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Comment on "Evolution of high-pressure mafic granulites and pelitic gneisses from NE Madagascar: Tectonic implications". Tectonophysics, 662, 219–242 (2015) by Ishwar-Kumar et al.

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ABSTRACT

Determining the possible tectonic regimes active during the Neoproterozoic is crucial for the knowledge of the evolution of the super-continent Gondwana. In Madagascar, that occupies a key position in Gondwana, there is an on-going debate regarding the location of possible suture zones and the implications in terms of paleo-geography. Recognizing high-pressure to ultra-high pressure conditions in mafic rocks is commonly viewed as a strong argument for paleo-subduction zones. Ishwar-Kumar et al. (2015) report unusual high pressure conditions (24 kbar) in Neoproterozoic to Cambrian rocks from North-Central Madagascar (Andriamena Complex). They propose a geodynamic model in which exhumation of the high pressure terranes from up to ~80 km to ~40 km occurred via vertical extrusion during the collision of various crustal blocks after subduction and closure of an oceanic domain during the formation of Gondwana in the late Neoproterozoic to Cambrian. We question this model and in particular the (ultra-)high pressure conditions reported, because their estimation is based on a misinterpretation of the petrography and inaccurate thermodynamic modeling for the crucial metabasite sample. The authors suggest that garnet-quartz coronas around orthopyroxene and ilmenite coexist with clinopyroxene. The postulated garnet-clinopyroxene-quartz assemblage is interpreted to document an eclogite facies overprint. However, the presence of abundant plagioclase in the sample and the lack of high jadeite content in clinopyroxene clearly refute the postulated eclogite facies conditions. According to the presented photographs clinopyroxene is part of the rock matrix. We therefore suggest that the sample represents a common two-pyroxene granulite, formed at mid- to low-pressure granulite facies conditions of >700 °C and <6 kbar, consistent with PT data of former studies for the Andriamena Complex. Garnet-quartz-bearing coronas produced at the expense of the granulite-facies assemblage could have been produced during isobaric cooling. Although a subduction zone may have been active during this period of time in Madagascar, this interpretation is not justified by the data presented by Ishwar-Kumar et al. (2015).

1. Introduction

Ishwar-Kumar et al. (2015) present in their paper entitled "Evolution of high-pressure mafic granulites and pelitic gneisses from NE Madagascar: Tectonic implications", a new geodynamic model for the north-central Madagascar that involves subduction of mafic rocks down to a depth of c. 80 km (c. 24 kbar at ca. 780 °C) during the Neoproterozoic to Cambrian. Such metamorphic conditions would be the highest pressure conditions ever reported in Neoproterozoic to Cambrian rocks from Madagascar, and probably in the whole Gondwana, and contrast significantly with previous pressure estimates of 5 to 7 kbar (Nicollet, 1988; Goncalves et al., 2003, 2004) for very similar mafic samples of the same region.

Ishwar-Kumar et al. (2015) combine the estimated P-T evolution with geochronological data for apparently associated metasediments and metagranitoids, field observations and other published data to propose, in their words, a "speculative model" in which exhumation of the high pressure terranes from up to ~80 km to ~40 km occurred via vertical extrusion during the collision of the Antongil block with the Antananarive block after subduction and closure of an oceanic domain during the formation of Gondwana in the late Neoproterozoic to Cambrian. This model relies on the existence of a "paleo-subduction zone/

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suture" between the Antananarive and Antongil block at ca. 800 Ma: the so-called "Betsimisaraka suture zone". The authors acknowledge that the existence, location and age of the suture is still a major controversy (Tucker et al., 2011) and summarize in the discussion the evidences that support the existence of such Neo/Mesoproterozoic suture.

Recognizing a new eclogite facies event in Gondwana, and more generally in any orogenic belt, deserves a detailed determination of P-T conditions based on a precise identification of the mineral assemblages and reaction textures as well as detailed mineral chemical data, because the proposed geodynamic model is derived to a large extent from these P-T data. However, the PT evolution of the studied mafic sample presented by Ishwar-Kumar et al. (2015), which culminates at eclogite facies conditions, is based on a misinterpretation of the critical mineral reaction texture and on inappropriate mineral chemical data and is therefore incorrect. In addition, the assumed Neoproterozoic age of the postulated HP event, which is extrapolated through a correlation with age data for an adjacent tectonic unit remains speculative.

2. Petrology of mafic granulites and pseudosection modeling – no evidence for HP metamorphism

The postulated eclogite facies conditions and the consequential geodynamic conclusions of the paper are based on the petrological analysis and thermobarometric estimations performed on (only) one "mafic" granulite (MAD-03-145) from the Andriamena unit. However, both petrological and thermodynamic modeling suffer from weak petrographic observations and resultant misinterpretation of the reaction textures, as further elaborated below.

Ishwar-Kumar et al. (2015) postulate a primary metamorphic orthopyroxene-plagioclase-Fe-Ti- oxide assemblage which is overprinted by a garnet-clinopyroxene-quartz assemblage. However, the thin section photos (Fig. 4a–b in Ishwar-Kumar et al., 2015) show that clinopyroxene is an early porphyroblastic phase surrounded by a later garnet-bearing corona. Consequently, clinopyroxene is rather part of the high-temperature assemblage consisting of cpx-opx-pl-Fe-Ti oxides, while garnet belongs to a later assemblage. The cpx-opx-pl-Fe-Ti oxides assemblage, as well as the reported composition of clinopyroxene porphyroblasts (see later) are characteristic for mid-pressure granulite facies metamorphism (e.g. Green and Ringwood, 1967).

According to the authors, garnet, which is intergrown with quartz, forms corona textures around orthopyroxene and the Fe-Ti oxides separating them from plagioclase. This is perfectly consistent with photos of the corona textures (Fig. 4a–c in Ishwar-Kumar et al., 2015). However, the photos refute the author's interpretation of clinopyroxene as an overprinting phase, which is the base for their postulated detection of eclogite facies conditions. Indeed, clinopyroxene is not present in the corona textures (as also stated by the authors) and consequently not in equilibrium with coronitic garnet and quartz. Furthermore, if two distinct generations of clinopyroxene were present (an early porphyroblastic clinopyroxene and a later coronitic clinopyroxene), we would expect two distinct clinopyroxene compositions presented in Table 2 in Ishwar-Kumar et al. (2015).

Ishwar-Kumar et al. (2015) have calculated a PT pseudosection for the crucial mafic granulite sample MAD-03-145 in the system NCKFMASHT in order to reconstruct its PT evolution (Figs. 5 and 6 in Ishwar-Kumar et al., 2015). Irrespective of the misinterpretation of reaction textures, several of the author's constraints from the pseudosection are in contrast to the described phase relationships. Although garnet, clinopyroxene, quartz and biotite (biotite is not even mentioned in the petrography of the sample) are not part of the presented primary metamorphic assemblage (i.e. opx-pl-Fe-Ti oxides), the authors postulate initial PT conditions of ca. 10 kbar and 780 °C, which are located in the stability field of the assemblage gt-cpx-opx-pl-q-H_2O-bio. According to the pseudosection the sample should contain 32 mol% garnet at ca. 10 kbar and 780 °C. The authors interpret the assumed (but misinterpreted) formation of gt-cpx-q to result from isothermal burial from c. 10 kbar up to 24 kbar at 780 °C. Although rutile (and clinopyroxene) is not present in the corona (rutile is not even mentioned), they suggest progress of the reaction (1) opx + pl ± ilm = gt + cpx + q ± rt. for the formation of the corona. Reaction (1) has a positive slope in the P-T space and therefore can either be produced by an increase in pressure, like suggested by Ishwar-Kumar et al. (2015), or by a near-isobaric cooling. In contradiction to the statement that such garnet-bearing coronas are "uncommon" in mafic granulites, they have been described from early experimental studies (Green and Ringwood, 1967) as well as from several natural occurrences (e.g. Schenk, 1984; Mahan et al., 2008, Williams and Kopf, 2000, Williams et al., 2014, Kazimoto et al., 2015 and references in Pattison, 2003). Even in the Andriamena unit (the same study area as Ishwar-Kumar et al., 2015), Goncalves et al. (2003) have already described garnet-, clinopyroxene- and quartz-bearing coronas produced by reaction (1) in the CFMASH system (without Ti phases) but interpreted to reflect post-peak near-isobaric cooling, as also suggested for the other natural examples cited above.

Eclogite facies HP-conditions of 24 kbar and 780 °C are estimated by the authors by intersecting of mineral composition isopleths (XMg of opx, cpx, gt). However, the modeled XMg of opx (0.285) and cpx (0.36) used by Ishwar-Kumar et al. (2015) to constrain the HP conditions are inconsistent with measured values presented in Table 2 (XMg opx: 0.37–0.38; XMg cpx: 0.54–0.57). In addition, at eclogite facies conditions of 24 kbar plagioclase is not stable anymore. This is consistent with the computed phase diagram (Figs. 5a & 6d in Ishwar-Kumar et al., 2015) but inconsistent with the petrographical observation that shows a large amount of porphyroblastic plagioclase in the sample (Fig. 4a–c in Ishwar-Kumar et al., 2015). Furthermore, at eclogite facies conditions clinopyroxene should have a significant omphacite component with a jadeite content >26 mol% (see later and our Fig. 1d). Unfortunately, the jadeite content of clinopyroxene has not been calculated in the pseudosection presented by Ishwar-Kumar et al. (2015). Despite this, the analyses presented Table 2 show very low jadeite contents of <3 mol% (note that the values of jadeite content of analysis 96, 98 and 99 are equal to zero, although there is c. 0.04 mol of Na in the structural formula), clearly indicating that clinopyroxene of the sample did not form at eclogite facies conditions, but at mid- to low-pressure conditions of <6 kbar (see later and our Fig. 1d).

The authors suggest that the retrograde evolution of the sample is characterized by the formation of amphibole, which they ascribe to the consumption of garnet and clinopyroxene. The assumed phase relationships are used to constrain significant decompression and cooling, which is attributed to the exhumation of the rocks from 80 km to 40 km. Again, these assumptions are inconsistent with the textural relationships presented on the photos (Fig. 4a–c in Ishwar-Kumar et al., 2015). While amphibole, in fact, forms rims and coronas around clinopyroxene, no resorption of garnet is present. By contrary, the photos document the broadly coeval formation of amphibole and garnet, together with quartz. Consequently, the postulated post-HP decompression-cooling segment is not supported by the reaction textures. The presence of coronitic amphibole suggests that the formation of the gt-q corona was associated with the growth of amphibole through a simplified hydration reaction such as (2) opx + cpx + pl + H2O = gt + amph + q, which documents the transition from granulite to amphibolite facies conditions through cooling.

All these discrepancies between the observed and calculated phase relations and compositions produced at eclogite facies conditions led us to re-compute the phase diagram and contours presented in Figs. 5 and 6 in Ishwar-Kumar et al., 2015, in order to reconstruct the correct PT evolution of the rock (Fig. 1). The phase diagram has been computed using Perple_X version 6.7.2 (Connolly, 2005) using the updated version of the internally-consistent thermodynamic database of Holland and Powell (1998). The mineral activity models used for pseudosection modeling are taken from Table 2 of Ishwar-Kumar et al. (2015). We

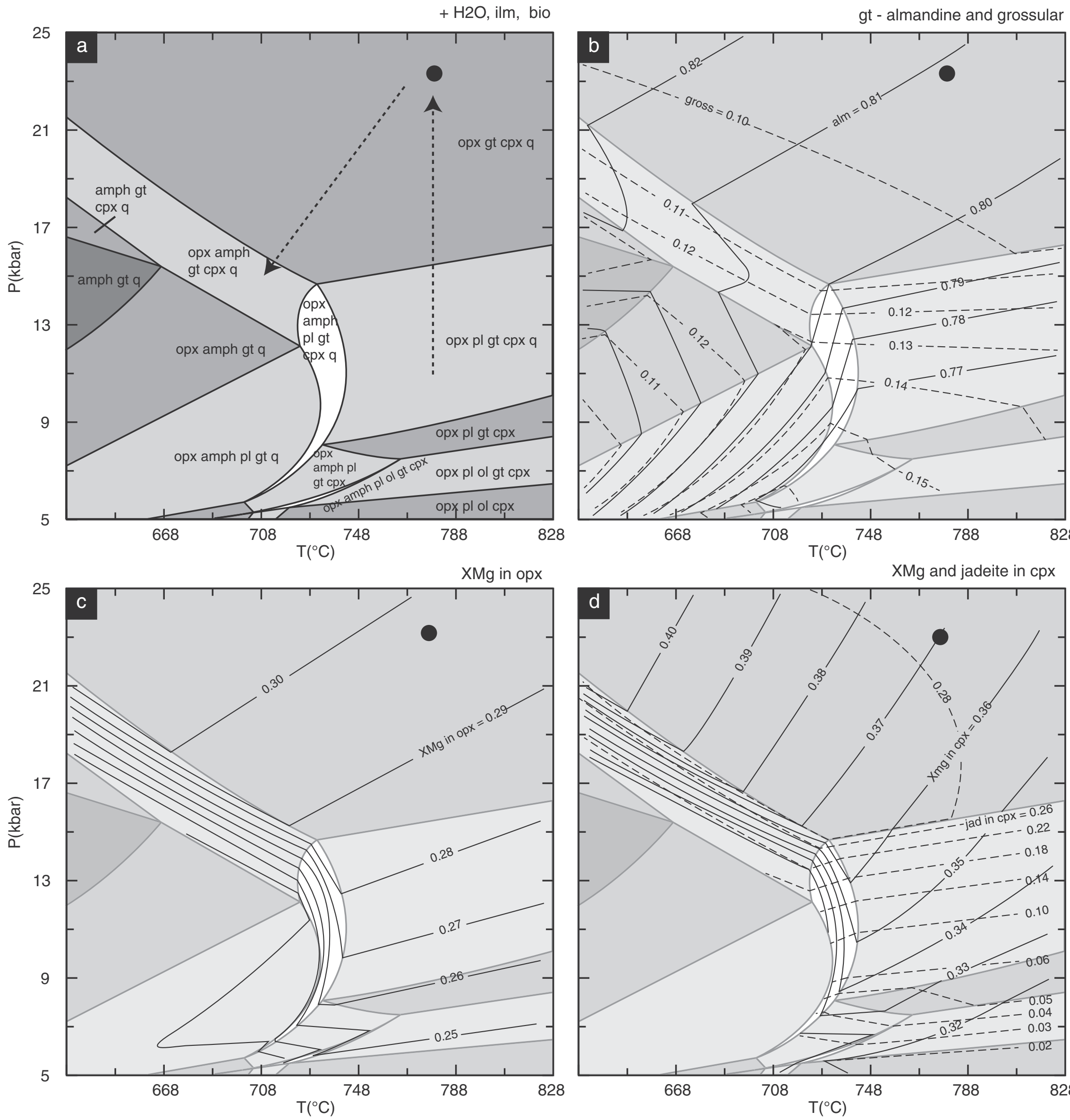

Fig. 1. (a) Pressure-temperature isochemical phase diagram section computed with the bulk composition presented in Fig. 5 of Ishwar-Kumar et al. (2015). The phase diagram is contoured for (b) almandine and grossular content in garnet, (c) XMg in orthopyroxene and (d) XMg and jadeite content in clinopyroxene. The P-T path of Ishwar-Kumar et al. (2015) is shown as a dotted arrow.

have additionally included olivine, using the activity model of Holland and Powell (1998), and have excluded the melt model of White et al. (2001) as it is a haplo-granitic melt model which is irrelevant for a (ultra)mafic bulk composition. The available amphibole activity models do not take into account Ti and K, which are present in significant amounts in the studied sample. Modeling phase relations in a P-T isochemical phase diagram (pseudosection) requires an accurate determination of the bulk composition that reflects the equilibrium composition. We have used the bulk rock composition of the sample, which is given in the figure caption of the pseudosection Fig. 5 in Ishwar-Kumar et al., 2015. The bulk composition used is referred by Ishwar-Kumar et al. (2015) as a “model composition estimated from mineral modes and the compositions of the mineral assemblages”. Unfortunately, details of the calculation method are not provided and it is not explained why they did not use a XRF analysis of the rock, which would be the typical and simple way to determine the bulk rock composition. The bulk composition “modeled” by Ishwar-Kumar et al. (2015) has a very low SiO_2 and alkaline ($Na_2O + K_2O$) content of 40.4 and 1.5 wt% respectively but high FeO + MgO (34.5 wt%) and high TiO_2 contents (5.7 wt%), and therefore represents an ultramafic instead of a mafic composition, as postulated by Ishwar-Kumar et al. (2015). Such Fe-rich rocks usually contain significant Fe^{3+}, which has not been taken into account by Ishwar-Kumar et al. (2015) in their modeling.

Our re-computed pseudosection (Fig. 1a) is similar to the one proposed by Ishwar-Kumar et al. (2015) in their Figs. 4 and 5, except that olivine occurs at low pressure and high temperatures. The phase diagram has been contoured for the almandine and additionally the grossular content in garnet (Fig. 1b), the XMg of orthopyroxene (Fig. 1c) and for the XMg and the jadeite component of clinopyroxene (Fig. 1d). To evaluate the HP conditions postulated by Ishwar-Kumar et al. (2015) the modeled mineral compositions at 24 kbar and 780 °C are compared in Table 1 with analyzed compositions provided by Ishwar-Kumar et al. (2015, Table 2). It appears that none of the predicted compositions fits the analyzed compositions (Table 1). Note also that modeled clinopyroxene contains ca. 28 mol% of jadeite at 24 kbar and 780 °C (Fig. 1d and Table 1). To conclude, none of the measured compositions reflect high pressure conditions of 24 kbar. Instead, the observed porphyroblastic assemblage opx-cpx-pl-ilm is stable at mid- to low

Table 1
Comparison of analyzed mineral compositions in sample MAD-03-145 (from Table 2 in Ishwar-Kumar et al., 2015) and modeled mineral compositions in equilibrium at 24 kbar and 780 °C, using the isochemical P-T phase diagram section shown in Fig. 1.

Mineral name	Component	Measured compositions by Ishwar-Kumar et al. (2015)	Our modeled composition and modes (vol%) @ 780 °C and 24 kbar	
Garnet	Almandine	0.68–0.70	0.81	33.5
	Pyrope	0.08–0.09	0.10	
	Grossular	0.20–0.21	0.09	
	XMg	0.11	0.11	
Orthopyroxene	XMg	0.37–0.38	0.30	15.2
Clinopyroxene	jd	0–0.03	0.28	29.0
	aug	0.76–0.85	0.70	
	XMg	0.54–0.57	0.36	

pressures (<6 kbar) and high temperatures (>700 °C) together with olivine (Figs. 1 and 2). The apparent presence of biotite is probably related to some ingress of K during post-peak hydration. K is incorporated in amphibole, as evident from the analyses in Table 2, but not included in the modeled amphibole composition, due to the lack of suitable solid solution models. The formation of garnet, amphibole and quartz is consistent with near-isobaric cooling into the gt-amph-opx-pl-q-ilm field to $T < 700$ °C, hence into the amphibolite facies. Fig. 2 shows that the formation of the garnet and amphibolite-bearing assemblage is consistent with the low variance reaction (2) opx + cpx + pl + H2O = gt + amph + q, that is located at 700–720 °C at $P > 6$ kbar. However, even in the stability of the two-pyroxene assemblage the analyzed mineral compositions are, with exception of the jadeite content, inconsistent with the modeled ones. This major discrepancy could be the result of an inappropriate "modeled" bulk composition and/or the strong effect of Fe^{3+} that might have a significant impact especially on the mineral XMg values but has been neglected.

Goncalves et al. (2003) provide a simplified map of the central part of the Andriamena unit that compiles P-T conditions derived from the same mafic granulites (see Fig. 9 in Goncalves et al. (2003)). The studied

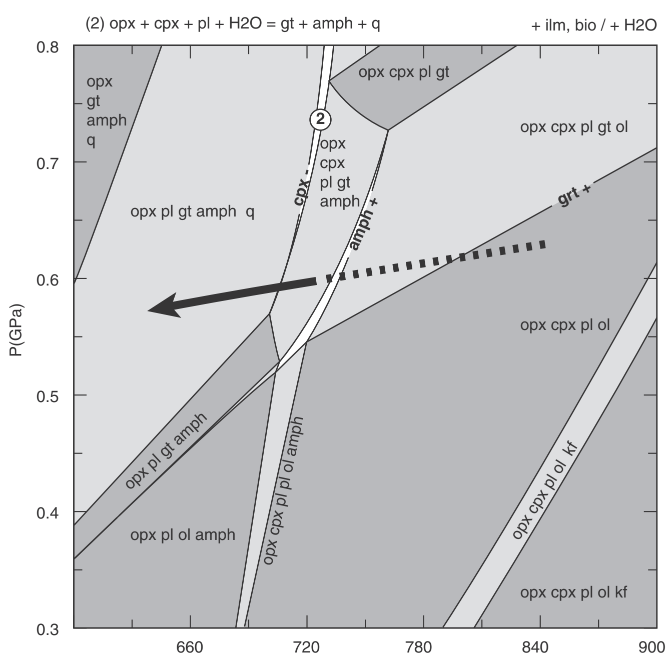

Fig. 2. Pressure-temperature isochemical phase diagram section computed with the same bulk composition as in Fig. 1 but for lower pressure conditions. Our alternative interpretation, consisting in an isobaric cooling path at c. 5–6 kbar, is shown as a black arrow. The main reaction observed in the mafic granulites opx + cpx + pl + H2O = gt + amph + q (2).

mafic granulites are characterized by a peak assemblage orthopyroxene-clinopyroxene-plagioclase-ilmenite-quartz, with garnet-bearing coronas produced by reactions like: opx + pl = cpx + gt + q; cpx + pl = gt + q; amph + pl = gt + q (Fig. 3). Goncalves et al. (2003) propose an alternative model where the coronitic textures were formed at 5–6 kbar during isobaric cooling from granulite to amphibolite facies conditions. The occurrence of amphibole within the corona (Fig. 3) is also consistent with isobaric cooling down to amphibolite facies conditions. P-T conditions have been obtained via multi-equilibrium thermobarometric calculations (TWEEQU software, version 2.02; Berman, 1991) on these coronas where the assumption of local chemical equilibrium is satisfied (Nicollet, 1988; St-Onge and Ijewliw, 1996). Mineral compositions and necessary data to evaluate the robustness of the thermobarometry are available from Goncalves (2002). Average P–T estimates of 5 to 6 kbar and 640 to 700 °C are constrained for the formation of the garnet-bearing coronas (Goncalves et al., 2003). The data is consistent with the PT data as constrained for sample MAD-03-145 by our re-interpretation of the phase relationships and constraints of the re-calculated pseudosection documenting near-isobaric cooling from >700 °C at 5–6 kbar. Based on petrological and geochronological studies on garnet-bearing migmatites and retrogressed Al-Mg granulites Goncalves et al. (2004) concluded that near-isobaric cooling at 6–7 kbar in the Andriamena Unit occurred between 790 and 730 Ma.

To conclude, we suggest that the garnet-bearing corona textures are misinterpreted and that high pressure metamorphism culminating at eclogite facies conditions of 24 kbar and 780 °C is incorrect. The crucial studied sample is in fact a typical two-pyroxene granulite and the formation of the garnet-bearing coronas is related to near-isobaric cooling into the amphibolite facies. Therefore, all the speculative tectonic interpretations regarding the mechanisms of burial to a depth > 80 km and subsequent exhumation are unjustified. Our re-interpretation of the PT evolution of the critical sample studied by Ishwar-Kumar et al. (2015) is in agreement with documentation of regional-scaled mid- to low-pressure metamorphism in the Andriamena and Aloatra unit (Goncalves et al., 2003, 2004). In contrast, Ishwar-Kumar et al. (2015) do not discuss the discrepancy of the apparent HP event constrained from one sample and the regional mid- to low-pressure metamorphism.

3. Geochronology of the "high pressure" event – no evidence for a Neoproterozoic age

Ishwar-Kumar et al. (2015) have conducted LA-ICPMS U–Pb zircon dating for four "pelitic" samples from the Betsimisaraka "suture" and one granitic gneiss of the Aloatra complex as well as mica K-Ar age dating for two Betsimisaraka "suture" samples, in order "to understand the timing of metamorphism" and "of arc magmatism", respectively. An explanation for the sample selection is not provided. Although the reader would expect that the authors aim to detect the timing of the postulated HP event, samples of the Andriamena unit are not dated and a link between the Andriamena unit and the two tectonic units, that are

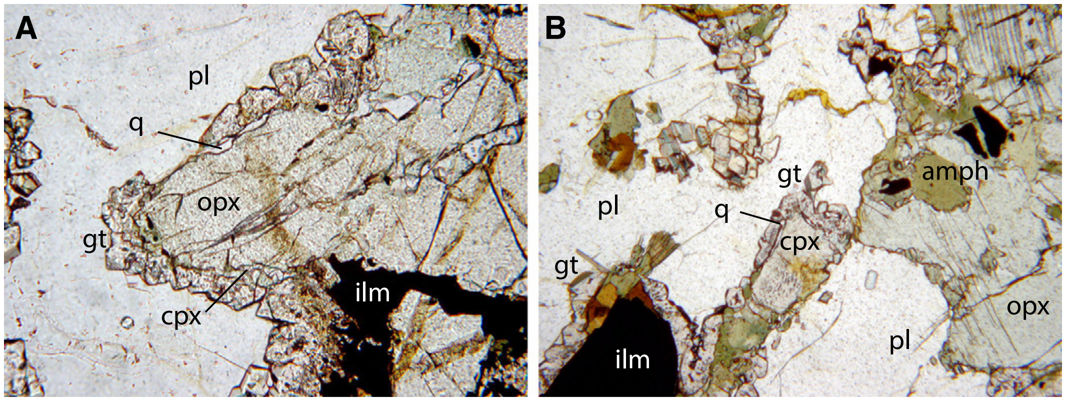

Fig. 3. Photomicrograph of mafic granulites from the Andriamena unit (C74 and C101), showing the garnet-amphibole-quartz ± clinopyroxene corona formed after orthopyroxene and plagioclase (Goncalves, 2002).

investigated by the geochronological study, is not explained. Only in the Introduction it is stated that the dating of the Betsimisaraka "suture" samples aims on the documentation of the timing of the suturing. However, a serious correlation of metamorphism in the Andriamena Unit and in the Betsimisaraka "suture" would additionally require 1) age data for metamorphism in the Andriamena Unit and 2) a petrological study of the metapelites of the Betsimisaraka "suture". Among the dated samples the mineral assemblage of a biotite-kyanite-sillimanite schist (R194) would be perfectly suited for a thermobarometric study. Without such studies it remains uncertain whether or not the ultramafic granulite of the Andriamena Unit and the pelitic rocks of the Betsimisaraka "suture" record the same metamorphic event(s).

Three different age groups have been obtained: 2.54–2.63 Ga, ca. 820 Ma and 694–490 Ma for the zircon of the pelitic and granitic gneisses and younger ages for the micas of the pelitic gneisses 486 ± 9 and 459 ± 9 Ma. These ages are well known in Madagascar (e.g. Tucker et al., 2011) but in this contribution they are never discussed and/or interpreted in any geological context. Only an upper-intercept age (818 ± 120 Ma) for a granitic gneiss of Aloatra complex is apparently interpreted as an intrusion age of the granite precursor in the discussion. Furthermore, no attempt is made to link the new age data for the Betsimisaraka "suture" rocks with the postulated high-pressure event postulated for the ultramafic sample from the Andriamena Unit. Despite this, Ishwar-Kumar et al. (2015) conclude that "during the Neoproterozoic collision and peak metamorphism, the rocks underwent subduction up to ~80 km depth and were exhumed to ~40 km depth from surface". Besides the inconsistency of this sentence and the fact that the youngest ages are in fact Cambrian, there is no justification to link the postulated high-pressure event and subduction in the Andriamena Unit with a poorly-constrained Neoproterozoic - Cambrian event in the Betsimisaraka "suture"; the sample locations in the two units are ca. 200 km distant from each other (Fig. 2 in Ishwar-Kumar et al., 2015). As a discussion of the age data for the metapelites of the Betsimisaraka "suture" is completely lacking, even the timing of metamorphism in this unit remains uncertain. The lower-intercept zircon ages of the Betsimisaraka metapelites, which record some kind of a weak overprint (no zircon re-growth), show a large age range with large errors (694 ± 120 Ma, 589 ± 60 Ma, 497 ± 150 Ma). Therefore, a distinct timing of metamorphism in the Betsimisaraka "suture" is impossible on the basis of the data and even a late Neoarchean - early Paleoproterzoic age could be possible with a weak overprint in the Neoproterozoic - Cambrian.

4. Emplacement of the Andriamena unit

Ishwar-Kumar et al. (2015) propose that the Andriamena unit was exhumed and thrusted over the Antananarivo block with a top-to-the-west kinematic. There is no structural data to justify this interpretation. Furthermore, this interpretation is inconsistent with the micro-structural observations carried out by Goncalves et al. (2003) on the basal mylonite zone beneath the Andriamena unit, which shows systematically top-to-the-east kinematic indicators. Ishwar-Kumar et al. (2015) quote Goncalves et al. (2003): "The late folding (D2 event) of this contact impede a direct kinematic interpretation of these shear sense indicators". We acknowledge that this sentence could be misleading. The late D2 folding could have changed the original dipping of the mylonitic contact and therefore it is impossible to determine if the contact was a thrust or a detachment. However the shear sense indicators will always show a top-to-the-east kinematic.

5. Conclusions

Based on petrological investigations of a ultramafic granulite of Andriamena unit Ishwar-Kumar et al. (2015) infer a counter-clockwise PT path that culminates at eclogite facies conditions of 24 kbar 780 °C. The postulated HP event is then used to constrain a Neoproterozoic subduction zone scenario in the adjacent Betsimisaraka "suture".

Our re-examination of the phase relationships in the critical (ultra)-mafic sample used to constrain eclogite facies conditions, documents that the counter-clockwise PT evolution and the inferred eclogite facies peak-metamorphism of 24 kbar and 780 °C, and hence the inferred Neoproterozoic subduction zone scenario presented by Ishwar-Kumar et al. (2015) are not justified. Especially the presence of abundant plagioclase and the lack of high jadeite content in clinopyroxene clearly refute the postulated eclogite facies conditions. In fact, the sample represents a common two-pyroxene granulite, which formed at mid- to low-pressure granulite facies conditions of > 700 °C and < 6 kbar, consistent with previous petrological studies in the area. Garnet coronas around the peak-phases document near-isobaric cooling into the amphibolite facies to < 700 °C.

Available age data for associated rocks with a very similar near-isobaric cooling evolution suggest a mid-Neoproterozoic age of 790–730 Ma for metamorphism in the ultramafic rock. Age and the re-interpreted PT path are inconsistent with a postulated subduction zone scenario in the adjacent Betsimisaraka "suture".

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