Petrostructural Signature of the Monazite of Andoharano
Ambatofinanadrahana, Madagascar

Dieudonné Razafimahatratra¹ and Alfred Andriamamonjy²
1. Ecole Normale Supérieure, University of Antananarivo, BP 881, Madagascar
2. Sciences of Earth and Environment, Faculty of Sciences, University of Antananarivo, BP 906, Madagascar

Abstract: The monazite deposit at Andoharano is 7 km NE of Ambatofinanadrahana. It is in the form of filons of hydrothermal chalcedony origin both with monazite and barite, which intersects the small syenitic post-tectonic massif, aged 550 to 510 Ma. The syenite is part of the Ambalavao-Kiangara-Maevaranomagmatic suite located in the Itremo sub-domain. The mineralized filon’s length is approximately 100 meters with an average thickness of 2 to 5 meters, direction N75 and a subvertical dip. It is characterized by the mineralogical association of monazite, chalcedony, barite, quartz and magnetite. Two deformation phases affect the emplacement of the deposit. The first phase corresponds to the crystallization of the automorphic monazites, while the second phase affects the filon which leads to the fracturing of the first through silicification and which leads to the formation of the small xenomorphic monazite crystals. The monazite appears as brownish spots scattered in the rocks. It is rich in ceric earth (32% to 33%) and low in thorium. It constitutes ceric earth ore in the region.

Key words: Monazite, syenite, ceric earths, chalcedony, Andoharano.

1. Introduction

The Ambatofinanadrahana region is known for its richness in rare earth mineralization for a very long time. Various studies have been conducted in this area, namely, Lacroix [1, 2] who studied Ifasina and Ambatofangehana rare earth minerals, and Ambatoarinamonazite, it is mineralization related to syenitic pegmatites; Guiges [3] worked on the pegmatites of Madagascar, including Ambatofinanadrahana rare earth mineralization, for this author, the mineralization is linked to Cambrian granitic pegmatites, in addition to syenitic pegmatites; Fournie [4] carried out a detailed study of the various deposits as part of the skarn mission in the region, this study proposes a hydrothermal origin of mineralization; Cerny [5] reported that Ambatofinanadrahana bastnaesite indices are related to intrusive veins; new mineralogical and chemical studies were conducted by Rasoamalala [6] in collaboration with the University of Toulouse. As a result, several Ambatofinanadrahana rare earth deposits deserve to be re-examined; chief among them is the Andoharano Monazite vein, which is the objective of this study.

2. Generalities on Monazite

2.1 Mineralogical Characteristics

Monazite is a PO₄ rare earth and thorium orthophosphate (rare earth, Th) particularly resistant to chemical agents. It was described for the first time by Lévy [7] under the name tumèrite. It was Breithaupt [8] who gave it its current name (from the Greek monozein = to be alone, to mark the originality of the mineral). Monazite is always in crystalline form in the monoclinic system. The crystals have very varied facies often having prismatic or rhombic appearance (Figs. 1A and 1B). It presents as elongated crystals along (001) and flattened on (001) with frequently rough, curved or striated faces. Monazite crystals are usually twinned according to (001) (twin...
in gutter) [9]. The alluvial monazites have faces rounded by wear (Fig. 1C) [10]. They are generally in translucent, shiny resinous with its color ranging from light yellow to brown (honey color) and even black, sometimes also reddish or greenish reflections [11]. From the optical point of view, the crystals are strongly birefringent. The density ranges from 4.9 to 5.3; it mainly depends on the thorium content, a very heavy element. The hardness is around 5.2 and 5.5.

2.2 Monazite Deposits in Madagascar

Madagascar’s rare earths (REEs) are found in various deposits, namely: (1) primary deposits such as monazite mineralization of anosyenne chains, granitic and peri-granitic veins, stockworks (greisen) and Cenozoic alkaline complexes; (2) secondary deposits such as inland placers, beach sands and offshore monazite (Taolagnaro) placer [12] (Fig. 2).

Monazite can be in the form of microscopic crystals disseminated in ancient crystalline rocks, granites, syenites, diorites, etc., or their metamorphic varieties (particularly migmatitic gneisses). In these same plutonic rock formations, veins of pegmatitic origin frequently contain massive monazite veins, where the mineral can be in the form of very large crystals. Very large monazite crystals are found at Manangotry, near Taolagnaro, Madagascar [10]. As an alteration-resistant mineral, monazite can form deposits

Fig. 1 Monazite crystals at Manangotry, Taolagnaro Madagascar [10]: A—Monazite crystal rhombic appearance, B—Various facies of monazite crystals, C—alluvial monazite.
of alluvial sands or coastal beaches which are the most interesting from an industrial point of view, because of the easy exploitation of the ore, among them include the deposits of monazite-ilmenite-zircon sand from the extreme South-East of Madagascar [13]. Monazite is the main rare earth ore, especially the
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3. Regional Geological Context

Madagascar is made up of two main formations. It is the Precambrian crystalline basement that occupies 2/3 of the oriental island, and the Quaternary Permian sedimentary formations that cover one-third of Western Island [14-16]. The Precambrian basement of Madagascar is subdivided into six major geological domains [12, 17], namely: the Antongil-Masora domain, the Antananarivo domain and the Itremo subdomain, the Ikalamavony domain, the Androyen-Anosyen domain, the Bemarivo domain and the Vohibory domain (Fig. 3).

The Antananarivo domain consists of old sedimentary and eruptive formations that have been transformed into graphite-rich crystalline-branded schists, paragneiss and orthogneiss as well as basal and ultrabasic rocks by various degrees of metamorphism in successive orogenies. This set is intersected by three magmatic suites: Dabolava suite (1,000 Ma), Imorona-Itsindrosuite (820-760 Ma) and Ambalavao-Kiangara-Maevaranosuite (570-520 Ma) [7].

Andoharano monazite deposit is located in the Itremo subdomain belonging to Antananarivo domain. This sub-domain is constituted by a para-metamorphic series of Schists, Quartzites and Cipolins, hence its name “SQC group”. It is Paleoproterozoic 2,500 to 1,600Ma [12, 18]. It is intersected by magmatic suites of the Imorona-Itsindro and Ambalavao-Kiangara-Maevarano types, made of gabbros, syenites and granites respectively (Fig. 4).

3.1 Quartzite

Quartzites and quartz arenas of the Itremo Group are homogeneous with some clay loaves, which are sometimes thick. Many sedimentary features have been conserved as laminae, wave lines, oblique and intertwined stratifications or rare current laminae [19]. Some conglomerates may exist and consist of rolled or drawn in a vitreous matrix with recrystallized quartz medium grain. These beds are usually 2 to 3 meters thick and are in contact with micaschists.

3.2 Schists

This pelitic unit is dominated by finely rolled argilites and siltstones, as well as biotite-muscovite schists and phyllites [19]. When the degree of metamorphism is lower, the pelitic units correspond to beds of schists, siltstone and fine-grained sandstones, but if the degree of metamorphism is higher, schists and fine-grained phyllites are observed with muscovite-biotite with or without garnet.

3.3 Cipolins

Carbonated rocks exist at the stratigraphic summit of the Itremo Group [20]. Two major facies are recognized with a white stromatolite marble and a sandy brown marble. These rocks consist of calcite and dolomite, quartz, tremolite, diopside, biotite, peridot, phlogopite, microcline, and sulphide disseminations with pyrite, chalcopyrite, and galena [19].

3.4 Orogenic and Post-Orogenic Magmatic Suites

3.4.1 Imorona-Itsindro Suite

It is very present in the Itremo subdomain [12]. This sequence dates back between 820 to 760 Ma. It generally shows a compositional bi-modality which made it possible to define two sub-suites. Imorona-type acidic granitoids have compositions ranging from granite (alkaline) to quartz syenite, whereas basic Itsindro varieties evolve either into gabbro-diorite and gabbronorite [12].

3.4.2 Ambalavao-Kiangara-Maevarano Suite

These are late- and post-tectonic plutons with a general semi-circular or stratoid appearance and they date back between 550 and 510 Ma [12]. The majority of these plutonic bodies are porphyroblastic. This suite ranges from syenites to granites. There are also
Fig. 3 Geological formations of Madagascar [12].
granodiorites, anorthosites and gabbros. Some varieties have orthopyroxene and therefore define charnockites. The Andoharanosyenite is one of these post-tectonic rocks.

4. Description of the Deposits

The Andoharanosyenite is a small massif which is located 7 km NE of Ambatofinandrahana. It is a circumscribed and intrusive massif in the surrounding marbles (Fig. 5).

The syenite is homogeneous, and sometimes shows an alteration into balls. It has leucocratic and granular structures, with microcline slats visible to the naked eye and punctuated by millimetric pyroxene and amphibole spots (Figs. 6A and 6B). We can also note the presence of millimeter sphene crystals. The syenite is composed of very abundant microcline and perthitic orthoses, albite, biotite, pyroxene and amphibole in millimetric spots, interstitial quartz, sphene, accessory minerals such as zircon, monazite and apatite [21].

The surrounding marbles have fine-grained, white colors. They are essentially formed of calcite associated with some large crystals of tremolite (Fig. 6C).

The monazite deposit is formed by a vein of brown silicified rocks (chalcedony) with monazite and barite that intersect the syenite. This chalcedony filon is well
individualized in the topography (Fig. 5A). It has a direction N75 sub-vertical dip, a hundred meters long, 2 to 5 meters thick. The contacts of the chalcedony vein with the host syenite are clear. Overall, the filon is deformed and is characterized by the presence of dextral shear and banded texture (Fig. 7). This texture is marked by the alternation of brown chalcedony and white barite bands. On such outcrops, small elongated druses, arranged parallel to the filon, can also be seen in siliceous levels. In some places, this filon has a “brecci” or “tubule” texture that consists of angular-section barite strips (Fig. 6D).

The strain field in the SQC group corresponds to a superposition of two distinct deformation phases [22]. The first (D1) would be associated with the tectonic contact overlapping at the SQC-based interface of the Antananarivo domain (around 800 Ma) while the second deformation phase (D2) is characterized by the development of shear zones and a sub-meridian vertical axial plane folding during the final Gondwana to Late Neoproterozoic and early Cambrian assemblage. This late phase is related to fluid circulation events that are connected to the emplacement of pegmatite veins in the region.

Fig. 5  A, B and C—outcrop mode of monazite-mineralized chalcedony vein in the syenite.
Fig. 6  Structure of the Andoharanosyenite; A—syenite block, B—macroscopic structure of rock, C—marble with tremolite, D—chalcedony seam with brechoid texture.

The formation of the monazite deposit corresponds to the second phase of deformation (D2) which takes place in several stages. The structural context for the emplacement of the mineralized vein is summarized as follows (Fig. 8):

(1) Emplacement of the small syenitic Andoharano massif during the pan-African orogeny. It could be derived from the process of magmatic differentiation of basic magma in a surrounding carbonate environment.

(2) Afterwards, the syenite has undergone opening fracturing which favors the circulation of hydrothermal fluids at low temperature leading to the emplacement of mineralized chalcedony filon. This is the first phase that corresponds to the crystallization of automorphic monazites.

(3) A second phase of deformation affects the filon which causes the shear formation and fracturing of the first monazite type; this process is related to silicification leading to the formation of small xenomorphic crystals of monazite.

The block diagram in Fig. 9 shows a metallogenic model of monazite chalcedony seam formation intersecting Andoharanosyenite.

5. Mineralogical Characteristics of Monazite

5.1 Mineralogical Description

Monazite occurs as small brownish spots scattered in the rock or grouped by level (Fig. 10). Some of these monazites can reach up to 5 mm long. However, on average, their size is 1 mm. Using an SPP2 counter, the filon has been identified with values up to 3,000 cps [21], while the host syenites have a bottom of 250
Fig. 7  Dextral shear mesostructure in the chalcedony filon.

Fig. 8  Schematic synthesis (outcrop on the left and synthetic cut on the right) of the structural context of the emplacement of the mineralized filon; A—intrusion of syenite into the marble, B—fracturing of the syenite and emplacement of the mineralized chalcedony filon during an east-west compression phase, C—deformation of the chalcedony filon associated with the dextral shear.
to 300 cps. These radio-activities show the presence of Thorium in the monazites. The mineralized rocks are characterized by the following mineralogical association: monazite, chalcedony, barite, quartz and magnetite.

Microscopic observation of the Mn1 sample shows a succession of dark chalcedony levels and clear barite levels. They are associated with opaque iron oxides. On the bottom of chalcedony and barite, the monazite stands out clearly by its high birefringence and its size of 0.5 to 2 mm. Monazite crystals come in two forms:

(1) Automorphic to sub-automorphic crystals that have a beginning of corrosion and micro-fracturing (Figs. 11A and 11B). The crystals sometimes have inclusions of opaque minerals with reddish weathering products.

Xenomorphic crystals, are smaller than the automorphic crystals (Figs. 11C and 11D). They probably result from automorphic crystal fracturing.

5.2 Chemical Composition

Table 1 shows the results of chemical analyses of the Andoharano monazite and those of Manangotry (Taolagnaro) Madagascar, which are considered as the world’s outstanding monazite deposit, as well as the
average content of the earth crust’s rare earth oxides of “classical monazite” as a reference value.

The average P_{2}O_{5} values range from 24.60% to 28.52% which are similar to the average large-crystal content of Manangotry monazite (26.41% to 26.49%) and that of classical monazite (20% to 30%), whereas the silica content is low; this indicates that the environment is favorable for the concentration of light rare earths such as cerium.

The thorium content of the Andoharano monazite is low (0.29% to 0.45%) compared to the conventional monazite (6.70%) and very low compared to those of Manangotry which are highly radioactive monazite, with a content of 11.89% to 13.57%. This low thorium content indicates that it is hydrothermal monazite [23].

For rare earths, Andoharano monazite has a high cerium content (32.14% to 33.13%) compared to that of Manangotry (28.09% to 28%) and is close to classical monazite (35%). They are ceric monazites that are rich in rare light earths.

The ratio La/Nd is around 2.01 to 2.37 which is a high value compared to conventional monazite (1.41). This places Andoharano monazite in alkaline monazites. This is consistent with the spatial relationship on the ground where the monazite showings are carried by veins that cross the syenites.

Fig. 11 Photomicrograph of monazite mineralized facies: A and C = natural light, B and D = polarized light. Clc = chalcedony; Brt = barite; Mnz = monazite; Mop = opaque minerals [24].
Table 1  Chemical analyses of some monazite deposits [24].

| Label                        | Andoharano-Ambatofinandrana | Manangotry-Taolagnaro | Monazite classique de l’écorce terrestre [25] |
|------------------------------|------------------------------|------------------------|-----------------------------------------------|
| Samples                      | Mnz1                         | Mnz2                   | Mnz3                                          | DN11 | DN12 |                  |
| La₂O₃                        | 18.07                        | 22.67                  | 21.05                                         | 14.22 | 13.82 | 24.00            |
| Ce₂O₃                        | 32.14                        | 33.13                  | 32.57                                         | 28.71 | 28.09 | 35.00            |
| Nd₂O₃                        | 8.98                         | 9.55                   | 9.33                                          | 9.43  | 9.90  | 17.00            |
| Sm₂O₃                        | 0.79                         | 0.98                   | 0.87                                          | 1.30  | 0.92  | 2.50             |
| Eu₂O₃                        | 0.07                         | 0.05                   | 0.03                                          | -     | -     | 0.05             |
| Gd₂O₃                        | 0.16                         | 0.46                   | 0.69                                          | 0.37  | 0.37  | 1.50             |
| Dy₂O₃                        | 0.05                         | 0.00                   | 0.02                                          | 0.03  | 0.00  | 0.70             |
| Er₂O₃                        | 0.01                         | 0.00                   | 0.01                                          | -     | -     | 0.20             |
| Yb₂O₃                        | 0.01                         | 0.00                   | 0.00                                          | -     | -     | 0.10             |
| Y₂O₃                         | 0.04                         | 0.02                   | 0.02                                          | 0.16  | 0.15  | 2.40             |
| SiO₂                         | 0.63                         | 0.78                   | 0.34                                          | 1.86  | 1.98  | -                |
| CaO                          | 0.13                         | 0.12                   | 0.13                                          | 0.94  | 1.04  | -                |
| P₂O₅                         | 24.60                        | 27.38                  | 28.52                                         | 26.41 | 26.49 | 20 to 30         |
| UO₂                          | 0.00                         | 0.01                   | 0.00                                          | 0.15  | 0.33  | 0.30             |
| Th                           | 0.45                         | 0.29                   | 0.36                                          | 11.89 | 13.57 | 6.70             |

6. Conclusions

The Monazite filon study of Andoharano brings complementary scientific information to the understanding of rare earth mineralization in the Ambatofinandrana region. First, the petrographic examination showed that there were two types of monazite crystals, some automorphic, and the other smaller xenomorphic, derived from the first by fracturing. These two forms can be explained as follows: the automorphic monazite crystallized first, and during the silicification it was fractured and corroded in part. The presence of low grade thorium indicates that the Andoharano monazite has a hydrothermal character. The paragenesis of the vein (chalcedony, barite, monazite) and the free contacts between the filons with the syenites show that the deposit is of epithermal nature (temperature around 200 °C). The emplacement of the Andoharano monazite deposit is related to the circulation of hydrothermal fluids that are associated with opening fractures within the syenite. Andoharano monazite is a terrestrial phosphate that is considered rare earth minerals.

Acknowledgments

This research is part of the development of outstanding metallogenic deposits of the subdomain of Itremo in the central region of Madagascar. Thanks to Zafiarisoa Régina Liziane and Rakotonirina Belarin for the translation into English of this article. We also thank all the colleagues in the field, in particular Rakotoarisoa Daniel and the students of the Higher Normal School.

References

[1] Lacroix, A. 1915. “La bastnæsite et la tscheffknite de Madagascar.” Bull. Soc. Franc. Min. 38: 106-25.
[2] Lacroix, A. 1922. “Minéralogie de Madagascar, Tome II, Minéralogie Appliquée Lithologie.” In Libraire Maritime Étcoloniale, edited by Challamel, A., Paris, 80-92.
[3] Guigues, J. 1954. “Etude des gisements de pegmatites de Madagascar.”
[4] Fournie, L. 1968. “Les gisements de terres cériques de la région d’Ambatofinandrana” Possibilités en Europium. Rapport inédit du BRGM 68 TAN 2.
[5] Cerný, P. 1993. “Rare-element granitic pegmatites. Part I. Anatomy and internal evolution of pegmatite deposits.” In Ore Deposit Models, Volume II, edited by Sheahan, P. A. Cherry, M. E., Geoscience Canada Reprint Series, 29-47.
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[6] Rasoamalala, V. 2009. Les Minéralisations en Terres Rares liées aux syénites et granites d’Ambatofinanadrahana. Rapport Final, Projet de Gouvernance des Ressources Minérales (PGRM), Ministère des Mines et des Hydrocarbures, Contrat n° 98/04 - MEM/SG/DG/UCP/PGRM, 156.

[7] Levy. 1823. *Ann. Phil. Thomson*, 21-241 (à compléter).

[8] Breithaupt. 1829. Schw. J. 55-311.

[9] Ni, Y., Hughes, J. M., and Mariano, A. N. 1995. “Crystal Chemistry of the Monazite and Xenotime Structures.” *Am. Mineral.* 80: 21-6.

[10] Razafimahatratra, D. 2008. *La Monazite des Chaines Anosyennes: des Gisements en Place Aux sables de plages à ilménite-zircon-monazite.* Université d’Antananarivo Ecole Supérieure Polytechnique Département Mines, Thèse de Doctorat, 319.

[11] Montel, J.-M., Razafimahatratra, D., Ralison, B., De Parseval, P., Michel Thibault, M., and Randranja, R. 2011. “Monazite from Mountain to Ocean: A Case Study from Trolognaro (FortDauphin), Madagascar.” *European Journal of Mineralogy* 23: 745-57.

[12] Tucker, R. D., Peters, S. G., Roig, J. Y., Théveniaut, H., and Delor, C. 2012. “Notice explicative des cartes géologiques et métallogéniques de la République de Madagascar à 1/100000.” Ministère des Mines, Antananarivo, République de Madagascar, 263.

[13] Razafimahatratra, D., and Montel, J.-M. 2011. “La monazite des chaines Anosyennes: des gisements en place aux sables de plages ailménite-zircon-monazite: [Abs].” Géologie et Métallogénie de Madagascar Société géologique de France, Paris, 6-7 décembre.

[14] Besaire, H. 1967. “The Precambrian of Madagascar.” In *The Precambrian*, vol. 3, edited by Rankama, K. London: Wiley Interscience, 133-42.

[15] Besaire, H. 1970. “Description géologique du massif ancien de Madagascar. Quatrième volume: La Region Centrale 2, Le Système du Vohibory, Série schisto-quartzo-calcaire, Groupe d’Ambatamalpy, Documentation du Bureau Géologique n177d, Service Géologique, Tananarivo.” Ministère de l’Industrie et des Mines, Direction des Mines et de l’Énergie, 86.

[16] Hottin, G. 1976. “Présentation et essai d’interprétation du Précambrien de Madagascar.” Bulletin du Bureau de Recherches Géologiques et Minières 4: 117-53.

[17] Roig, J. Y., Tucker, R. D., Delor, C., Peters, S. G., and Théveniaut, H. 2012. “Carte géologique de la République de Madagascar à 1/100000.” Ministère des Mines, PGRM, Antananarivo, République de Madagascar.

[18] Cox, R., Coleman, D. S., Chokel, C. B., DeOreo, S. B., Wooden, J. L., Collins, A. S., Krner, A., and DeWaele, B. 2004. “Proterozoic Tectonostratigraphy and Paleogeography of Central Madagascar Derived from Detrital Zircon U-Pb Age Populations.” *The Journal of Geology* 112 (4): 379-99. doi:10.1086/421070.

[19] Moine, B. 1974. “Caractères de sédimentation et de métamorphisme des séries précambriennes épizônales à catazonaux du centre de Madagascar (Région d’Ambatofinanadraha), Approche structurale, pétrographique et spécialement géochimique.” Thèse de Doctorat é Sciences Naturelles. Université de Nancy I, France, 293.

[20] Lenoble, A., 1936a. “Sur la découverte d’une faune et d’une flore fossiles dans les formations schisto-calcaires du centre de Madagascar.” *C.R. Acad. Sci. Paris* 202: 674-5.

[21] Andriamampihantona, M. J. 1984. “Contribution à l’étude du complexe alcalin d’Ambatofinanadraha et de ses minéralisations à lanthanides (Région centrale de Madagascar).” Thèse des Doctorat é Sciences Naturelles. Université Joseph Fourier-Grenoble I, 191.

[22] Fernandez, A., Schreurs, G., Villa, I. M., Huber, S., and Rakotondrazafy, M. 2003. “Age Constraints on the Tectonic Evolution of the Itremo Region in Central Madagascar.” *Precambrian Research* 123 (2-4): 87-110.

[23] Cuney, M. 1981. “Comportement de l’uranium et du thorium au cours du métamorphisme : rôle de l’anatexie dans la génèse des magmas riches en radioéléments.” Thèses d’Etat, INPL, Nancy, 511.

[24] Razafimahatratra, D., Andrianaivo, L., Andriamamonjy, A., and Andriamifidisoa, M. 2018. “Étude métallogénique de la monazite d’AndoharanoAmbatofinanadraha, Madagascar.” *MADA-HARY* 7: 16-25. ISSN 2410-0315.

[25] Vlasov, A. 1966. Statistical Distribution Functions. Nauka.