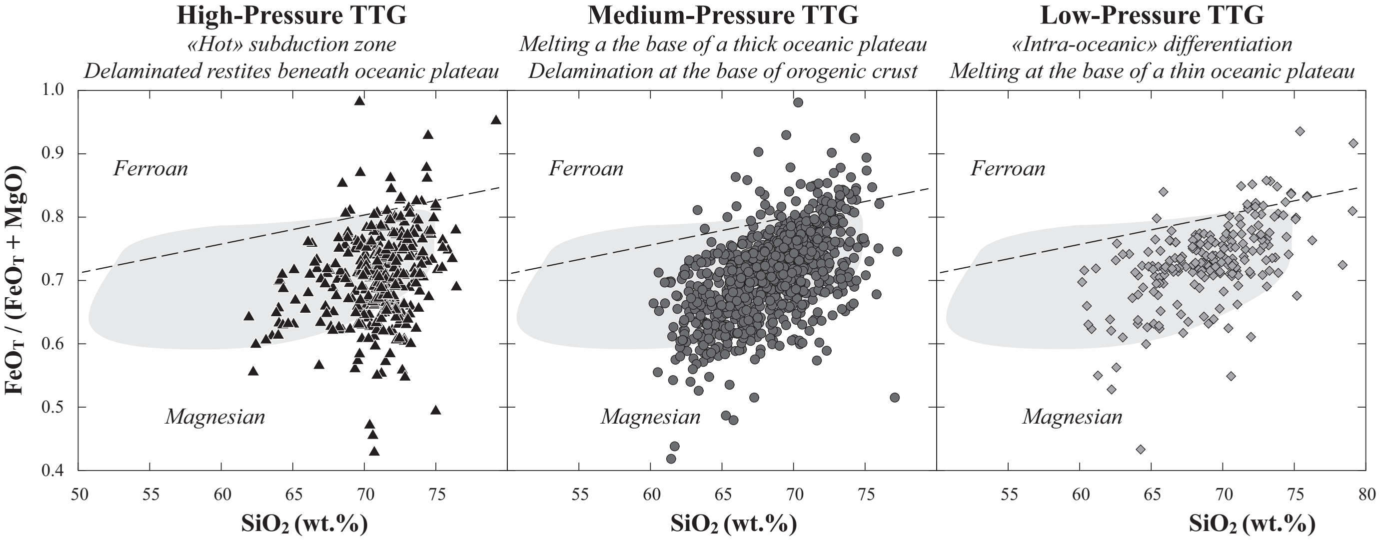

Fig. 1. $FeO_t/(FeO_t + MgO)$ vs. SiO_2 diagram of Frost et al. (2001) presenting the composition of representative samples of the three groups of sodic TTGs defined by Moyen (2011). As specified on the top of each plot, these different groups can form in contrasted geodynamic environments, implying convergent plate settings, but also intraplate or even divergent ones (e.g. intra-oceanic differentiation at a mid-ocean ridge – see Moyen, 2011 for details and discussion). More than 90% of TTGs are magnesian, regardless the petrogenetic group they belong to and thus the geodynamic setting in which they formed. The light grey field represents the field of "magnesian charnockites" defined by Rajesh (2012).

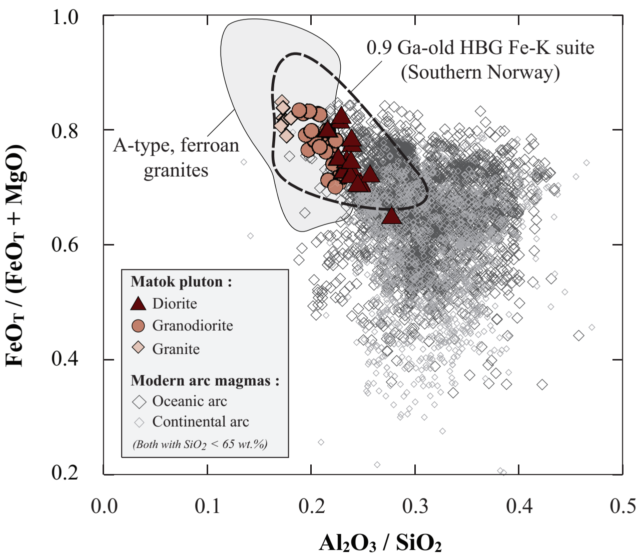

Fig. 2. FeO$_t$/(FeO$_t$ + MgO) vs. Al$_2$O$_3$/SiO$_2$ diagram where the whole-rock compositions of granitoids from the Matok pluton (data from Laurent et al., 2014) are reported, together with that of the Proterozoic "ferro-potassic" Hornblende–Biotite–Granitoid suite of southern Norway (data from Bogaerts et al., 2003 and Vander Auwera et al., 2007) as well as typical A-type, Fe-rich granites and modern subduction-related magmas from both continental and oceanic arcs (>5000 samples from the GEOROC database). In average and at similar SiO$_2$ contents (<65 wt.%), rocks from the Matok pluton clearly show higher FeO$_t$/(FeO$_t$ + MgO) and lower Al$_2$O$_3$/SiO$_2$ than arc magmas.

(2014), Laurent et al. (2014) concluded that the Matok granitoids are akin to "ferro-potassic" suites, very common in Proterozoic terranes (e.g. Duchesne et al., 2010; Ferré et al., 1998; Peucat et al., 2005; Vander Auwera et al., 2011) and intermediate in composition between (1) Al-, Mg-rich sanukitoids and (2) Al-poor, Fe-rich anorthosite–mangerite–charnockite–granite (AMCG) suites. This intermediate composition is well illustrated in the FeO$_t$/(FeO$_t$ + MgO) vs. Al$_2$O$_3$/SiO$_2$ diagram of Fig. 2. This diagram also shows unequivocally that the Matok granitoids are globally more ferroan and less aluminous than modern, classical arc magmas from both oceanic and continental convergent margins (Fig. 2).

4. Geodynamic model

The geodynamic model proposed by Rajesh et al. (2014) is that the SMZ was a microcontinent, which was accreted to the northern margin of the Kaapvaal Craton by ∼2.72 Ga at the latest, after a period of north-verging subduction. This interpretation, however, suffers two major problems:

(1) This model is in conflict with the fact that the Matok pluton (suggested to be subduction related) intruded at ∼2.68 Ga (U–Pb age data of Barton et al., 1992; Laurent et al., 2013; Zeh et al., 2009), whereas terrane collision happened at 2.71–2.72 Ga, as indicated by U–Pb ages of metamorphic zircons obtained from granulite-facies rocks of the SMZ (Rajesh et al., 2014; Taylor et al., 2014). Furthermore, field observations and additional age data from the Hout River Shear Zone indicate that uplift and southward thrusting of the SMZ granulites over the Pietersburg block started prior to the intrusion of the Matok pluton, i.e. around 2.70 Ga (Kreissig et al., 2001; Laurent et al., 2013). In summary, the Matok pluton is clearly 10–30 Ma *younger* than the inferred age of collision, such that it cannot be related to subduction and rather represents a typical post-collisional intrusion as recently proposed by Laurent et al. (2014).

(2) Accretion of the SMZ as an individual microterrane to the northern edge of the Kaapvaal Craton is also at odds with previous studies based on Hf–Sr–Nd–Pb isotopes (e.g. Barton et al., 1992, 2006; Kreissig et al., 2000; Zeh and Gerdes, 2012; Zeh et al., 2009). These data unequivocally show that the SMZ and the adjacent rocks of the Pietersburg block actually belong to the same crustal domain. Specifically, the SMZ results from internal reworking of the Pietersburg block crust owing to continental collision at 2.72 Ga (Laurent et al., 2014; Zeh et al., 2009, 2013), with a northward-located terrane that could be represented by the Central Zone of the Limpopo belt. Internal reworking is for instance supported by Pb isotopic data indicating similarly low μ-values ($^{238}U/^{204}Pb$) of ≤10 for all rocks of the Northern Kaapvaal Craton (including the SMZ), which are very different to the high-μ rocks exposed in the Central Zone of the Limpopo belt and the Zimbabwe Craton, both having values ≥11.5 (Barton et al., 2006). Combined age and Hf isotope data also support that all granitoids of the northern Kaapvaal Craton, including the SMZ, formed by reworking of a single crustal component, which derived from a depleted mantle source between 3.3 and 3.0 Ga (e.g. Zeh and Gerdes, 2012; Zeh et al., 2009, 2013). Ortho- and paragneisses from both the SMZ and the Pietersburg block also show undistinguishable Nd model ages (2.9–3.2 Ga), as well as similar major- and trace-element systematics (Kreissig et al., 2000). It is worthwhile noting, in addition, that detrital zircon grains in the metasedimentary samples investigated by Rajesh et al. (2014) yield ages of ∼3.40, ∼3.33, 3.00–2.95 and 2.85–2.75 Ga. These ages actually correspond to the main magmatic episodes in the Pietersburg block (Laurent et al., 2013; Zeh et al., 2009). The youngest ages (2.85–2.75 Ga) are typical for granite emplacement (Turfloop batholith and associated intrusions; Henderson et al., 2000; Kröner et al., 2000; Laurent et al., 2013; Zeh et al., 2009), whereas all ages ≥2.95 Ga are that of the Pietersburg TTGs (Kröner et al., 2000; Laurent et al., 2013; Zeh et al., 2009) and are also recorded by detrital zircons from low- to medium grade metasedimentary rocks of the Murchison and Pietersburg greenstone belts (Zeh and Gerdes, 2012; Zeh et al., 2013). All lines of evidence therefore support that rocks of the SMZ and the Pietersburg block belong to the same crustal domain, but underwent contrasted *P*–*T* evolution during the ∼2.72 Ga collision event.

5. Conclusion

The recent contribution by Rajesh et al. (2014) proposes a new geodynamic model for the evolution of the SMZ of the Limpopo belt and the Kaapvaal Craton in the Neoarchean, implying that both terranes were amalgamated at ∼2.72 Ga as a result of north-verging subduction and subsequent collision. The main supporting evidence for such a model is the spatial and temporal association of UHT granulites in one hand, and subduction-related magmatic rocks referred to as "magnesian charnockites" on the other hand. However, their arguments to support both (1) UHT metamorphic conditions in the SMZ; and (2) a subduction-related origin for the Matok granitoids are unreasonable and/or equivocal. Moreover, this new geodynamic model does not fit at all with the results of a great deal of previous studies in the area, and must therefore be regarded with some criticism.

Nevertheless, we believe that the data presented by Rajesh et al. (2014), especially their new U–Pb ages on detrital zircons from the SMZ, provide valuable information regarding (1) the timing of granulite-facies metamorphism and continental collision in this terrane; and (2) the provenance of the studied metasediments. These new data must be reconsidered in the scope of ongoing work about the evolution of the Pietersburg block and the SMZ during the Neoarchean.

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