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Airborne magnetic data compared to petrology of crustal scale shear zones from southern Madagascar: A tool for deciphering magma and fluid transfer in orogenic crust

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ABSTRACT

The southern part of Madagascar consists of a granulitic metamorphic belt with a complex Proterozoic shear zone network. Aeromagnetic maps reveal sharp magnetic spatial gradients, especially across shear zones. All shear zones are associated with high magnetic values, except one, the Beraketa shear zone. Based upon relationships between rock magnetic properties, petrographic and aeromagnetic data, we show that the magnetic signal is controlled by variations in proportions of iron-rich oxides. Their nature and texture are variable and complex. Magnetite and ilmenite are often observed together showing intergrowths texture, suggesting possible lamellar magnetism. Detailed petrographic observations of the Zazafotsy shear zone show that a strong magnetic signal is correlated with metamorphic reactions and especially with biotite breakdown to peritectic phases such as orthopyroxene and iron-rich oxides (metamorphic charnockitization). Magmatic material can migrate easily inside the Zazafotsy shear zone and inside the fold hinges close to the shear zone, increasing the kinetics of charnockitic reaction. In opposition, inside the Beraketa shear zone, lower magnetic values are correlated with the absence of iron-rich oxides. This is interpreted as back reaction melting. Thus, peritectic phases, such as iron-rich oxides, react with the water released when magmas crystallise to produce biotite. Inside the Zazafotsy shear zone, iron-rich oxides are stable because part of the migmatite was segregated and escaped with dissolve H_2O. In this case, back reaction was no longer possible.

1. Introduction

Regional magnetic surveys are a powerful method to complement geological mapping (Nabighian et al., 2005). The magnetic properties of rocks (induced and remanent) are controlled by iron-bearing minerals and especially iron-bearing oxides (Clark, 1997). Textures, grain size, metastable remanent magnetization or lamellar magnetism of rocks play a role in controlling bulk rock magnetic properties (the magnetic petrology, Clark, 1997; McEnroe et al., 2009). The remanent magnetic record is also a witness of a specific magnetic field over time (normal or reverse magnetic field) for a given place. Rocks with strong reverse-polarity remanence can produce negative magnetic anomalies (Nabighian et al., 2005). All these parameters make it difficult to establish a straight relationship between regional magnetic maps and the lithology in the field.

For example, airborne magnetic surveys have been used in India to map geometry of volcanic traps, tectonic units, shear zones and iron ore deposits (Anand and Rajaram, 2003; Mishra and Vijaya Kumar, 2005; Rajaram et al., 2003; Reddy et al., 1988). Interesting relationships linking metamorphism and magnetic anomalies have been identified in the Kerala where charnockites (group II, Ramachandran, 1990) show strong magnetic susceptibility. This correlation allowed the regional mapping of prograde metamorphism from amphibolite to granulite facies since Fe-Ti oxides together with orthopyroxene are produced at the expense of hornblende or biotite. Thus, the orthopyroxene isograd could be mapped at the regional scale using magnetic surveys (Harikumar et al., 2000; Rajaram et al., 2003). In Madagascar, similar observations have been made where the magnetic susceptibility of rocks increases with increasing charnockitization. Magnetic susceptibilities of samples from north-west of Antananarivo allowed

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identifying influxes of CO_2-rich fluid in the field (Rakotondrazafy et al., 2006). Using new aeromagnetic maps, we extend this approach to the south of Madagascar where a kilometric shear zone network is observed (Martelat et al., 2000). We bring new constraints on the origin of the regional magnetic signal by comparing it to meter-scale outcrops, thin sections observations and rocks magnetic susceptibilities. This study provides a new example of deciphering large magma and fluid transfers in orogenic crust from regional geophysical data for the specific case of Madagascar.

2. Geological setting

The studied magnetic data covers a wide part of Madagascar with a complex geological history that began in the Neoarchean (Fig. 1). Most of this region is made up of Precambrian rocks and different domains have been proposed by several authors since the sixties (Malagasy-French geological survey), mainly based on lithology and geochronology. Among the variously defined geological units, we choose to use here the nomenclature of Tucker et al. (2011). In addition to the Vohibory lithotectonic domain, they defined several other important geological domains: (1) Antananarivo, (2) Itremo-Ikalamavony, (3) Anosyen, and (4) Androyen. Vertical granulitic shear zones (SZ) can be mapped within all these domains. Some of them are close to these domain's limits (Beraketa, Ampanihy) and could constitute their boundaries. However, others are located inside the domains (Zazafotsy, Tranomaro, Fig. 1). These shear zones are named : Ejeda, Ampanihy, Beraketa (also named Vorokafotra, Rolin, 1991), Ihosy, Zazafotsy, Tranomaro (Martelat et al., 2000; Randrianasolo, 2009) and Ifanadiana; the latter representing a southward prolongation of the Angavo SZ (Nédélec et al., 2000; Windley et al., 1994). They usually show steeply dipping foliations and sub-horizontal lineations. This set of anastomosed SZ is north–south striking and developed in a transpressive regime under east–west continental convergence. The N150°–160°-trending of Bongolava-Ranostara shear zone or Ranotsara zone (Hottin, 1976; Martelat et al., 2000; Randrianasolo, 2009; Schreurs et al., 2010) corresponds to the sinistral deflection of the set of north–south SZ by indentation of a rigid buttress represented by Antananarivo domain. The Ranotsara zone is difficult to map as it coincides with kilometric faults and relief with similar strikes ("Ranotsara Bongolava fault line" Bazot, 1975; Hottin, 1976). This set of anastomosing SZ is dated at around 570 and 535 Ma and reached granulitic metamorphism (Ackermand et al., 1991; JICA, 2012; Jöns, 2006; Martelat, 1998; Nicollet, 1988, 1990; Rasoamalala et al., 2012a, 2012b) and ultra-high temperature (UHT) metamorphism in some places (T: 950–1000 °C and P: 8–11 kbar, Jöns and Schenck, 2011; Martelat et al., 2012; Nirihaja et al., 2010), followed by a decompression at high temperatures. The exact beginning and duration of this granulitic event are not well constrained. The problem of age determination has two causes: first, this event closely follows a previous high-amphibolite to granulite facies metamorphism (650–600 Ma, Jöns and Schenck, 2011). Secondly, it is partly overprinted by Cambrian metamorphism and late Cambrian or younger low grade fluid circulation (Berger et al., 2008; Giese et al., 2011). In some places, Precambrian rocks are covered or intruded by volcanic sequences belonging to the Cretaceous (the thick elliptic Androy volcanic massif with 1.7 km of basalt lavas and 1.1 km of rhyolite lavas, Fig. 1, Mahoney and Nicollet, 1991; Rasamimanana et al., 1998; Rechenmann, 1982), with some kilometric dyke networks (Boulanger, 1957; Randrianasolo, 2009). The opening of the Mozambique channel produced vertical displacements associated with the development of sedimentary basins such as the Morondava basin, located westward, beyond the aeromagnetic cover. They display a sequence 4–8 km thick (Karoo trough, Fig. 1, Besairie and Collignon, 1972; Coffin and Rabinowitz, 1988). The last geological events are related to late quaternary sediments and an especially efficient laterization (red soil) can be observed locally.

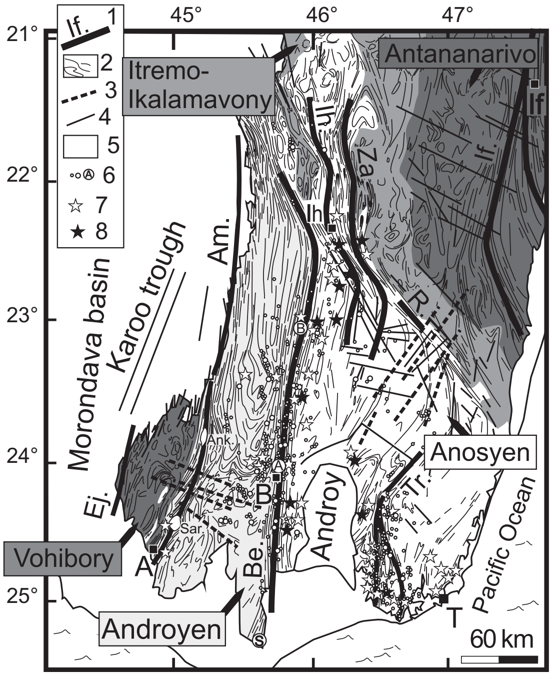

Fig. 1. Simplified geological map of southern Madagascar and km-scale SZ network, modified from Martelat et al. (2000), Nédélec et al. (2000), Randrianasolo (2009), Rolin (1991), Windley et al. (1994). Domains: Antananarivo, Itremo-Ikalamavony, Vohibory, Androyen and Anosyen, are from Tucker et al. (2011). R. = Ranostara deflexion; (1) major kilometric SZ: If. = Ifanadiana; Ej. = Ejeda, Am. = Ampanihy, Be. = Beraketa, Ih. = Ihosy, Za. = Zazafotsy; Tr. = Tranomaro; (2) foliation trajectories; (3) dykes; (4) major faults; (5) Palaeozoic sediments and volcanics; (6) small and big phlogopite deposit (Besairie, 1966), circle with a letter indicate main mines close to Beraketa SZ (A = Ampandrandava, B = Benato, S = Sakamasy); (7) 850 °C spinel – quartz paragenese (Jöns, 2006; Martelat, 1998; Nicollet, 1988, 1990); (8) UHT parageneses (orthopyroxene–sillimanite–quartz, saphirine–quartz, osumilite, Jöns, 2006; högbomite, Nirihaja et al., 2010; ductile garnet, Martelat et al., 2012). Ank. and Sar. localize two main anorthositic bodies Ankafotia and Saririaky inside Ampanihy SZ. A: Ampanihy, B: Beraketa, T: Tôlanaro, If: Ifanadiana, Ih: Ihosy towns.

3. Magnetic data and regional geology

3.1. Aeromagnetic data processing

Aeromagnetic data covering 289.677 km^2 were obtained by the BPGRM (Base de Données Pour la Gouvernance des Ressources Minérales) in 2005–2007 (Fig. 2). They were acquired by Fugro airbone surveys at an elevation of 100 m above the ground, along east–west flight lines with 500 m spacing. The total magnetic intensity was gridded with a resolution of 100 m. Data were corrected for diurnal variation and the Earth's main field was subtracted (International Geomagnetic Reference Field IGRF, Fig. 2, Nabighian et al., 2005). The resulting corrected data correspond to the magnetic anomaly, which is observed to vary between −3319 to 6357 nT. It clearly highlights the geological trends as well as lithologies such as the southern anorthosites (Saririaky, Ankafotia). Data were filtered to emphasize specific geological features like volcanic dykes, not shown here (Randrianasolo, 2009). In this study we preferentially produced maps without complex filtering as we prefer to look at absolute magnetic values. We used magnetic anomaly for regional geology (Figs. 2 and 3), and reduction to the pole for local studies (Figs. 4 and 8) the scale at which we