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PII: S1464-343X(14)00031-4
DOI: http://dx.doi.org/10.1016/j.jafrearsci.2014.02.005
Reference: AES 1972

To appear in: *African Earth Sciences*

Please cite this article as: Andre-Mayer, A.S., Ramiandrisoa, N., Vanderhaeghe, O., Reisberg, L., Rabeandrasana, S., Zimmermann, C., Re-Os geochronological constraints on the Dabolava mesothermal gold occurence, Madagascar: implications for the Ikalamavony sub-domain deposition age, *African Earth Sciences* (2014), doi: http://dx.doi.org/10.1016/j.jafrearsci.2014.02.005

Journal of African Earth Sciences

Precambrian Geology of Madagascar

Re-Os geochronological constraints on the Dabolava mesothermal gold occurence, Madagascar: implications for the Ikalamavony sub-domain deposition age

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Abstract

New Re-Os ages for early concordant veins and later discordant veins in the Ikalamovony sub-domain of west-central Madagascar require respectively a Paleoproterozoic age for metasedimentary rocks and a Pan-African age for the orogenic type occurrences. Indeed, this paper focuses on Re-Os geochronology of Dabolava gold occurrences, located in the Ikalamavony sub-domain, western central part of Madagascar. Two types of gold veins have been identified in this region; (i) type 1, centimetre-thick quartz veinlets, with diffuse contacts and concordant to the main regional foliation of the host amphibolites, part of the upper-Group of the Ikalamavony sub-domain; (ii) type 2, 30 to 50 centimetre-thick quartz veins variously transposed in shear zones affecting the Dabolava granodioritic orthogneisses, part of the Dabolava magmatic suite. These two types of veins with Au-Py assemblages have been sampled for Re-Os geochronology. The type 1 pyrite and electrum assemblage yields a Palaeoproterozoic age (1961±79Ma) whereas the pyrite and electrum assemblage of discordant type 2 veins yields a Pan-African age (533±23 Ma). These ages record two main gold mineralization events that affected this crustal segment. Assuming that the Re-Os systematics were not perturbed by more recent events, the 1961±79Ma Ma age obtained in this study on type 1 gold vein concordant in amphibolites favours a Palaeoproterozoic deposition age for the whole Ikalamavony sub-domain, both lower- and upper Groups. This age contrasts with the previously proposed Mesoproterozoic age for the deposition of the upper Group of the Ikalamavony sub-domain but is consistent with the Paleoproterozoic age (~1800 Ma) deduced from detrital zircon ages in the Ikalamavony quartzites located in the Ikalamavony lower Group. The Pan-African age obtained on the type 2 gold deposits is much younger than the emplacement age of the host granodiorite and precludes a porphyry-type model for this gold mineralization and rather favours an orogenic type with a deposition during the Pan-African orogeny.

Keywords: Madagascar, Dabolava, orogenic gold, Re-Os geochronology

1. Introduction

Reassessment of Madagascar's geology during the last two decades has provided new comprehensive geologic and geodynamic models (e.g. Handke et al, 1999; Tucker et al., 1999; Kröner et al., 2000; Martelat et al. 2000; Collins et al., 2000; Collins et al., 2003; De Wit, 2003, Collins and Windley, 2002), notably as a result of the World Bank PGRM project (2003-2012) (De Waele et al. 2011, Tucker et al. 2011, Tucker et al., 2012 and the references cited therein). This new geological framework has also reinvigorated metallogenic studies (e.g. Augé and Legendre, 1992; Andriamampihantona, 1992; Windley et al., 1994, Rakotondrazafy et al., 1996; Kabete et al. 2006; Giuliani et al., 2007; Andrianjakavah et al., 2007) inaugurated by the historical treatise of Besairie (1966), and Peters et al. (2003, 2012) have presented a renewed interpretation of the data compiled in Besairie's treatise.

Since 1883, gold in Madagascar has been essentially the object of artisanal exploration and exploitation and Besairie (1966) described these gold occurrences as "Au-bearing quartz veins with relative amount of sulphides". Recent increase in the gold value has renewed interest in gold exploration elsewhere in the world and also in Madagascar. Studies by Rambeloson (1999), Nawaratne and Dissanayake (2001), Premoli (1996) and Andrianjakavah et al. (2007) have focused on gold occurrences located in the central and northern part of the island (Figure 1A). Except for Andavakoera in the northern area, Madagascar gold occurrences are considered to be mesothermal deposits in quartz-sulfide veins hosted in metamorphic rocks of various facies and lithologies (amphibolites, magnetite bearing quartzite (BIF), and gneisses). Andrianjakavah et al. (2007) have shown the "orogenic gold" character of the Maevatanana occurrence. However, structural controls and ages of these mesothermal-orogenic occurrences are unknown or debated. The associated shear zones and metamorphism are considered to be Pan-African (about 550 Ma) and hydrothermal processes linked to gold deposition are supposed to be related to this East-African Orogeny (Peters et al. 2003; Peters et al. 2012).

FIGURE 1

The majority of Madagascar's gold occurrences are hosted by greenstone belts with a Neo-Archaean protolith variously reworked during the Pan-African orogeny (Rambeloson 1999, Nawaratne and Dissanayake 2001, Peters et al. 2003, Andrianjakavah et al. 2007, Peters et al. 2012, Tucker et al. 2012, Figure 1A). Accordingly, two distinct working hypotheses can be formulated regarding the source of gold and its behaviour during the Pan-African orogeny, namely: (i) Gold mineralization is related to Archaean juvenile extraction and has been partially remobilized owing to deformation, metamorphism and hydrothermalism during the Pan-African orogeny; (ii) Gold mineralization is associated with the introduction of a new Au stock related to a huge hydrothermal event linked to the Pan-African orogeny.

In order to contribute to this debate, this paper will report new Re-Os geochronological constraints obtained on pyrite- and-gold-bearing quartz veins sampled in amphibolites from the Ikalamavony tectonometamorphic unit and in granodioritic orthogneisses and gabbros that are part of the Dabolava suite in the western part of Madagascar (Figures 1 and 2). These geochronological data (i) provide new insights into the source of gold and the timing of mineralization events and also (ii) contribute to the debate on the age of the Ikalamavony sub-domain and its correlation with the Itremo sub-domain.

2. Geological context of the gold occurrences

The Precambrian shield of south-central Madagascar, excluding the Vohibory region, is comprised from north-east to south-west of (i) the Antananarivo domain, (ii) the Ikalamavony-Itremo domain, and (iii) the Anosyen–Androyen domain (Figure 1A). The central domain (Ikalamavony-Itremo) consists of two distinct parts (Figure 1B).

- The Itremo sub-domain, in the east, is composed of complexly deformed shallow marine low-grade metasediments comprising a sequence of quartiztes, schists and dolomitic marbles with some tectonic intercalations of Neoarchaean gneiss (Tucker et al., 1999, 2007; CGS, 2009a, b) from the Antananarivo domain (Itremo Group, Moine, 1974). The Itremo sub-domain is of Palaeo- to Mesoproterozoic age, as inferred from the youngest Paleoproterozoic detrital zircons in quartzites clustered in age around 1.7 Ga (Cox et al. 1998 and 2004, CGS 2009a) and was intruded by the metamorphosed granitic-gabbroic Imororona-Itsindro suite (~800 Ma, Tucker et al. 1999, CGS 2009a) and by weakly deformed granites of the Ambalavao suite (~ 550 Ma, U/Pb, Tucker et al. 2007, CGS 2009a).

- The Ikalamavony sub-domain, to the west, contains abundant volcano-clastic metasediments and lesser quartzites, paragneiss and marbles, and is intruded both by the igneous rocks of the Dabolava suite composed of the granodioritic-tonalitic orthogneiss (1013 Ma and 1002 Ma, U/Pb on zircon, GAF-BGR 2008; Tucker et al. 2007; CGS 2009 a,b; Tucker et al. 2011 and Tucker et al. 2012), and metagabbros (981 Ma and 994 Ma, U/Pb on zircon, Rakotoarimanana et al. 2000, Rakotoarimanana 2001; Tucker et al. 2007, CGS 2009). According to Rakotoarimanana (2001), Tucker et al. (2007, 2011, 2012), CGS (2009a, b), the Ikalamavony sub-domain is composed from bottom to top of (i) a lower Group consisting of quartzites, paragneiss and marbles, attributed to the Palaeoproterozoic and (ii) an upper Group consisting of a volcano-sedimentary unit interpreted to be deposited around ca. 1 Ga (Figure 2).

TABLE 1

Whereas the lithostratigraphy of the Itremo sub-domain has been relatively well understood since the map publication of Moine (1968), the much more intense fold and thrust deformation and the greater lithologic and stratigraphic variety has led to a wide range of litho-tectonic subdivisions and stratigraphic nomenclature for the Ikalamavony sub-domain. Table 1, from De Waele et al. (2011), is summarizing these litho-tectonic subdivisions.

Gold in the Dabolava region is the object of intensive artisanal exploration and exploitation in both laterite and basement rocks (Figure 3). Exploitation of alluvial deposits has been the main source of gold in this region with 2.5t of gold (80 000 Oz Au) extracted between 1901 and 1921 (Tucker et al. 2012).

FIGURE 3

Gold mineralization in this area has been poorly studied with the exception of the pioneering work published in the early 20th century (Auclair, 1911; Benevisse, 1938) and the recent study of some occurrences hosted in Dabolava and Ambatomiefy granodiorites using modern geological techniques (Rakotoarimanana, 2001; Rakotoarimana et al., 2000). These studies suggest (i) a genetic relationship between gold occurrences and the Dabolava and Ambatomiefy pluton emplacement, (ii) affinities of these gold occurrences with porphyry-type deposits and (iii) a Mesoproterozoic age for gold deposition based on the 1013 to 982 Ma U/Pb ages obtained on zircon grains from the granodiorite (Tucker et al. 2007) and gabbro plutons of this region. However, the gold mineralization has not been directly dated.

Based on our field investigations, we have identified two types of gold occurrences in the Dabolava region (Figure 4):

- Type 1: Centimetre-thick quartz veinlets, with diffuse contacts and concordant to the main foliation of the host amphibolites striking dominantly east-west and dipping from 5 to 50 degrees to the southwest.
- Type 2: 30 to 50 centimetre-thick quartz veins variously transposed in dominantly EW striking subvertical shear zones affecting the granodioritic orthogneisses corresponding to the quartz veins already described in Rakotoarimanana (2001).

These two types of veins with Au-Py assemblages, within amphibolites near Kiranomena (S19°32'86'', E45°35'58'') (Type 1, Figure 2, Figure 4A and B) and within granodiorite near Dabolava (S19°38'68'', E45°42'76'') (Type 2, Figure 2, Figure 4C and 4D), have been sampled for Re-Os geochronology.

Tucker et al. (2012) described gold occurrences (Amberobe and Ampitambe) around the Vongoa gabbroic intrusion (Figure 1B) associated with discordant Quartz-Pyrite veins. Pyrite observed as veins inside the Miandrivazo gabbro (S19°36'19'', E45°35'97'') (Figure 2, Figure 4E and 4F) has also been dated in this study even if we did not detect any gold in the samples used for geochronology.

FIGURE 4

3. Analytical Methods and results

The Re-Os geochronological measurements (Table 2) were performed on pyrite (Miandrivazo gabbro) or on intergrown pyrite and electrum, the most common metal-bearing phases in the two observed paragenesis (Ramiandrisoa 2010, Ramiandrisoa et al. 2009).

FIGURE 5

The pyrite and intergrown pyrite and electrum samples were pulverizing in an agate mortar to fine powder. Re-Os isotope analyses were carried out at the CRPG laboratory (Nancy, France). Analytical techniques applied in our study are based on those described in Birck et al. (1997), Cardon et al. (2008), and Reisberg and Meisel (2002) and are briefly summarized here. For each sample, 300 mg of pyrite powder were placed in a quartz tube with ^{185}Re and ^{190}Os spikes, hydrochloric acid (2 mL), nitric acid (5 mL), and 0.1 ml of H_2O_2 (Table 2). Quartz tubes were placed in a high pressure asher (HPA-S Anton Paar) and heated at 300°C during 3 hours, under a pressure of 100 bars. This operation permits sulphide dissolution and assures homogenization of sample and spike Os. Osmium was then extracted into liquid bromine, an immiscible phase. After two extractions, Os was trapped in the Br_2 solution, whereas Re remained in the acidic solution. After adding HBr to transform Os to a non-volatile form, the Br_2 was removed from the Os-bearing fraction by evaporation at low temperature. The separated Os was then purified by microdistillation. Rhenium was extracted from the acidic solution using chromatographic columns filled with AG1 X-8 resin.

Re measurements were made using an inductively coupled plasma mass spectrometer (ICP-MS; ELAN 6000 at the SARM, Nancy). Instrumental mass fractionation was repeatedly controlled during the measurements with a 0.3 ppb Re standard, normalized to an assumed $^{187}Re/^{185}Re$ ratio of 1.6738. Os samples were loaded on platinum filaments and analyzed by negative thermal ionization mass spectrometry (N-TIMS; Creaser et al., 1991; Volkening et al., 1991) using a Finnigan MAT 262 instrument at CRPG, Nancy. Analyses were made in peak jumping mode using an ETP electron multiplier. During the period of measurement, our in-house Os standard yielded a value of 0.17383 ± 0.00062 (2σ, n=40) identical within error to the value obtained for this standard over the past 10 years. A total Os blank analyzed with the samples yielded 0.35 pg and a $^{187}Os/^{188}Os$ ratio of ~0.4, which is comparable to typical blank values in the laboratory. Two Re blanks yielded 3.6 and 5.6 pg. The obtained Re-Os values for these py (pyrite), py+el (electrum) assemblages are presented in Table 2.

TABLE 2

In this table 2, Re concentrations and $^{187}Os/^{188}Os$ ratios are blank corrected. We note that because of the very low ^{188}Os concentrations, the $^{187}Os/^{188}Os$ ratios are highly sensitive to the blank correction, particularly for the pyrite sample, and should thus be considered only as approximate values. Ages are determined using the calculated radiogenic ^{187}Os concentrations ($^{187}Os^*$) which are much more robust. The ^{188}Os values listed in Table 2 include the common Os contributions from both the Os incorporated into the minerals and the analytical blank. Common Os is assumed to have a $^{187}Os/^{188}Os$ ratio of 0.6 ±0.5. The uncertainty on this assumed composition, which includes both the Os blank and the initial Os components, is propagated into the final uncertainty on the age. The final uncertainty also takes into account the Re blank uncertainty, standard errors of individual analyses, reproducibility of liquid standards, Re isotopic fractionation during analysis, and weighing and decay constant uncertainties, all taken at the 2σ level.

Two distinct ages are obtained for type 1 and type 2 gold occurrences. The pyrite and electrum assemblage hosted as concordant veins in amphibolites yields a Palaeoproterozoic age (1961±79Ma) whereas the assemblage observed as discordant veins in the Dabolava granodiorite yields a Pan-African age (533±23 Ma). The pyrite sampled from a vein inside the Miandrivazo gabbro also gives a Pan-African age (526±6 Ma).

4. Discussion

4.1. Timing of gold event(s)

The Re-Os ages obtained directly on pyrite+electrum assemblages for Type 1 concordant veins (1961±79Ma) and Type 2 discordant veins (533±23 Ma) respectively hosted in amphibolites and in granodiorite clearly express two main gold deposition events in this crustal segment.

The Re-Os result (1961±79Ma) on a type 1 gold vein suggests that an initial gold concentration is associated with the Ikalamavony basic volcano-sedimentary sequence, within the upper Group of the Ikalamavony sub-domain. The significance of this age in terms of the depositional age of the Ikalamavony sub-domain will be discussed in section 4.2.

The Re-Os result (533±23 Ma) on a type 2 gold vein contrasts with the model of Rakotoarimanana (2001) invoking a genetic relationship between the deposition of these gold-quartz veins, and the Dabolava suite emplacement, i.e. around 1 Ga. Ramiandrisoa et al. (2009) and Raminandrisoa (2010) have demonstrated the orogenic character of this gold mineralization with structural, mineralogical and microthermometric evidence. The Pan-African age obtained on the type 2 gold deposits is much younger than the emplacement age of the host granodiorite (1013 Ma and 1002 Ma, U/Pb on zircon, Tucker et al. 2007). That precludes a porphyry-type model for this gold mineralization and rather favours an orogenic type with a deposition during the Pan-African orogeny.

The initial metal stock observed in the Ikalamavony volcano-sedimentary formation may have been remobilized by a mesothermal fluid during the Pan-African orogeny (Ediacaran, ~560–530 Ma) within a D2 (EW) deformational event around 550 Ma.

This hydrothermal event led to the formation of numerous EW orogenic gold veins observed in the area irregardless of the host rocks (Figure 2). These are nevertheless particularly well expressed in the more competent rock of this area, i.e. the Daboalava orthogneissic granodiorite.

4.2. Implications for the depositional age of rocks of the Ikalamavony Sub-Domain

The age obtained on the type 1 concordant gold vein in amphibolites (1961±79Ma) may imply a Palaeoproterozoic depositional age for the upper Group of the Ikalamavony volcano-sedimentary sequence (Upper NW package, Table 1, CGS 2009b) and therefore, may suggest that the whole Ikalamavony sub-domain is the lateral equivalent of the Palaeoproterozoic Itremo domain. This proposition is consistent with earlier models interpreting the Ikalamavony sub-domain as a distal sequence to the west of the Itremo Group (Fournié and Heurtebize, 1963; Moine, 1963, 1967, 1974, Joo', 1963, Alsac, 1963a, b).

According to Rakotoarimanana (2001), Tucker et al. (2007, 2011, 2012), CGS (2009a, b), the Ikalamavony sub-domain is composed from bottom to top of:

- A lower Group consisting of quartzites, paragneiss and marbles, attributed to the Palaeoproterozoic. The synchronicity and the equivalence between the Ikalamavony lower Group and the Itremo sub-domain has been advocated on the basis of the minimum ages obtained on detrital zircon grains from both the Itremo and the Ikalamavony quartzites (~1800 Ma), (Tucker et al. 2011 and 2012). In contrast, rocks interpreted to be part of the Itremo sub-domain have been considered as tectonic intercalations of rocks from the Antananarivo Domain (Figure 1; CGS 2009a).

- An upper Group consisting of a volcano-sedimentary unit interpreted to be deposited around ca. 1 Ga. Tucker et al. (2012) identified four lines of evidence allowing to distinguish the Ikalamavony upper Group from the Itremo sub-domain: (i) Metasedimentary feldspar rich rocks are predominant at the top of the sequence which is not the case for the Itremo sub-domain (CGS, 2009a, b); (ii) These metasedimentary rocks are estimated to be of Mesoproterozoic age based on a ~ 1,013 Ma age obtained on a Meta-rhyolite (CGS, 2009a, b ; Tucker et al., 2011); (iii) These formations express a unimodal 1,070-1,020 Ma signature of the detrital zircons implying their potential derivation from a source in the Dabolava suite (CGS, 2009a, b; Tucker et al., 2011); (iv) These feldspar-rich rocks, which are cross-cut by the Dabolava suite, contain zircon with rims dated at ~1 Ga (CGS, 2009a, b ; Tucker et al., 2011). From all these observations, Tucker et al. (2011 and 2012) concluded that the magmatic Dabolava suites and volcano-sedimentary sequences of the Upper part of the Ikalamavony Group were emplaced from 1,035 Ma to 910 Ma and consequently argue that this upper Group of the Ikalamavony sub-domain is not a lateral facies of the Itremo sub-domain. This Ikalamavony upper Group is thus considered to be Mesoproterozoic for Tucker et al. (2011), even if they argue that the Dabolava Suite, apparently absent in the Itremo sub-domain, is present within feldspathic gneiss of this Ikalamavony Group and that indicates that the Ikalamavony Group must be Mesoproterozoic or older.

The 1961±79Ma Ma age obtained in this study on a concordant type 1 gold vein in the amphibolites of the upper Group of the Ikalamavony sub-domain favours a Palaeoproterozoic depositional age for the whole Ikalamavony sub-domain, and may suggest a correlation of both the upper and lower Groups of the Ikalamavony sub-domain with the Itremo sub-domain. This proposed age for this Ikalamavony upper

Group contrasts thus with the Mesoproterozoic age proposed for the upper part of the Ikalamavony sub-domain by Tucker et al. (2011).

However, this age is slightly older than that (~1800 Ma) deduced by Tucker et al. (2011) for the maximum deposition age based on detrital zircon ages in the quartzites of the lower Ikalamavony Group. This interpretation also does not address the difference in metamorphic grade between these two domains with Greenschist facies for the Itremo sub-domain and Upper amphibolite- to granulite facies for the Ikalamavony sub-domain (Fernandez et al. 2003) as it does not address the nature of the original contact between these two units. As metamorphism could potentially perturb the Re-Os system, the 1961±79Ma Ma age obtained for the type 1 veins, while intriguing, should be viewed with some caution. Nevertheless, it highlights the need for further dating of these rocks to clarify the relationship between the Ikalamavony and Itremo sub-domains.

Acknowledgements

This work is a part of Njjararivelo Ramiandriosa's Ph.D thesis carried out within the scientific and financial framework of the PGRM program. The authors would like to thank Bernard Moine for the proposal to participate at the PGRM program and for all the very rich scientific exchanges. This study has benefited from the analytical facilities of GeoRessources and CRPG laboratories (Nancy - France). Sandrine Matthieu, Alain Kohler, Christiane Parmentier and Cédric Demeurie are greatly thanked for their technical supports. Many thank's to the editorial board of JAES, especially Bernard Moine, and for the constructive comments of both Wilfried Bauer and an anonymous reviewer, that really help to improve this paper.

REFERENCES

Alsac, C., 1963a. Feuille Ankotrofotsy I.49, Dabolava J.49, Anjoma — Ramartina K.49, 1/100,000, Service Géologique de Madagascar.

Alsac, C., 1963b. Etude géologique et prospection des feuilles au 1:100 000: Ankotrofotsy (I49); Dabolava (J-49); Anjoma Ramartina (K-49). Service du Bureau Géologique, Antananarivo, Madagascar, 147–157.

Andriamampihantona, J. 1992. Contribution à l'étude du complexe alcalin d'Ambatofinandrahana et de ses minéralisations à lanthanides (Région Centrale de Madagascar). Thèse d'Université de Grenoble, 202p.

Andrianjakavah, P., Salvi, S., Béziat, D., Guillaume, D., Rakotondrazafy, M., Moine, B. 2007. Textural and fluid inclusion constraints on the origin of the banded-iron-formation-hosted gold deposits at Maevatanana, central Madagascar. Mineralium Deposita 42, 385-398.

Auclair, 1911. Or Dabolava, Rapport annuel 1911. Centre de documentation de la direction des mines et de la géologie. Antananarivo, Madagascar

Augé, T., Legendre, O., 1992. Pt–Fe nuggets from alluvial deposits in Eastern Madagascar. Canadian Mineralogist 50, 983–1004.

Benevisse, O., Auclair, A., Chabert, T., 1938. Exploitation aurifère d'Ampandrana-Tsimivolovolo-Andevoka, Antanimiety, Amberoka, Andasimaromaro-Or et graphite du basin de l'Onia. Centre de documentation de la direction des mines et de la géologie, Antananarivo, Madagascar.

Besairie, H., 1966. Gîtes minéraux de Madagascar: Annales Géologiques de Madagascar 34, 93 maps.

Birck, J.L., Roy Barman, M., Capmas, F., 1997. Re-Os isotopic measurements at the femtomole level in natural samples. Geostandards Newsletter 20, 19-27.

Cardon, O., Reisberg, L., André-Mayer, A.S., Leroy, J., Milu, V., Zimmermann, C., 2008. Re-Os systematics of pyrite from the Bolcana porphyry copper deposit, Apuseni mountains, Romania. Economic Geology 103, 1695-1702.

CGS, 2009a. Map Explanation of 1:100 000 scale (Zone E) Sheets I46 -Ambararata, J46 – Beopoaka, 47-Itondy, J47 -Belobaka, K47 -Ambatofotsy, I48 -Miandrivazo, J48 – Betrondro, K48 Ambatondradama, I49 -Ankotrofotsy, J49 -Dabolava, K49 -Anjoma-Ramartina, L49 – Vasiana, M49 – Ankazomiriotra, N49 -Antsirabe. République de Madagascar, Ministère de L'Energie et des Mines – Project de Gouvernance des Ressources Minérales, Antananarivo, Madagascar and Council for Geoscience, Pretoria, South Africa.

CGS, 2009b. Map Explanation of 1:100 000 scale (Zone F) feuilles G41 - Ambohipaky, H41 - Bevary, G42 - Mangoboky, H42 - Bekodoka, G43 - Andolamasa, H43 - Andrafialava et partie de G40 - Ankasakasa, F40 - Saint-Andre, F41 - Betsalampy, H40 - Maroboaly-Sud, I40 - Soalala-Sud, I41 - Andranomavo, F42 - Marovoay Kely, I42 - Mahabe, F43 - Bebao, F44 - Antranogoaika, G44 - Morafeno, I43 - Ampoza, H44- Bemolanga et I44 Makaraingo. Ministère de L'Energie et des Mines - Projet de Gouvernance des Ressources Minérales, Antananarivo, Madagascar and Council for Geoscience, Pretoria, South Africa.

Collins, A.S., 2000. The tectonic evolution of Madagascar: Its place in the East African Orogen. Gondwana Research 3, 549–552.

Collins, A.S., 2006. Madagascar and the amalgamation of Central Gondwana. Gondwana Research 9, 3-16.

Collins, A.S., Windley, B.F., 2002. Tectonic evolution of central and northern Madagascar and its place in the final assembly of Gondwana Journal of Geology 110, 325–339.

Collins, A.S., Johnson, S., Fitzsimons, I.C.W., Powell, C.M., Hulscher, B., Abello, J., Razakamanana, T., 2003. Neoproterozoic deformation in central Madagascar: a structural section through part of the East African Orogen. In: Yoshida M., Windley, B.F., Dasgupta, S. (Eds.), Proterozoic East Gondwana: Supercontinent Assembly and Breakup, vol. 206. Special Publication of the Geological Society, London, pp. 363–379.

Cox, R., Armstrong, R.A., Ashwal L.D., 1998. Sedimentology, geochronology and provenance of the Proterozoic Itremo Group, central Madagascar, and implications for pre-Gondwana palaeogeoraphy. Journal of the Geological Society London 155, 1009-1024.

Cox, R., Coleman, D.S., Chokel, C.B., De Oreo, S.B., Wooden, J.L., Collins, A.S., DeWaele, B., and Kröner, A., 2004. Proterozoic tectonostratigraphy and paleogeography of central Madagascar derived from detrital zircon U-Pb age populations. Journal of Geology 112, 379-400.

Creaser, R.A., Papanastassiou, D.A., Wasserburg, G.J., 1991. Negative thermal ion mass spectrometry of osmium, rhenium and iridium. Geochimica et Cosmochimica Acta 55, 397-401.

De Waele, B., Thomas, R.J., Macey, P.H., Pitfield, P.E., Schofield, D.I., Goodenough, K.M., Horstwood, M.S., Bauer, W., Key, R.M., Potter, C.J., Armstrong, R.A., Miller, J.A., Randriamananjary, T., Ralison, V., Rafahatelo, J.-M., Rabarimanana, M.H., Bejoma, M., Tucker, R.D., 2011. Provenance and tectonic significance of the Paleoproterozoic metasedimentary successions of Madagascar. Precambrian Research 189, 18–42.

de Wit, M.J., 2003. Madagascar: heads it's a continent, tails it's an island. Annual Review of Earth and Planetary Sciences 31, 213–248.

Fernandez, A., Schreurs, G., 2003. Tectonic evolution of the Proterozoic Itremo Group metasediments in central Madagascar. In: Yoshida, M., Windley, B., Dasgupta, S. (Eds.), Proterozoic East Gondwana: Supercontinent Assembly and Breakup. Special Publication of the Geological Society London, 381–399.

Fournié, L., Heurtebize, G., 1963. Géologie de la région d'Ikalamavony–Ampadramaika–Bekisopa, Centre-Sud de Madagascar. Comptes Rendus de la Semaine Géologique, in Ann. Géol. Madagascar XXXIII, 137–144.

GAF-BGR, 2008. Final report: Explanatory notes for the Itremo–Ikalamavony Domain, central and western Madagascar. Réalisation des travaux de cartographie géologique de Madagascar, révision approfondie de la cartographie géologique et minière aux échelles 1/100,000 et 1/500,000 zone Sud. République de Madagascar, Ministère de l'Energie et des Mines MEM/SG/DG/UCP/PGRM), 79 pp.

Giuliani, G., Fallick, A., Rakotondrazafy, M., Ohnenstetter, D., & et al. 2007. Oxygen isotope systematics of gem corundum deposits in Madagascar: relevance for their geological origin. Mineralium Deposita 42, 251–270.

Handke, M.J., Tucker, R.D., Ashwal, L.D., 1999. Neoproterozoic continental arc magmatism in west-central Madagascar. Geology 27, 351–354.

Joo', J., 1963. Feuille Ambararata I.46, Bepoaka J.46, 1/100 000. Service Géologique de Madagascar.

Kabete, J., Groves, D., McMaughton, N., Dunphy, J., 2006. The geology, shrimp U–Pb geochronology and metallogenic significance of the Ankisatra-Besakay district, Andriamena belt, northern Madagascar: Journal of African Earth Sciences 45, 87–122.

Kröner, A., Hegner, E., Collins, A.S., Windley, B.F., Brewer, T.S., Razakamanana, T., Pidgeon, R.T., 2000. Age and magmatic history of the Antananarivo Block, central Madagascar, as derived from zircon geochronology and Nd isotopic systematics. American Journal of Science 300, 251–288.

Martelat, J.-E., Lardeaux, J.-M., Nicollet, C., Rakotondrazafy, R., 2000. Strain pattern and late Precambrian deformation history in southern Madagascar. Precambrian Research 102, 1–20.

Moine, B., 1963. Feuille Miandrivazo I.48, Betrondro J.48, Ambatondradama K.48, 1/100 000. Service Géologique de Madagascar.

Moine, B., 1967. Relations stratigraphiques entre la série «schisto-quartzo-calcaire » et les gneiss environnants (centre-ouest de Madagascar): Données d'une première étude géochimique. Comptes Rendus de la Semaine Géologique de Madagascar, 49–53.

Moine, B., 1968. Carte Géologique à 1/200,000 du massif schisto–quartzo–dolomitique, région d'Ambatofinandrahana, centre-ouest du socle cristallin du Précambrien de Madagascar. Centre de l'Institut Geographique National à Tananarive (imprimeur), Sciences de la Terre, Nancy (éditeur).

Moine, B., 1974. Caractères de sédimentation et de métamorphisme des séries précambriennes épizonales à catazonales du centre de Madagascar (Région d'Ambatofinadrahana). Sciences de la Terre, Nancy (France), 293 pp and color map.

Nawaratne, S.W., Dissanayake, C.B., 2001. Gold occurrences in Madagascar, South India and Sri Lanka; Significance of a possible Pan-African event: Gondwana Research 4, 367–375.

Peters, S.G., Bawiec, W.J., Sutphin, D.M., eds., 2003. Pre-assessment of Madagascar's undiscovered non-fuel mineral resources: U.S. Geological Survey Administrative Report, 159 pages 14 plates.

Peters, S.G., Roig, J.Y., Tucker, R.D., Théveniaut, H., Delor, C., 2012. Carte des substances métalliques de la République de Madagascar à 1/1 000 000. Ministère des Mines, PGRM, Antananarivo, République de Madagascar.

Premoli, C. 1996. Gold in Madagascar. Mining Journal Publication London 326, 362.

Rakotoarimanana, R.H., 2001. Geology and petrology of the Dabolava region, west-central Madagascar, with emphasis on granite-hosted gold mineralization. Unpublished M.Sc. dissertation, University of Witswatersrand, 89 pp.

Rakotoarimanana, R.H., Ashwal, L.D., Robb, L.J., Tucker, R.D., 2000. Quartz vein hosted gold mineralisation in Proterozoic dioritic plutons within the Dabolava metavolcanic complex, west Madagascar (abstr). Geol. Soc. S. Afr. Geocongress 2000, Stellenbosch, J. Afr. Earth Sci. 31, 59.

Rakotondrazafy, A.F.M., Moine, B., Cuney, M., 1996. Mode of formation of hibonite ($CaAl_{12}O_{19}$) within the U-Th skarns from granulites of S-E Madagascar. Contributions to Mineralogy and Petrology 123, 190-201.

Rambeloson, R.A., 1999. Gold in Madagascar: Gondwana Research 3, 423–-431.

Ramiandrisoa, N., Rasolomanana, E., Rabenandrasana, S., Vanderhaeghe, O., André-Mayer, A.S., Boiron, M.C., 2009. Mineralisation aurifère dans les formations Protérozoiques de Dabolava, Miandrivazo Centre-ouest de Madagascar: Etude Pétrographique et Géochimique des veines de quartz aurifères. MadaGéo 13, 20-29.

Ramiandrisoa, N., 2010. Etude métallogénique du gisement d'or de Dabolava, Centre Ouest de Madagascar. Un exemple de minéralisation aurifère mésothermale dans des formations protérozoïques. Thèse Université d'Antananarivo, 143 p.

Reisberg, L., Meisel, T., 2002. The Re-Os isotopic system: A review of analytical techniques. Geostandards Newsletter 26, 249-267.

Smoliar, M.I., Walker, R.J., Morgan, J.W., 1996. Re-Os ages of group IIA, IIIA, IVA and IVB iron meteorites. Science 271, 1099-1102.

Tucker, R.D., Ashwal, L.D., Handke, M.J., Hamilton, M.A., Le Grange, M., Rambeloson, R.A., 1999. U-Pb geochronology and isotope geochemistry of the Archean and proterozoic rocks of north-central Madagascar. Journal of Geology 107, 135-153.

Tucker, R.D., Kusky, T.M., Buchwaldt, R., Handke, M.J., 2007. Neoproterozoic nappes and superposed folding of the Itremo Group, west-central Madagascar. Gondwana Research 12(4), 356–379.

Tucker, R.D., Roig, J.Y., Macey, P., Delor, C., Amelin, Y., Armstrong, R.A., Rabarimanana, M.H., Ralison, A.V., 2011. A new geological framework for south-central Madagascar, and its relevance to the “out-of-Africa” hypothesis. Precambrian Research 185, 109–130.

Tucker, R.D., Peters, S.G., Roig, J.Y., Théveniaut, H., Delor, C., 2012. Notice explicative des cartes géologique et métallogéniques de la République de Madagascar à 1/1,000,000. Ministère des Mines, PGRM, Antananarivo, République de Madagascar.

Windley, B.F., Razafiniparany, A., Razakamanana, T., Ackermand, D., 1994. Tectonic framework of the Precambrian of Madagascar and its Gondwana connections: a review and reappraisal. Geologische Rundschau 83, 642–659.

Völkening J., Walczyk T., and Heumann K.G., 1991. Osmium isotope determinations by negative thermal ionization mass spectrometry: International Journal of Mass Spectrometry and Ion Physics 105, 147–159.

FIGURE CAPTIONS

Figure 1. A. Simplified map of the tectono-metamorphic units of Madagascar (Modified from Tucker et al. 2011). Ad-Androyen, An-Anosyen, A/M-Antongil/Masora, A-Antananarivo, B-Bemarivo, Ik-Ikalamavony, It-Itremo, Ts-Tsaratanana, V-Vohibory. The main mesothermal gold regions are indicated and include Antalaha, Maevatanana, Tsaratanana, Betsiri, Mananjary and Itea. **B.** Map of the Dabolava auriferous district, modified from Peter et al. (2012).

Figure 2. Geological map of the Miandrivazo-Dabolava region (extracted from CGS, 2009a, sheets I48, I49, J48 and J49). The localization of the studied samples is indicated with white stars: 1. Auriferous concordant vein in amphibolite-leucogneiss, upper-Group of the Ikalamavony sub-domain, west of Kiranomena. 2. Quartz vein discordant to the Dabolava granodioritic orthogneiss and 3. pyrite inside the Miandrivazo gabbro.

Figure 3. Artisanal exploitation of gold. **A.** in the basement. **B.** within laterites.

Figure 4. Macroscopic views of the sampled veins. **A.** Type 1, auriferous quartz vein concordant to the amphibolite-leucogneiss. Kiranomena: S19°32’’86’’, E45°35’’58’’. **B.** Type 2, auriferous quartz vein discordant to the granodioritic orthogneiss foliation. Dabolava: S19°38’68’’, E45°42’76’’. **C.** Pyrite observed as veins inside the Miandrivazo gabbro: S19°36’19’’, E45°35’97’’.

Figure 5. A. SEM pothograph of the Py-Po assemblages, Type 2 quartz veins and **B.** Microphotographs of Py as veins in Miandrivazo gabbro.

TABLE CAPTIONS

Table 1. Tectonic and lithostratigraphic units of the Itremo-Ikalamavony Domains as mapped by the CGS (2009b) with previous subdivisions for comparison (from De Waele et al. 2011).

Table 2. Re-Os data for Type 1 py+el assemblage (concordant vein in amphibolites near Kiranomena, S19°34’’86’’, E45°35’’58’’), Type 2 py+el assemblage (discordant vein in Dabolava granodiorite, S19°38’68’’, E45°42’76’’) and py (veins in Miandrivazo gabbro, S19°36’19’’, E45°35’97’’). Analytical details are given in the table notes. λ^{187}Re = 1.666 x 10^{-11} (Smoliar et al., 1996).

FIGURE 1

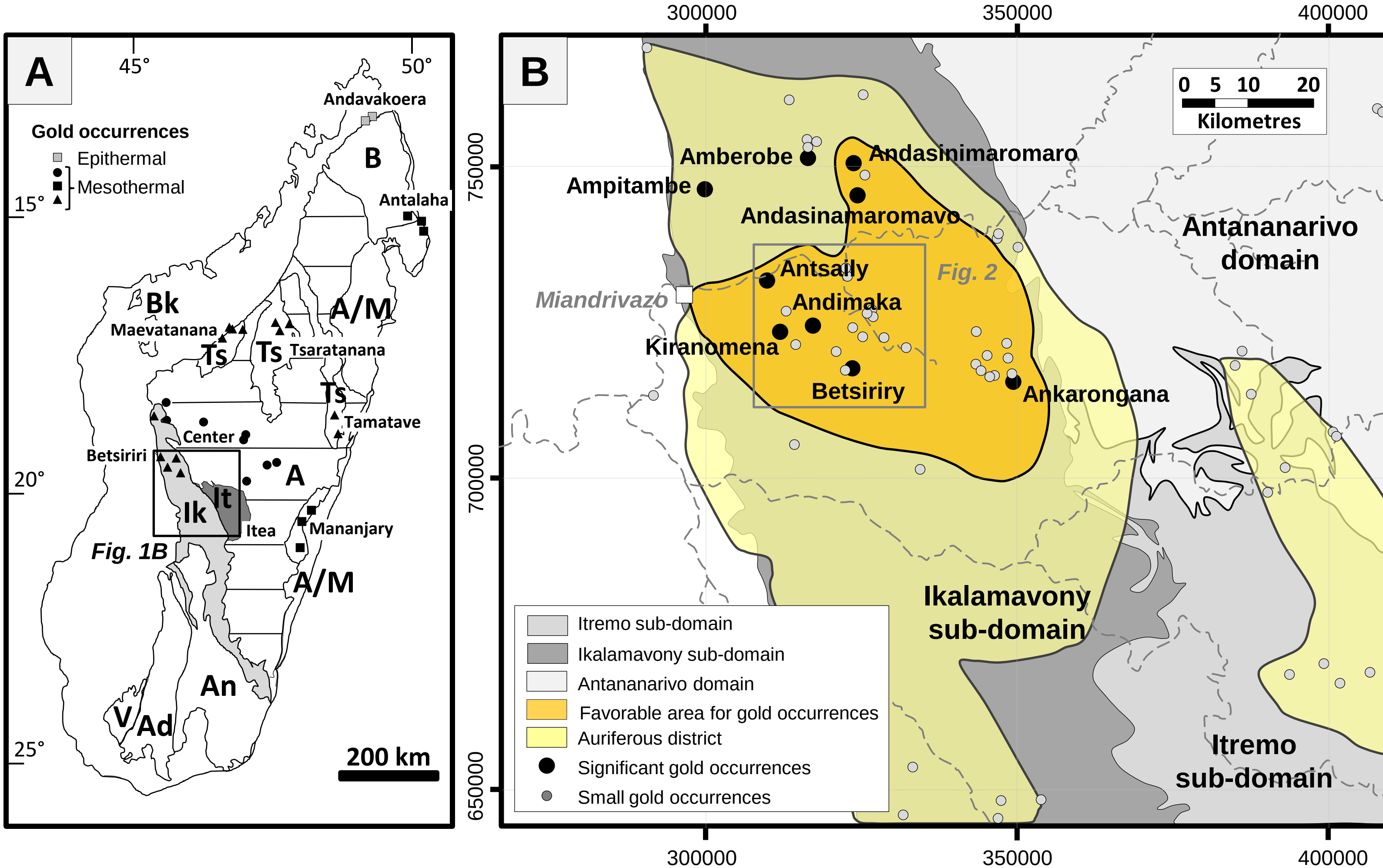
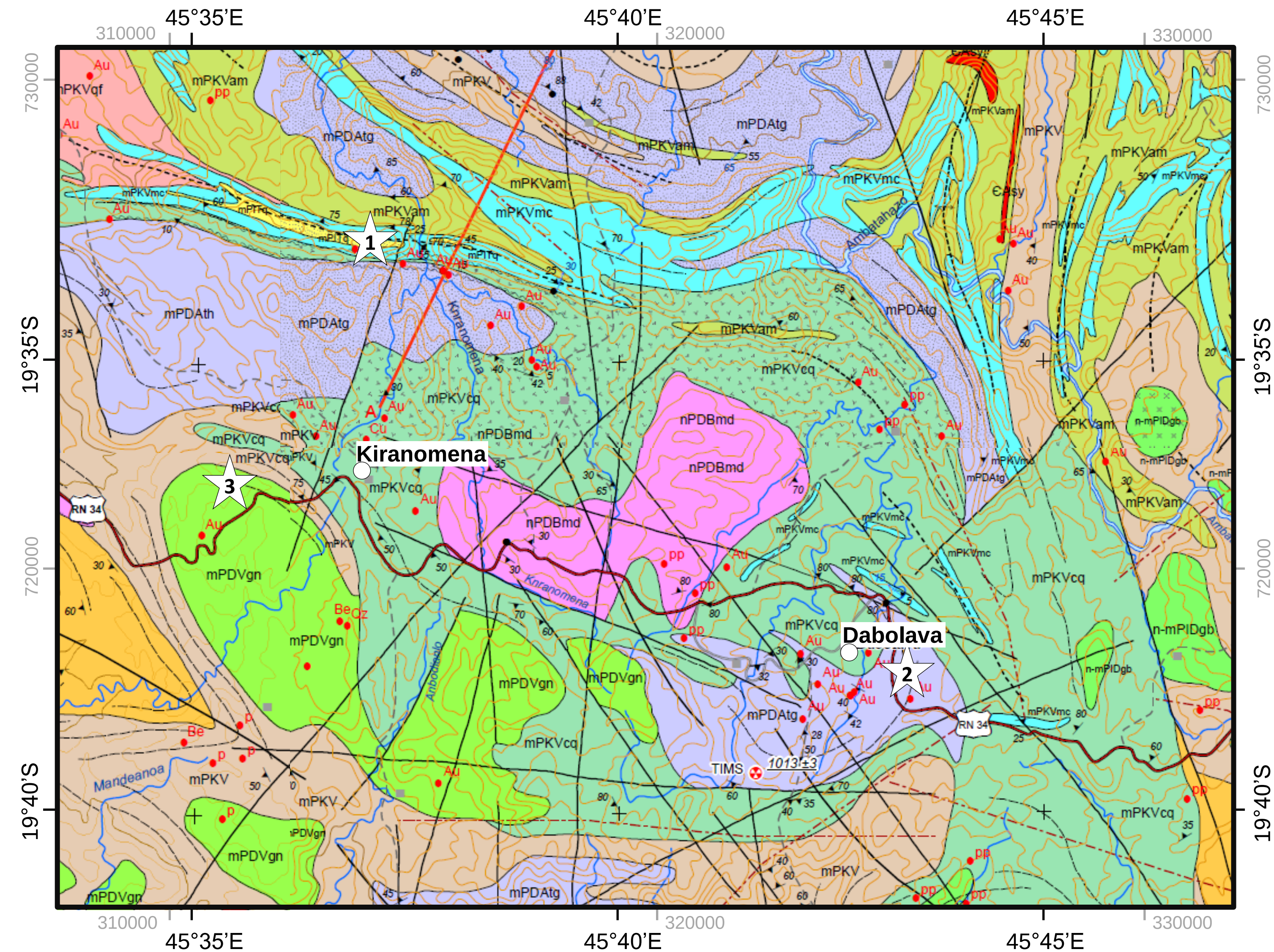

A
45°
50°
Andavakoera
Gold occurrences
Epithermal
Mesothermal
B
Antalaha
15°
Bk
A/M
Maevatanana
Ts
Ts
Tsaratanana
Ts
Tamatave
Center
Betsiriri
20°
A
It
Ik
Itea
Mananjary
Fig. 1B
A/M
An
V
Ad
25°
200 km
B
300000
350000
400000
0 5 10 20
Kilometres
Amberobe
Andasinimaromaro
Ampitambe
Andasinamaromavo
Antananarivo domain
Antsaily
Fig. 2
Miandrivazo
Andimaka
Kiranomena
Betsiriry
Ankarongana
750000
700000
650000
Ikalamavony sub-domain
Itremo sub-domain
Itremo sub-domain
Ikalamavony sub-domain
Antananarivo domain
Favorable area for gold occurrences
Auriferous district
Significant gold occurrences
Small gold occurrences

FIGURE 2



45°35'E
45°40'E
45°45'E
310000
320000
330000
730000
720000
19°35'S
19°40'S
Kiranomena
Dabolava
1
2
3
RN 34
TIMS
1013±3
mPKVam
mPKVmc
mPKVcq
mPDAtg
mPDAth
mPDVgn
nPDBmd
n-mPIDgb
mPKV
mPKVqf
Kiranomena
Ambatahazo
Mandeanoa

FIGURE 2 (legend)

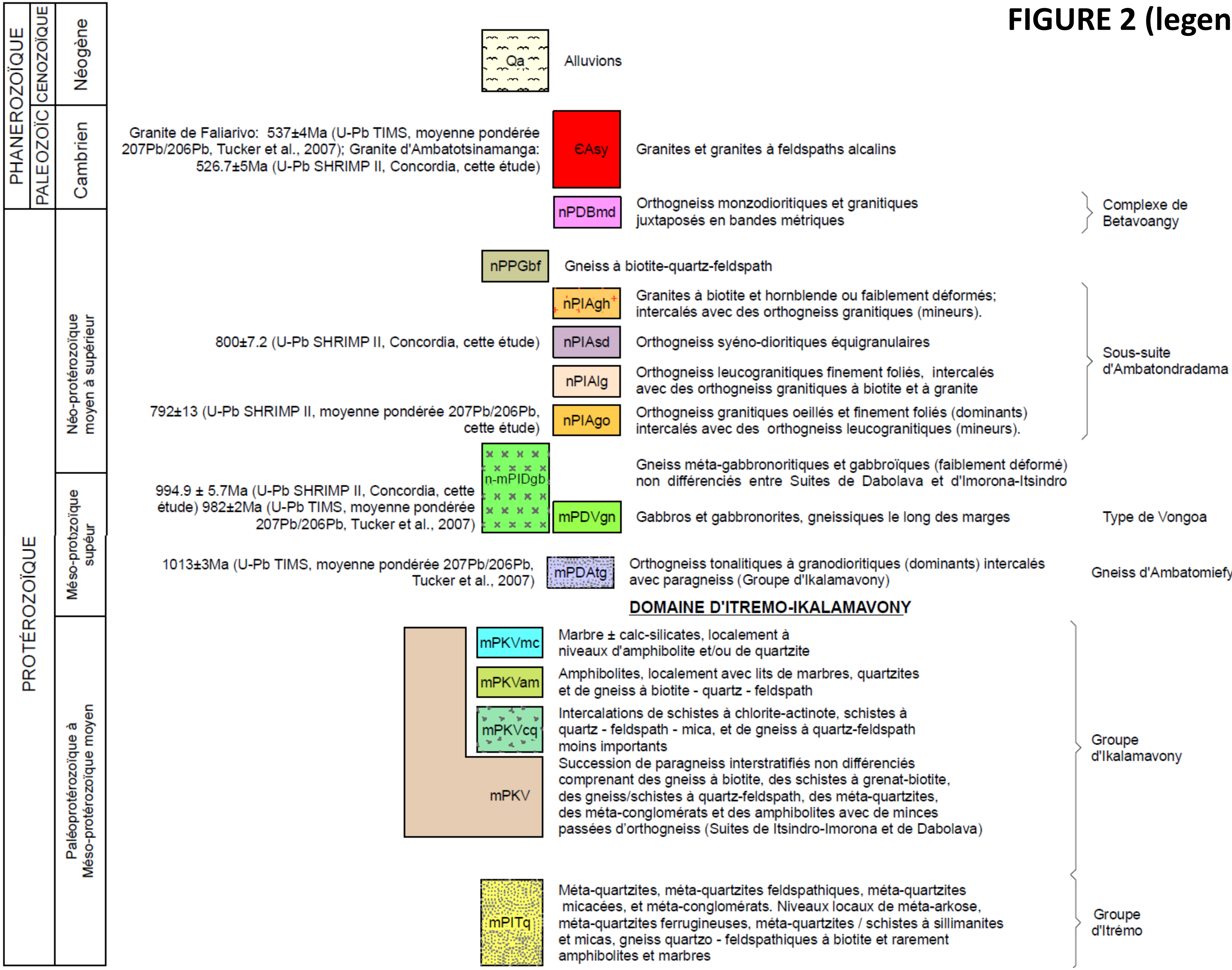


FIGURE 3

FIGURE 4

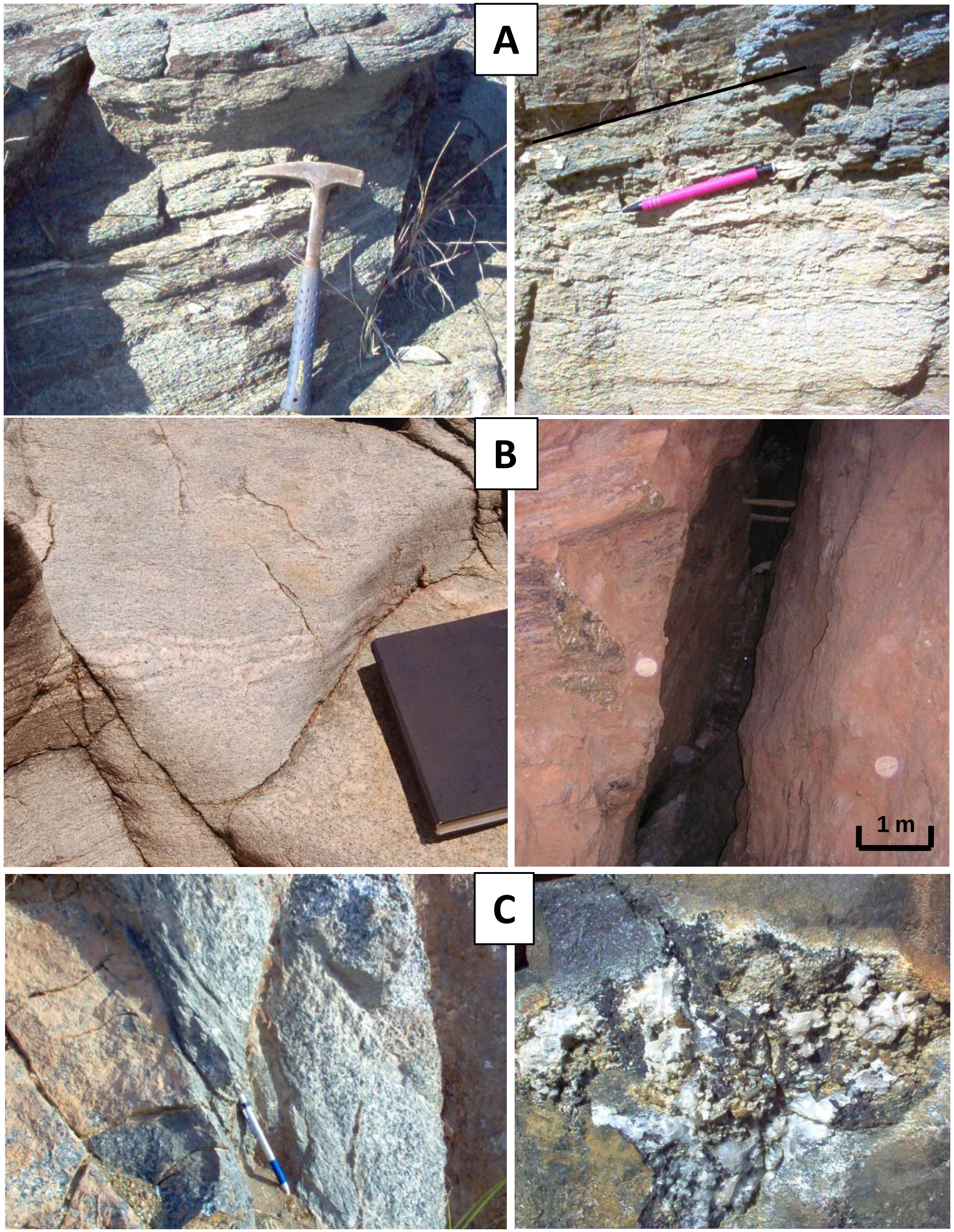


FIGURE 5

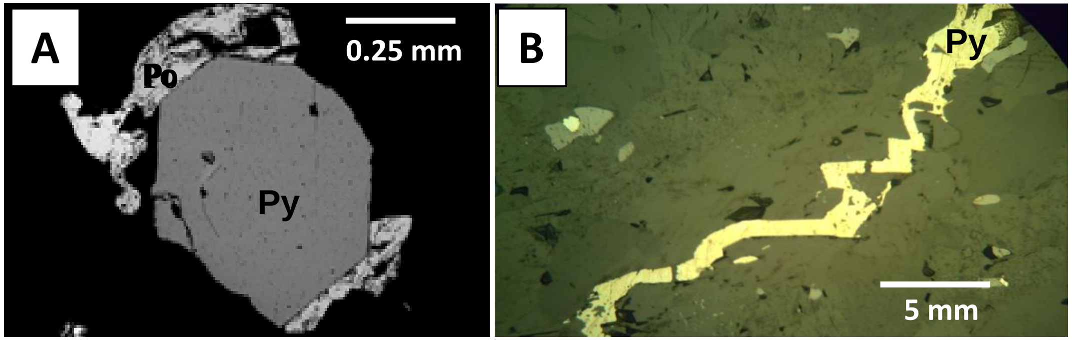


Table 1

CGS (2009b)					Besairie (1964) 1:1 000 000 map	Moine (1968) 1:200 000 map	Besairie (1969) 1:500 000 map		Hottin (1976) 1:200000 map	Windley et al. (1994)	Collins (et al.)	
Litho-tectonic subdivisions			Supracrustal rocks	Orthogneisses							2003	2006
Ikalamavony sub-domain	Upper NW Package	Miandrivazo	Ikalamavony Group	Dabolava Suite Imorona-Itsindro Suite	Groupe d'Amborompotsy		Migmatite Quartzite Amphibolite		Système Amborompotsy-Ikala Série du Vohinema	Miandrivazo	Itremo Sheet	Molo Group
	Middle Package	Kinangaly-Tinjomay-Bevitsika Ridge	Itremo Group	None	Série de Schisto Quartzo-Calcaire		Série de Schisto Quartzo-Calcaire			Série de Schisto-Quartzo-Calcaire Vohimena		
	Lower SE package	Molo	Molo Group	Imorona-Itsindro Suite	Groupe d'Amborompotsy Groupe de Malakialina	Groupe gneissique	Groupe d'Ikalamavony	Ikalamavony Vohimena Malakialina				
Itremo sub-domain			Itremo Group	Imorona-Itsindro Suite	Série de Schisto-Quartzo-Calcaire/Série Schisto-Quartzo-Dolomitique							Itremo Group

Table 2

Sample type	Minerals	Sample mass (g)	[Re] (ppb)	^{187}Re (pM/g)	^{187}Os/^{188}Os	Total ^{188}Os (ppt)	%^{188}Os from blank	Total ^{187}Os (ppt)	% ^{187}Os*	^{187}Os* (pM/g)	^{187}Os*/^{187}Re	Age (Ma)
1	*1*		*2*	*2, 3, 4*	*5*	*6*			*7*	*3, 7*	*3, 7*	*3, 8*
Type 1	py + el	0.41019	2.01	6.74 ± 0.25	37.9 ± 2.4	1.23	9	42.6	98.3	0.228 ± 0.004	0.03322 ± 0.00134	1961 ± 79
Type 2	py + el	0.40948	2.17	7.35 ± 0.07	14.3 ± 1.1	1.01	11	12.8	95.3	0.069 ± 0.003	0.00891 ± 0.00038	533 ± 23
Py in gb	py	0.40617	127	429.7 ± 2.3	*~22000*	0.14	77	707.6	99.99	3.785 ± 0.036	0.00881 ± 0.00010	526 ± 6

Notes:

1. See text for explanation of sample types; gb = gabbro; py = pyrite; el = electrum.
2. Re data are blank corrected. Uncertainty in blank value is included in the total uncertainty.
3. All listed uncertainties are 2σ.
4. pM/g = 10^{-12} moles/grams
5. ^{187}Os/^{188}Os is corrected using the values of the associated blank given in the text; uncertainty is based on uncertainty of lab blanks during analysis period. Because of its very low ^{188}Os content the blank correction on the pyrite sample is extremely large and its uncertainty cannot be evaluated as the maximum blank exceeds the total common Os content.
6. Includes both the common Os included in the minerals and the blank contribution.
7. ^{187}Os* = radiogenic ^{187}Os only, calculated assuming that the common Os (initial + blank contribution) has ^{187}Os/^{188}Os = 0.6 ±0.5. Uncertainty on ^{187}Os* includes uncertainty on this ratio.
8. Age uncertainty includes uncertainties related to weighing, standard reproducibility and decay constant as well as measurement uncertainty.

Highlights:

- Re-Os geochronological constraints were obtained on the Madagascar Dabolava gold occurrence
- Two gold deposition events have been highlighted.
- The type 1 concordant veins in amphibolites yield a 1961±79Ma Palaeoproterozoic age.
- The Type 2 discordant veins yield a 533±23 Ma Pan-African age which favours an orogenic gold style.
- A Palaeoproterozoic age is favoured for the whole Ikalamavony sub-domain.