

Petrology and Geochemistry of the Granitic Rocks from the Itremo Domain, Central Madagascar

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Received February 08, 2022; Revised March 10, 2022; Accepted March 17, 2022

Abstract Granitic rocks of the Ibity, Tsarasaotra, and Ambatofinandrahana areas of the Itremo domain, in the Precambrian basement of Madagascar were characterized by using the naked eye, microscopic observations, and whole rock chemical analyses with the aim of understanding their petrogenesis, their interrelations, and their membership in the known magmatic suites in the Itremo domain. The granitic rocks of this study are mainly composed of monzonitic rocks for the Tsarasaotra and granite for the other areas. Major minerals identified are alkali feldspars, quartz, plagioclase, and accessory minerals are amphiboles, micas, pyroxene, iron-titanic minerals, titanite, and epidote. Major element compositions are intermediate for the Tsarasaotra monzonitic rocks and felsic for the other rocks. All the studied rocks are silica-saturated with enough aluminum, ferroan, calc-alkalic to alkalic, metaluminous, rarely peraluminous, I-type granitic rocks. Transition elements contents are generally low for the granites and high for the monzonitic rocks, while the compositions of compatible elements are in general high. Chondrite-normalized patterns of REE show high enrichment of LREE and low to moderate enrichment of HREE. The behaviors of major elements (especially Ti, Al, Fe, Mn, Mg, and Ca oxides) and trace elements (Eu anomaly, La/Sm) in the studied rocks show magmatic differentiation signatures in relation to crystal fractionation. These rocks' magmatic sources were most likely enriched-MORBs that evolved through within-plate enrichment for the Tsarasaotra monzonitic rocks and Ifasina granite, and through subduction for the Ibity granite, Tsarasaotra granite dyke, and Antsahakely granite. The succession of these two different processes identified in the studied rocks reveals their membership in the Imorona-Itsindro. Although some of the studied rocks are adakite-like, their characteristics as well as their interrelations indicate magmatic differentiation signatures rather than slab-melting origin. This work is a contribution to the promotion of scientific and geologic research in Madagascar, and it is in perspective of its extension to the geochemical characterization of laterites and mineralization potential identification related to the studied rocks in the Itremo domain as well as in the Antananarivo domain of Madagascar's Precambrian basement.

Keywords: *geochemistry, petrology, rocks, mineral, granite, monzonitic, Itremo, Ibity, Tsarasaotra, Ambatofinandrahana, Ifasina, Antsahakely, Imorona-Itsindro, magmatic, adakitic*

Cite This Article: Désiré Alphonse Rakotonravaly, and Roger Randrianja, “Petrology and Geochemistry of the Granitic Rocks from the Itremo Domain, Central Madagascar.” *Journal of Geosciences and Geomatics*, vol. 10, no. 1 (2022): 31-44. doi: 10.12691/jgg-10-1-3.

1. Introduction

The Itremo domain is located in the center-south of Madagascar, in the western part of the Ambatofinandrahana district. As it is overlaid with the Antananarivo domain, it is classified by [1] and [2] as a subdomain of the Antananarivo domain in the tectonic subdivision of Madagascar. Like the Antananarivo domain, in the central part of Madagascar, the Itremo subdomain is marked by several Neoproterozoic age intrusive rocks, which are the Imorona-Itsindro suite (800 - 780Ma) and the Ambalavao-Maevarano suite (580-520Ma) [3,4,5].

Ambatofinandrahana and Ibity areas are famous in the Itremo subdomain for their mineral potentials and attract the attention of researchers to better understand their

geology. Ambatofinandrahana (“worked stones” in the Malagasy language), located in the central part of the Itremo subdomain, owes its name from its richness in stones and rocks. Its potential and productivity in gemstones and semi-precious stones, in particular, have been reported [6], with some of it thought to be related to the Imorona-Itsindro complex (e.g., [5]), which geographically and geologically extends to the Ambositra area. As for the Ibity area, located in the northeastern part of the Itremo group, it is also known to be one of the mineral richest zones in Madagascar. The famous Sahatany valley pegmatite field, in particular, is very productive in various pegmatite semi-precious and precious stones (see [7,8]). Because of those mineral potentials, the interest of [9] recently brought them to the new mineral species discovery, and that of [10] led to the investigation of a secondary blue tourmaline in the

Sahatany pegmatite field. In addition, those mineral potentials are the main reason why the “Société d’Exploitation et de Valorisation du Marbre et du Cipolin d’Ambatofinandrahana” or SEVMACAM (1973-1990) was succeeded by the “Marbre et Granite de Madagascar” or MAGRAMA (1990-2013) in operating the Ambatofinandrahana marble quarries [11], as well as the operation of the cement factory for more than 60 years in the Ibity town [12].

Several investigations were conducted in those areas concerning the Imorona-Itsindro suite [2,5,13,14,15,16] and the Ambalavao suite [1,2,4,5]. Still, the petrogenetic interpretation related to these suites remains somewhat controversial. In particular, the proposed tectono-magmatic configurations at the origin of the Imorona-itsindro suite emplacement are disputed between arc-magmatism and an intraplate extension magmatism followed by lithospheric subduction and arc-magmatism. In addition, the geographical distribution of both the Imorona-Itsindro and Ambalavao suites in the Itremo subdomain draws the attention to the membership of the granitic rocks in that subdomain as well as their possible relationships.

This work is a contribution to that research, and will focus on the study of the granitic rocks from the Ibity Antsirabe, Tsarasaotra-Ambositra, and Ambatofinandrahana areas

within the Itremo subdomain by using geological, petrologic, and geochemical approaches. The aims of this work are mainly to understand their magmatic origins and their interrelations.

2. Geological Setting

Madagascar’s geology is generally divided into three main divisions: the crystalline basement, occupying about two thirds in the central and eastern parts of the Island; the sedimentary formation, around one third in the western parts of the Island, and intrusive/extrusive rocks visible in the first two divisions [18,19,20,21].

2.1. Precambrian Terrane of Madagascar

In general, the Precambrian terrane of Madagascar is geologically divided into two by the Ranotsara Shear Zone: the northern part is composed of Archean rocks, and the southern part is mainly occupied by Proterozoic rocks [21]. Madagascar is divided into nine (09) tectonometamorphic domains, such as Antongil, Antananarivo, Tsaratanàna, Betsimisaraka, Bemarivo, Itremo, Ikalamavony, Anosyen-Androyen, and Vohibory domains [22,23]. References [1] and [2] provide a detailed description of each domain.

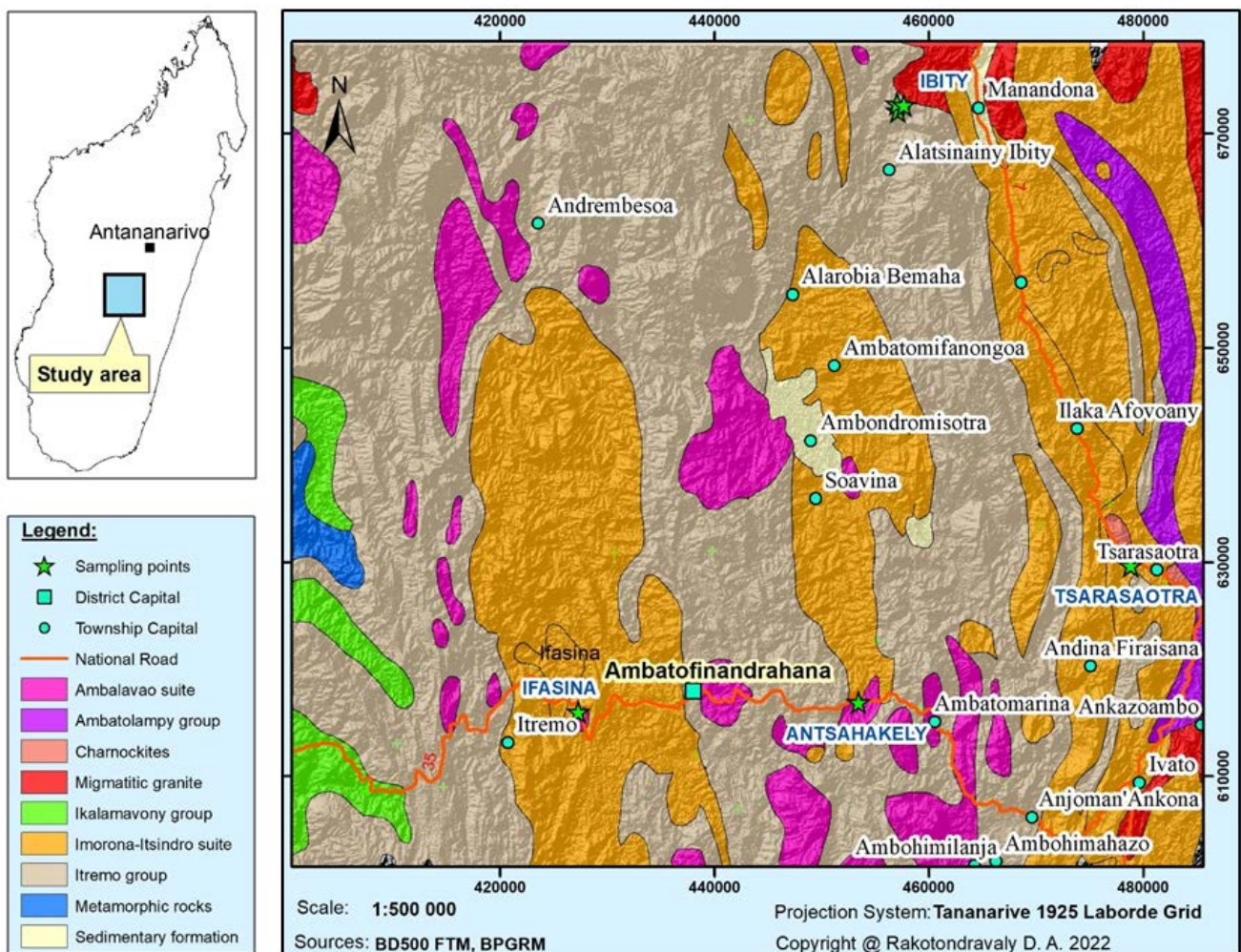


Figure 1. (Top left)- Map of Madagascar showing the study area; (right)-Simplified geologic map of the Itremo domain after [1,2,5] and [17] with sampling points of this study.

2.2. Itremo Domain

The Itremo subdomain consists of parametamorphic formations composed of schist, quartzite, and cipolin known as the Schisto-Quartzo-Dolomite formation, or Itremo group. Schistes are fine-grained pseudo-slates which appear as an ensemble of marked plane schistous quartzo-mica or as a homogenous micaschist bench. Quartzite, occupying the main part of this group, appears in metric to decametric interstratified trays within the other facies of the group. Mostly, these facies show sedimentary figures such as intertwined stratifications, ridges, conglomerate levels, and itacolumite levels [24,25]. The Itremo group is intruded by two magmatic events: the Imorona-Itsindro and the Ambalavao suite [1].

The Imorona-Itsindro suite is composed of basic facies of gabbro and diorite compositions, and granitic facies typical of calco-alkaline porphyritic massive granite [4,24,26]. One part of this suite, the Imorona rocks, was retransformed into orthogneiss during the metamorphism and recognized as facies of amphibole orthogneiss, syenitic orthogneiss, and leptynitic orthogneiss [24]. The Tonian (850-750Ma, [17,27]) suite of Imorona-Itsindro is thought to have been emplaced during continental extension and plutonic activities between 840 and 760Ma [28]. Reference [13] proposed that these Neoproterozoic rocks (around 790Ma) were emplaced at the time or preceding the Rodinia supercontinent separation within an Andean-type magmatism setting. However, recent works by [2] and [29] have questioned the supra-subduction origin of the Imorona-Itsindro suite [30]. Recent research proposed two age domains for the Imorona-Itsindro suite: (i) plutonic rocks with delamination crustal signatures, asthenosphere upwelling, and crustal extension before 747Ma, and (ii) lithospheric subduction and arc magmatism around and after 729-727Ma [16].

The Ambalavao suite consists of alkali-potassic plutonic formations which include massive intrusive and dykes intruding into the old crystalline basement and the Itremo group [4,31]. The Ambalavao suite (580-540Ma, [17,32,33]) represents mainly the granitic magmatism during the descending stage of the Gondwana amalgamation with the Maevarano suite (537-522Ma, [17,32,33]). These plutonic suites correspond temporally and spatially with Neoproterozoic shear zones and are intimately associated with deformations and intense regional metamorphism. Reference [34] assigned these 580-520Ma magmatic events to the effects of the continental collision between East and West Gondwana. Recent work proposed that the Ambalavao and Maevarano suites were formed in Madagascar during a late syn to post-collisional magmatism [33].

3. Sampling and Analytical Techniques

Field research and sample collection were carried out in the outcrops of Ibity (around 20.049°S/46.983°E), Tsarasaotra Ambositra (20°26'15.7" S/47°11'35.1" E), Antsahakely (20°33'14.8" S/46°57'01.6" E), and Ifasina Itremo (20.56°S/46.70°E). Thirteen (13) granitic rock samples were selected for observations and laboratory work.

Petrographic characterizations were conducted by naked eye observations of rock samples and rock-slabs combined with microscopic observations of slide glass-covered thin sections using a NIKON ECLIPSE 50i microscope.

Whole rock major element and some trace elements (Ba, Co, Cr, Nb, Pb, Sr, Ta, Y, and Zr) analyses were conducted using a Rigaku ZSX Primus II and a Rigaku Primini MJ09-00 X-ray fluorescence spectrometer. Rocks were powdered and dried overnight in a drying oven at 110°C to measure the absorbed water. Powdered rocks were also heated at 900 °C for 3 hours and 30 minutes to measure the loss on ignition (LOI). Heated powder samples were mixed with fluxes and fused to make glass beads with a Bead Sampler NT-2100. Other whole rock trace element concentrations were analyzed using an Agilent Technologies 7500 Inductively Coupled Plasma Mass Spectrometer (ICP-MS). 0.1g of finely ground powder samples were put in a Teflon container and digested on a hot plate using perchloric acid, hydrofluoric acid, and nitric acid. After the digestion, 1000 times the dilution of the solution samples were prepared by using nitric acid and ultrapure distilled water. 10.000 times dilution samples were prepared by diluting 10 times more than the 1000 times dilution samples. Three types of solutions were prepared for each sample: blank solution, standard-free solution, and standard-added solution. The quality of the analyses was monitored by simultaneously preparing and analyzing Japanese standard rock samples.

Both microscopic observations and whole rock analyses were carried out at the Faculty of International Resource Sciences of Akita University, Japan.

4. Petrography

4.1. Ibity Granite

Ibity granitic rocks are mainly leucocratic holocrystalline pseudo-idiomorphic grainy granite (Figure 2). They are classified into granite after the [35] classification scheme (Figure 3). Ibity granite is essentially composed of plagioclase (33.0-43.5%), alkali feldspar (27.4-36.5%), and quartz (25.2-30.2%). Mafic silicate minerals have a modal composition of less than 2%. Other accessory minerals are magnetite (0.30-0.55%), apatite (less than 0.10%), ilmenite (0.14-0.20%), and a trace of zircon.

4.2. Tsarasaotra Main Rocks

In Tsarasaotra, two granitic rock types are found: the principal granitic rock is intruded by a granite dyke. Tsarasaotra's principal granitic rocks are mesocratic holocrystalline hypidiomorphic rocks having a medium to coarse-grained texture (Figure 2). They are classified into monzonite and quartz monzonite according to [35] (Figure 3). They are mainly composed of plagioclase (46.3-49.7%), alkali feldspar (28.5-31.2%) and mafic silicate minerals (9.25-14.3%). Accessory minerals are quartz (1.51-7.17%), magnetite (2.08-2.51%), ilmenite (2.02-2.39%), apatite (1.69-1.85%) and zircon (less than 0.20%).

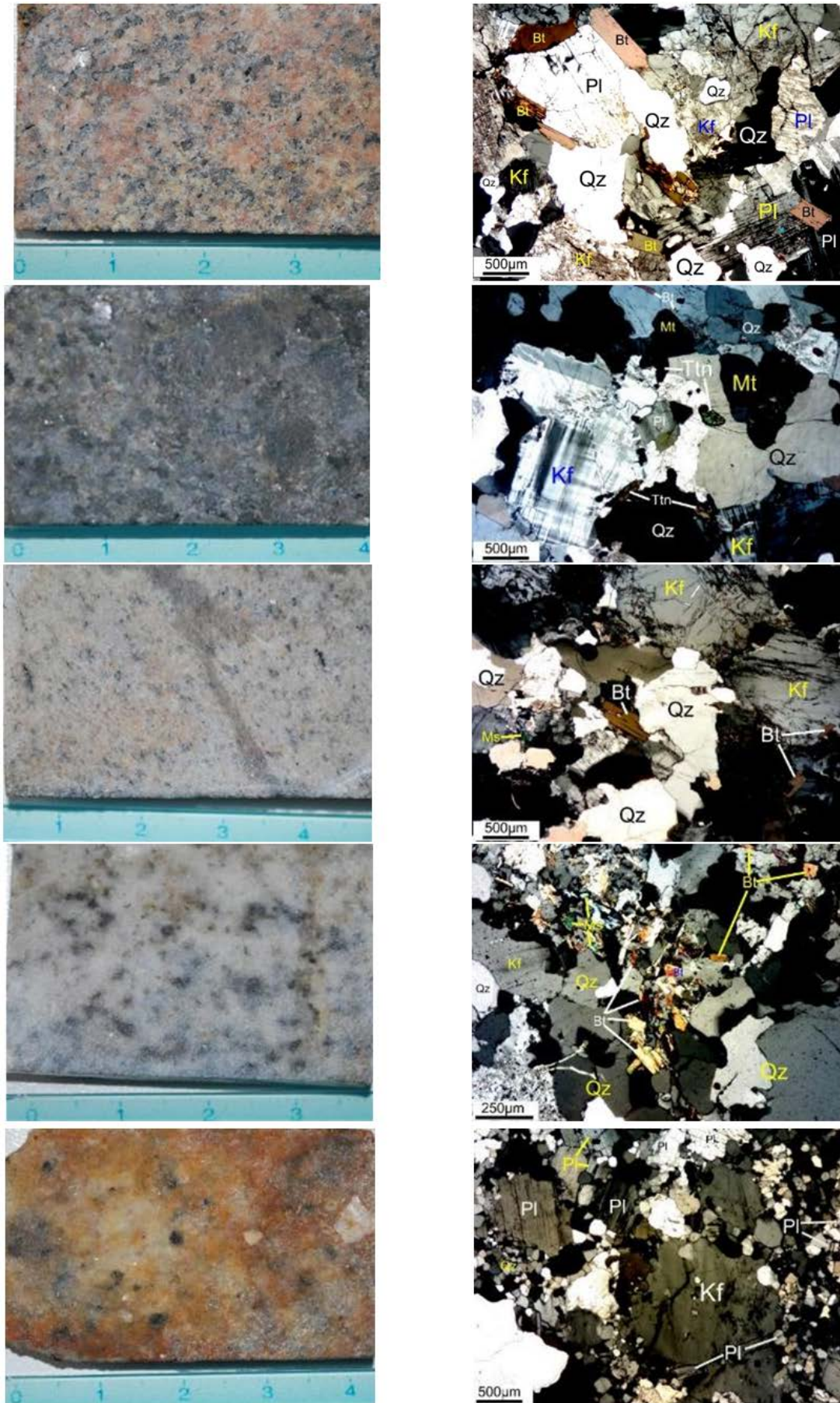


Figure 2. Representative of photo(left) and crossed-polarized light microphotographs (right) of studied rocks. From top to bottom: Ibity granite, Tsarasaotra monzonitic rock.; Tsarasaotra granite dykes, Antsahakely granite, and Iremo granite.

4.3. Tsarasaotra Granitic Dykes

Tsarasaotra granitic dykes are leucocratic holocrystalline pseudo-idiomorphic coarse-grained rocks (Figure 2). They are classified as granite after [35] (Figure 3). These rocks are essentially made of plagioclase (33-35%), alkali feldspar (33-35%), and quartz (26-30%). Mafic silicate minerals are between 1.5 and 2%. Other accessory minerals are magnetite (about 0.5%), apatite (about 0.1%), ilmenite (about 0.2%) and zircon in trace.

4.4. Ambatofinandrahana Granitic Rocks

In the Ambatofinandrahana area, the sampling locations at Antsakakely, near the town of Fiadanana in the east of Ambatofinandrahana, and at Ambohimanantahotra in the south of Ifasina Itremo in the west of Ambatofinandrahana township, were considered. Ambatofinandrahana granitic rocks are leucocratic holocrystalline hypidiomorphic medium to coarse grained rocks (Figure 2). They are classified into granite according to [35] (Figure 3). These rocks are essentially composed of plagioclase (42-48%), alkali feldspar (24.5-28%) and quartz (21.5-32%). Other minerals include mafic silicate minerals (1-1.5%), magnetite (approximately 0.5%), apatite (approximately 0.3%), ilmenite (0.7%), and zircon in trace amounts.

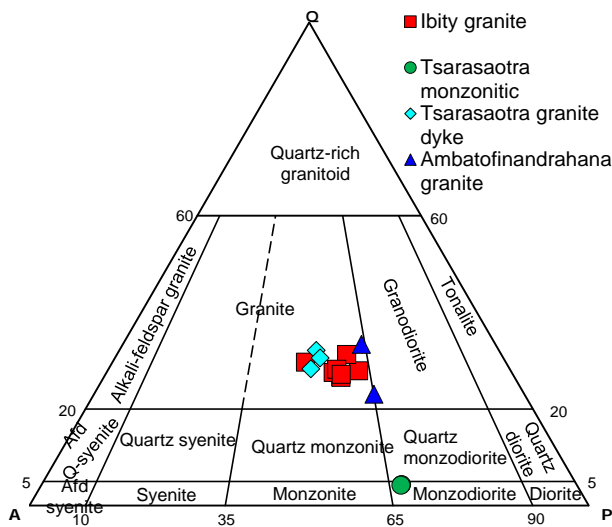


Figure 3. Quartz-Alkali Feldspar-Plagioclase (QAP) classification diagram of intrusive rocks in the IUGS system after [36].

5. Whole Rock Geochemistry

5.1. Major and Minor Elements

The major oxide ranges of the Ibity granite are as follows: high SiO_2 (72.7-74.8wt%), low TiO_2 (0.1-0.2wt%), $\text{T-Fe}_2\text{O}_3$ (1.3-2.5wt%), MnO (0.03-0.05wt%), MgO (0.1-0.3wt%), CaO (0.5-1.0wt%) and P_2O_5 (0.03-0.05wt%), slightly higher Al_2O_3 (13.0-14.1wt%), and intermediate Na_2O and K_2O (Na_2O =3.62-4.58wt% and K_2O =4.42-5.74wt%) relative to normal (Table 1).

The Tsarasaotra monzonitic rocks have major oxide compositions of intermediate SiO_2 (54.8-57.1wt%), high

TiO_2 (1.8-2.0wt%), Al_2O_3 (14.8-15.6wt%), $\text{T-Fe}_2\text{O}_3$ (8.7-10.3wt%), MnO (0.13-0.17wt%), MgO (2.0-2.4wt%), CaO (4.0-5.3wt%), and P_2O_5 (0.81-0.88wt%), and intermediate Na_2O (3.43-4.15wt%) and K_2O (3.77-4.57wt%) (Table 1).

The Tsarasaotra granite dykes have a high range of SiO_2 (73.0-75.0wt%), low TiO_2 (0.1-0.2wt%), $\text{T-Fe}_2\text{O}_3$ (1.4-2.3wt%), MnO (0.02wt%), MgO (0.1-0.2wt%), CaO (1.1wt%) and P_2O_5 (0.02-0.05wt%), and slightly higher Al_2O_3 (13.2-13.6wt%) relative to normal and intermediate Na_2O (3.53-3.71wt%) and K_2O (5.34-5.36wt%) (Table 1).

The Ambatofinandrahana granites have a high silica contents (SiO_2 =73.3-76.0wt%), a low TiO_2 , $\text{T-Fe}_2\text{O}_3$, MnO , MgO , CaO and P_2O_5 contents (TiO_2 = 0.1wt%; $\text{T-Fe}_2\text{O}_3$ =1.2-1.3wt%; MnO =0.01-0.02wt%; MgO = 0.1-0.2wt% and CaO =0.7-1.3wt% and P_2O_5 =0.02wt%, respectively), slightly higher Al_2O_3 than normal (Al_2O_3 =13.6-13.7wt%) and an intermediate Na_2O (4.22-5.49wt%) and K_2O (3.99-4.44wt%) (Table 1).

The classification diagram of [37] shows that the Ibity granite and the Tsarasaotra granite dykes are distributed in the alkaline granite field (SiO_2 =72.7-74.8wt%; $\text{Na}_2\text{O}+\text{K}_2\text{O}$ =8.8-9.6wt% and SiO_2 =73.0-75.0wt% ; $\text{Na}_2\text{O}+\text{K}_2\text{O}$ =8.9-9.3wt%, respectively), the Tsarasaotra monzonitic rocks are within the monzonite field (SiO_2 =54.8-57.1wt% ; $\text{Na}_2\text{O}+\text{K}_2\text{O}$ =7.9-8.1wt%), and the Ambatofinandrahana granites distribute in the granite and alkaline granite fields (SiO_2 =73.3-76.0wt% ; $\text{Na}_2\text{O}+\text{K}_2\text{O}$ =8.2-10.0wt%) (Figure 4).

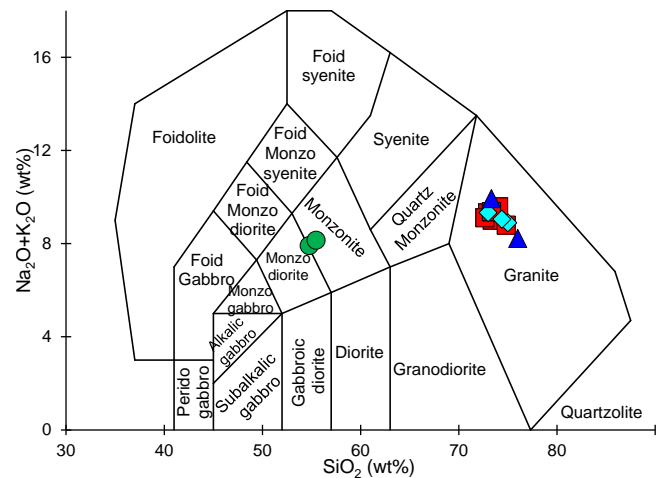


Figure 4. Total Alkali versus Silica (TAS) diagram for plutonic rocks after [37]. Designations follow Figure 3.

The Alkalinity Index (AI) versus Feldspathoid-Silica Saturation Index (FSSI) diagram after [38] and [39] shows that all the studied rocks are silica saturated ($\text{FSSI}>1,1$) with alkalinity indexes adequate to excessive ($\text{AI}>0$) (Figure 5a). The studied rocks are all ferroan, according to the $\text{FeO}/(\text{FeO}+\text{MgO})$ versus SiO_2 diagram after [38] and [39] (Figure 5b). The Modified Alkali-Lime Index (MALI) diagram of [38] and [39] displays alkali rocks for the Tsarasaotra monzonitic ($\text{MALI} = 1.9-5.0$), alkali-calcic for the Ibity granite ($\text{MALI} = 8.0-9.0$), and calc-alkalic to alkali-calcic for the Tsarasaotra granite dykes and the Ambatofinandrahana granites ($\text{MALI} = 7.8-8.2$; and $\text{MALI} = 6.9-9.3$, respectively) (Figure 6).

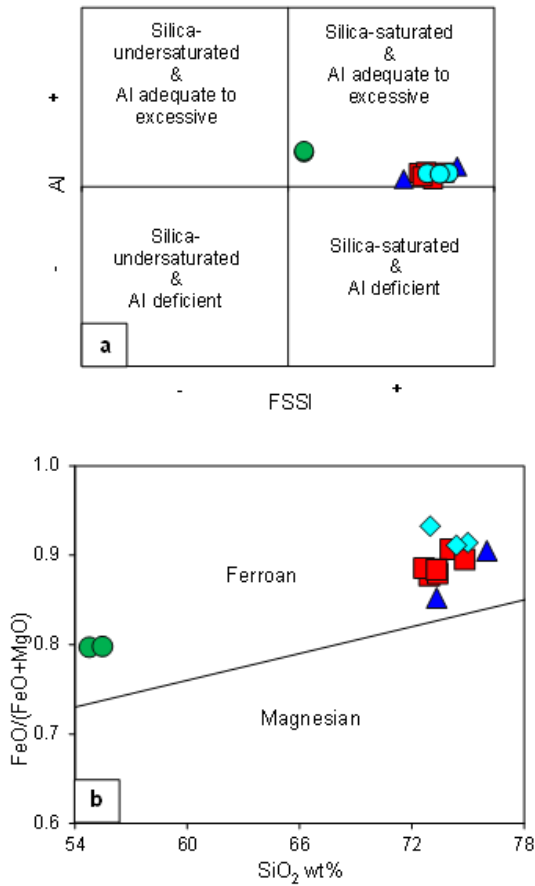


Figure 5. a)-Normative Feldspathoid Silica-Saturation Index (FSSI) versus molecular Alkalinity Index (AI); b)- Fe-Index versus SiO₂ after [38] and [39]. FSSI= $Q-[Lc-2(Ne+Kp)]/100$. (AI after [40]). Designations follow Figure 3.

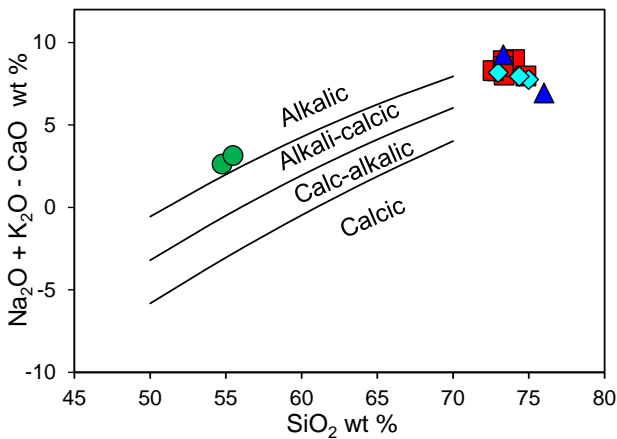


Figure 6. Modified Alkali Lime Index (MALI) diagram after [38] and [39]. MALI=Na₂O+K₂O-CaO; AI=Al-(K+Na). Designations follow Figure 3

The Aluminum Saturation Index (ASI) diagram of [41] displays metaluminous and peraluminous for the Ibyty granite, while metaluminous for the other studied rocks (Figure 6). The K₂O versus SiO₂ diagram of [42] and [43] shows that the Ibyty granite (SiO₂=72.7-74.8wt%; K₂O=4.4-5.7wt%), the Tsarasaotra granite dykes (SiO₂=73.0-75.0wt%; K₂O=5.3-5.7wt%), and the Ambatofinandrahana granites (SiO₂=73.3-76.0wt%; K₂O=4.0-4.4wt%) are within the high K calc alkaline series, while the Tsarasaotra monzonitic is among the

shoshonite series (SiO₂=54.8-57.1wt% ; K₂O=3.8-4.6wt%) (Figure 7).

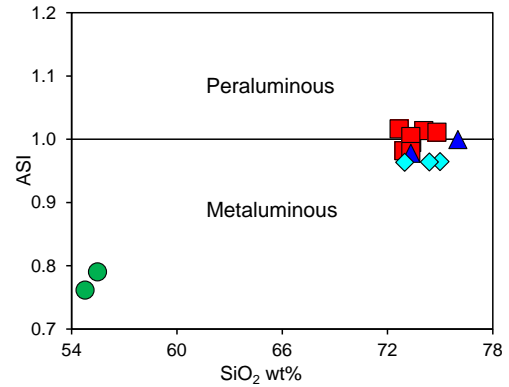


Figure 7. Alumina Saturation Index (ASI) molar versus SiO₂ diagram after [41]. ASI=Al/(Ca-1.67P+Na+K) (ASI after [40]). Designations follow Figure 3.

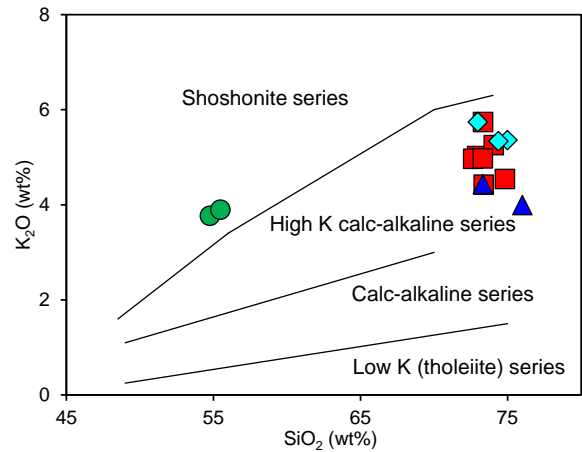


Figure 8. K₂O versus SiO₂ diagram: boundaries after [42] and nomenclature after [43]. Designations follow Figure 3.

The variation diagrams of [44] show a systematic decrease of Ti, Al, Fe, Mn, Mg and Ca with the increase of SiO₂. It is also observed that the Tsarasaotra monzonitic rocks formed in a less evolved environment relative to which the Ibyty granite, the Tsarasaotra granite dyke, and the Ambatofinandrahana granites were formed (Figure 10). These diagrams display that the Tsarasaotra granite dykes are chemically close to the Ibyty granite in terms of major and minor elements' behavior.

5.2. Trace and Rare Earth Elements

The Ibyty granite has relatively low compositions in V(14.4-23.0ppm), Cr(2.62-5.20ppm), Cu(1.30-10.9ppm) and Ni(1.93-10.1ppm); high concentrations in Sr(88-354ppm), Zr(127-226ppm), Ba(304-1305ppm) et Rb(243-503ppm); and varied contents in Nb(6.6-38ppm) and Y(17.0-100ppm). Ni, Zr, Rb, Nb and Y contents rapidly vary while Cr and Cu decrease with the increase of SiO₂; V and Sr contents stay relatively constant (Table 1 and Figure 10). MORB-normalized trace element patterns display LILE enrichment such as Rb (122-151), K (29.5-38.3) and Ba (15.2-65.3); excessive depletion of P (0.25-0.42) and Ti (0.09-0.13); moderate enrichment of Nb (4.64-11.35) and Ce (8.54-21.0) as well as normal

abundances of Sr (0.73-2.95) and Y (0.57-3.35) relative to MORB (Figure 9).

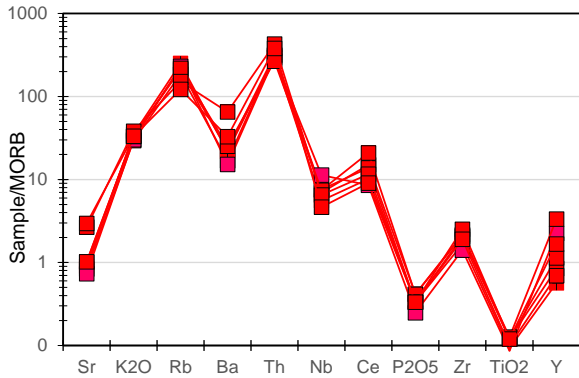


Figure 9. N-MORB trace element multidiagrams of the Ibity granite.

The Tsarasaotra monzonitic rocks have low compositions in Cr(0.15-4.32ppm), Cu(5.23-10.8ppm), Ni(0.82-3.66ppm) Zr(19.1-32.7ppm), Y(14.4-56.2ppm) and Rb(21.9-113ppm), relatively high contents in Sr(235-1089ppm), Ba(536-3428ppm) and Nb(29-48ppm), and varied contents in V(40.3-130ppm). Consequent variations of V, Sr, Nb, and Y compositions are observed for a narrow range of SiO₂ contents, while constant variations of Zr and light decrease of Cu, Cr, and Ni contents are observed with the increase of silica content (Table 1 and Figure 10). MORB normalized trace elements patterns show a moderate to high enrichment of Ba (26.8-171), a moderate enrichment of K (25.1-30.5), Rb (11.0-56.7), Th (10.5-12.9) and Ce (13.4-29.6), and a low to moderate enrichment of Sr (1.96-9.08) and P (6.74-7.33); depletion of Zr (0.21-0.36) relative to MORB; Ti (1,17-1,37) and Y (0,48-1,87) vary around the normal abundances of MORB (Figure 11).

Table 1. Whole rocks major (in wt%) and trace elements (in ppm) compositions of selected samples

wt%/ppm	Ibity							Tsarasaotra					Ambatofinandrahana	
	IB-6	IB-7A	IB-8	IB-9A	IB-14	IB-15	IB-16A	Monzonitic		Granite dykes			ANH-1	IT-3-2
SiO ₂	72.9	73.4	74.1	74.8	72.7	73.3	73.3	54.8	55.5	75.0	73.0	74.4	76.0	73.3
TiO ₂	0.18	0.18	0.14	0.13	0.19	0.18	0.15	2.05	1.97	0.13	0.16	0.15	0.07	0.07
Al ₂ O ₃	14.1	14.0	14.0	13.5	13.8	13.0	13.8	14.8	15.3	13.2	13.6	13.3	13.6	14.7
T-Fe ₂ O ₃	2.45	2.19	1.72	1.32	2.14	2.38	2.03	10.3	9.91	1.42	2.31	1.94	1.27	1.22
MnO	0.04	0.05	0.04	0.04	0.05	0.04	0.03	0.16	0.15	0.02	0.02	0.02	0.02	0.01
MgO	0.31	0.27	0.16	0.14	0.25	0.28	0.24	2.36	2.26	0.12	0.15	0.17	0.12	0.19
CaO	1.04	0.98	0.61	0.82	0.81	0.46	0.82	5.29	5.00	1.14	1.15	1.10	1.29	0.67
Na ₂ O	4.29	4.58	4.32	4.25	4.14	3.62	4.40	4.15	4.25	3.53	3.59	3.71	4.22	5.49
K ₂ O	5.03	4.42	5.25	4.54	4.97	5.74	4.98	3.77	3.90	5.36	5.74	5.34	3.99	4.44
P ₂ O ₅	0.05	0.04	0.04	0.03	0.05	0.04	0.04	0.88	0.81	0.02	0.05	0.04	0.02	0.02
H ₂ O	0.04	0.02	0.01	0.02	0.02	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.06	0.05
LOI	0.24	0.16	0.28	0.62	0.45	0.19	0.08	0.05	0.06	0.22	0.21	0.06	0.32	0.24
Total	101	100	101	100	100	99.3	100	98.6	99.1	100	100	100	101	100
Li	50.3	48.1	71.7	53.4	51.1	26.2	20.1	14.2	18.4	8.85	12.5	10.6	51.4	3.46
Be	6.73	8.22	7.55	13.1	11.1	4.77	3.61	2.59	2.82	3.55	3.53	2.78	3.34	1.49
Sc	2.34	2.35	1.02	1.94	2.18	0.92	0.66	12.9	12.5	0.06	0.71	0.45	0.17	0.46
V	16.4	14.8	13.9	14.4	19.7	23.0	22.7	130	119	24.2	13.0	23.6	6.40	15.8
Cr	5.20	3.20	2.62	2.86	3.73	4.32	4.21	3.22	4.35	1.94	1.53	2.46	2.96	3.36
Co	1.86	1.21	1.13	0.89	1.99	1.99	1.30	14.0	13.0	1.02	1.31	2.36	0.84	3.73
Ni	4.38	2.01	5.62	10.1	1.93	4.68	4.53	2.74	2.75	5.21	3.09	3.35	4.82	1.43
Cu	10.8	5.50	10.1	1.30	10.9	8.00	4.10	4.40	8.16	1.60	1.90	3.20	3.11	5.10
Zn	42.0	49.3	43.1	50.2	65.3	40.8	33.8	192	175	19.7	42.5	28.8	17.8	16.7
Ga	20.4	23.0	19.6	22.1	22.4	17.6	17.6	23.8	23.8	16.0	18.7	16.3	14.5	14.7
As	3.68	1.15	0.63	1.23	2.94	1.44	0.75	3.43	2.18	0.68	1.77	1.57	1.95	1.22
Rb	423	372	503	461	438	303	243	75.4	113	214	232	231	155	95.2
Sr	121	100	108	87.8	122	320	354	1089	1033	339	321	308	114	735
Y	25.4	34.0	17.0	67.3	100	50.2	20.8	56.2	48.1	6.10	13.8	7.00	11.8	5.30
Zr	195	185	149	127	190	226	171	1173	1174	106	133	57	104	67.4
Nb	15.0	22.7	15.5	37.8	27.6	18.6	6.60	47.5	47.5	0.70	1.70	5.26	8.40	0.20
Cs	7.01	9.11	11.2	12.6	7.28	7.13	5.97	0.37	1.15	4.26	4.97	5.15	7.48	0.35
Ba	458	338	434	304	503	1305	657	3428	3427	1156	909	787	338	1346
La	82.5	104	57.2	88.9	197	93.9	47.7	137	121	5.0	111	75.3	14.5	5.84
Ce	151	138	102	85	210	116	91	296	270	7.60	215	134	38.8	9.71
Pr	14.9	19.1	10.6	17.4	34.7	18.6	9.29	34.4	31.8	0.76	20.7	13.9	2.89	1.11
Nd	45.9	60.9	32.6	60.9	109	59.6	29.3	141	132	2.56	63.0	41.2	10.3	3.62
Sm	6.70	9.40	5.10	11.0	16.6	10.3	4.79	23.7	22.6	0.42	8.31	4.65	2.43	0.52
Eu	0.72	0.77	0.59	1.60	1.97	1.40	0.55	5.77	5.75	0.68	1.26	0.91	0.44	0.16
Gd	6.12	7.73	4.65	10.8	16.4	9.31	4.41	19.7	18.3	0.38	6.70	3.63	2.67	0.47
Tb	0.67	0.90	0.54	1.55	2.34	1.27	0.50	2.10	1.99	0.04	0.62	0.24	0.39	0.05
Dy	3.54	4.78	2.87	9.06	13.7	7.21	2.64	9.98	9.60	0.20	2.78	0.98	2.32	0.27
Ho	0.68	0.98	0.56	1.85	2.78	1.40	0.52	1.66	1.61	0.04	0.50	0.15	0.45	0.06
Er	1.98	2.93	1.59	5.36	7.60	4.07	1.46	4.01	3.98	0.13	1.30	0.41	1.30	0.16
Tm	0.31	0.44	0.24	0.84	1.04	0.62	0.23	0.50	0.50	0.02	0.19	0.06	0.20	0.02
Yb	1.95	2.76	1.47	5.63	6.03	4.10	1.50	2.56	2.53	0.17	1.17	0.37	1.33	0.20
Lu	0.32	0.44	0.24	0.91	0.90	0.65	0.23	0.38	0.37	0.04	0.20	0.07	0.20	0.03
Hf	9.20	8.20	8.90	8.30	9.30	10.3	8.90	18.0	18.1	8.60	9.60	8.30	9.00	8.30
Ta	2.45	1.35	1.78	7.13	31.9	4.19	2.44	2.09	1.88	0.32	1.37	0.40	0.91	0.31
Th	63.6	61.9	59.4	58.5	53.5	85.6	76.2	2.58	2.41	42.7	59.1	30.9	27.2	0.30
U	12.6	10.3	10.4	14.3	11.1	11.5	14.1	0.49	0.98	3.30	4.79	1.84	3.45	0.44
Pb	16.0	15.8	15.7	17.4	15.9	15.3	12.3	17.0	16.3	14.7	11.7	14.0	11.9	18.0

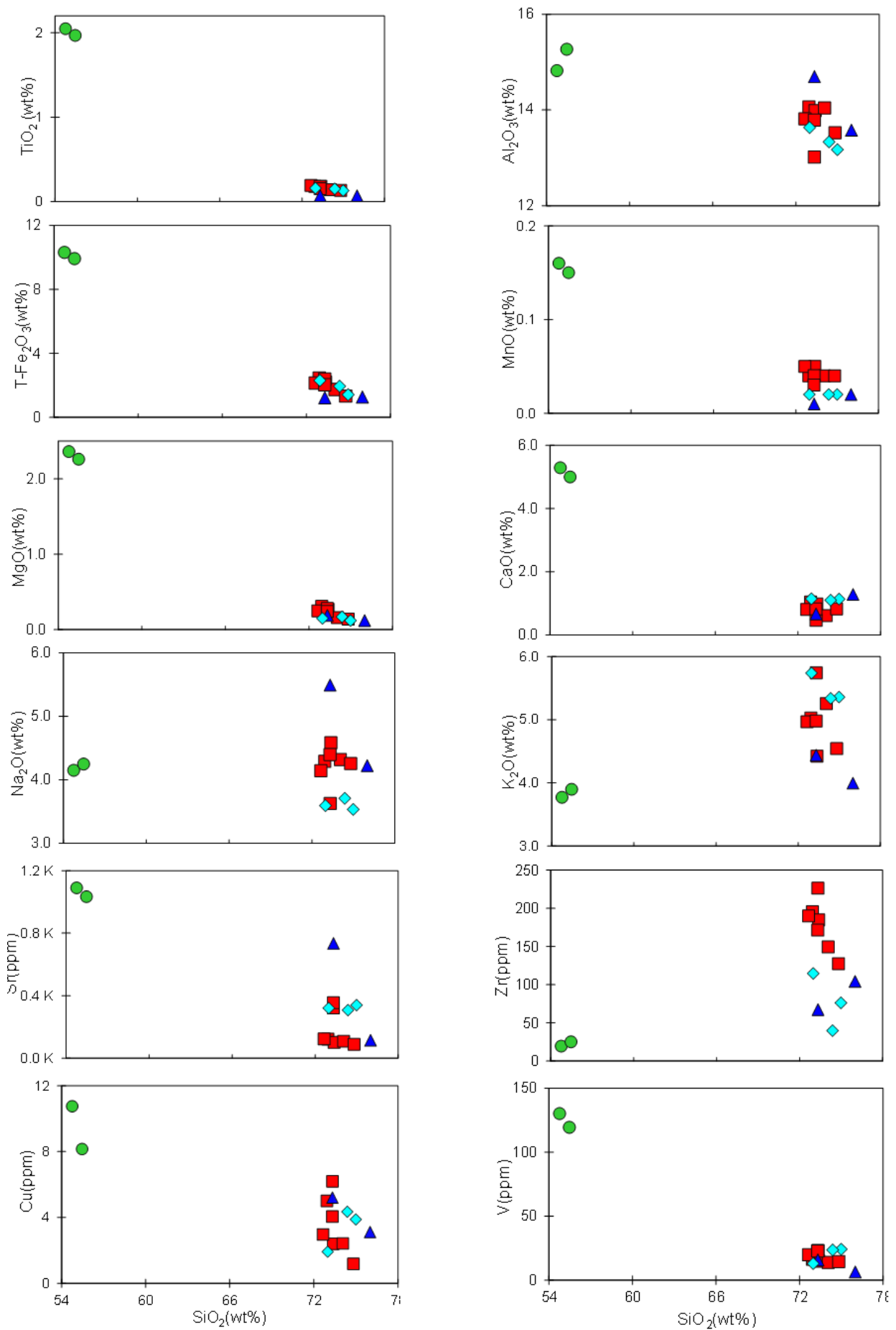


Figure 10. Variation diagrams of [44] for major elements and representative trace elements. Designations follow Figure 3.

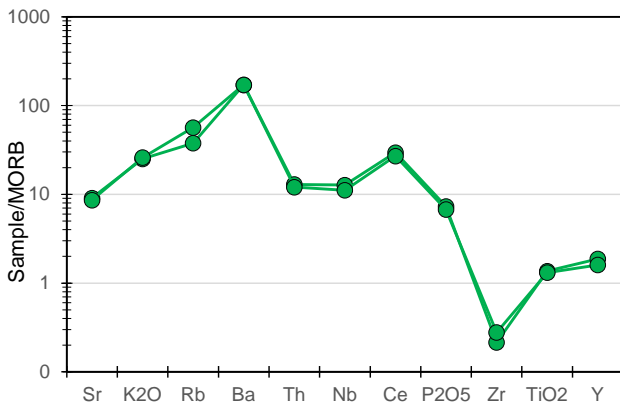


Figure 11. N-MORB trace element multi-diagrams of the Tsarasaotra monzonitic rocks.

The Tsarasaotra granite dykes have low contents in V(13.0-24.2ppm), Cr(1.53-1.94ppm), Cu(1.92-4.35ppm), Ni(3.09-5.21ppm), Nb(0.7-5.3ppm) and Y(6.10-13.8ppm); high contents in Sr(308-339ppm), Ba(787-1156ppm) and Rb(214-232ppm), and varied compositions in Zr(39.9-115ppm). These rocks display low variations of V, Cr, Cu, Ni, Ba, Zr, Nb and Y contents in function of SiO₂(Table 1 and Figure 10). MORB normalized incompatible element spectra show general enrichment of LFSE (Sr>>Th) such as K (35.6-38.3), Rb (107-116), Th (155-296), with negative anomalies of Ba (39.3-57.8) and Nb (1.52-3.09), and depletion of HFSE (Nb, P, Zr, Ti, Y) such as P (0.17-0.42) and Ti (0.09-0.11), with positive anomalies of Y (0.20-0.46). Zr (0.44-1.27); and LREE Ce (0.76) stays in normal abundance relative to MORB for samples TS-2, TS-3, and for TS-4, respectively (Figure 12).

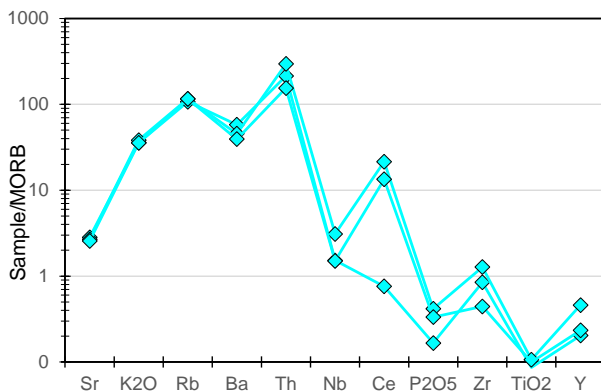


Figure 12. N-MORB trace element multi-diagrams of the Tsarasaotra granitic dykes.

The Ambatofinandrahana granites contain relatively low concentrations of V(6.40-15.8ppm), Cr(2.96-3.6ppm), Cu(3.11-5.22ppm), Ni(1.43-4.82ppm), Nb(0.2-8.4ppm), and Y(5.30-11.8ppm), as well as relatively high concentrations of Sr(114-735ppm), Ba(338-1346ppm), and varied concentrations of Zr(67.4-104ppm), Rb(95.2-155ppm). Minor variations of Cr, Cu, Ni, de Zr, Rb and Nb contents are observed in the function of SiO₂ compared to considerable variations of V, Ba and Sr (Table 1 and Figure 10). MORB normalized multi-incompatible element spectra show enrichment of LFSE like K (26.6-29.6) and Rb (47.6-77.7), a depletion of HFSE such as P (0.17), Ti (0.05) and Y (0.18-0.39), and a normal abundance of Zr (0.75-1.16) relative to MORB.

Negative anomalies of Ba (16.9) relative to Rb (77.7) and Th (136), and of Nb (1.82) relative to Th(136) and Ce (3.88) were particularly observed in Antsahakely sample ANH-1, whereas Th (1.52) and Nb (0.77) remained in normal abundance relative to MORB in Ifasina Itremo sample IT-3-2 (Figure 13).

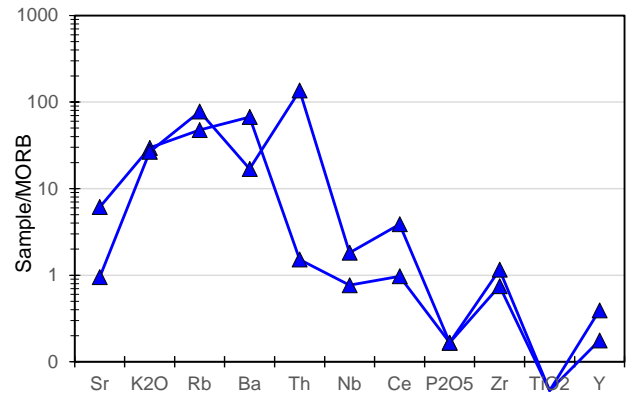


Figure 13. N-MORB trace element multi-diagrams of the Ambatofinandrahana granitic rocks.

The Ibity granite chondrite normalized REE has high variations in LREE compared to HREE (slope softening from LREE to HREE), indicating LREE fractionation is lower than HREE ((La/Sm)_N=5.1-7.8 and (Gd/Yb)_N=1.6-2.6). A high Eu negative anomaly (Eu/Eu* =0.3-0.4) is observed, which is independent of the chondrite normalized La/Yb ratio ((La/Yb)_N=10,7-28,6) is observed (Figure 14 and Figure 21a).

The Tsarasaotra monzonitic rocks' chondrite normalized REE patterns show low variation of LREE in comparison to HREE (slope strengthening from LREE to HREE), indicating low variation of LREE ((La/Sm)_N=2.4-3.6) in comparison to HREE ((Gd/Yb)_N=5.1-6.2). In these rocks, the negative Eu anomalies (Eu/Eu* =0.8-0.9) vary with the La/Yb ratio ((La/Yb)_N=19.6-36.0) (Figure 15 and Figure 21a).

In the case of the Tsarasaotra granite, the chondrite normalized REE of samples TS-3 and TS-4 show a high variation of HREE compared to that of LREE (slope strengthening from LREE to HREE), indicating a low variation of LREE ((La/Sm)_N=8.4-10.2) relative to HREE ((Gd/Yb)_N=4.6-8.0), whereas sample TS-2 shows a high Eu positive anomaly (Eu/Eu*=5.2) (Figure 16).

The Ambatofinandrahana area granite's chondrite normalized REE shows more pronounced variations of LREE ((La/Sm)_N = 3.8-7.0) than HREE ((Gd/Yb)_N = 1.6-1.9). The Eu negative anomaly is moderately high for sample ANH-1 (Eu/Eu*=0.53) and absent for sample IT-3-2 (Eu/Eu*=1.01) (Figure 17).

6. Discussion

6.1. Crystal Fractionation

Systematic decreases of Ti, Al, Fe, Mn, Mg and Ca oxides are observed with the increase of SiO₂; indicating a magmatic differentiation process related to crystal fractionation of rock-forming minerals among the studied rocks (Figure 10). In the Ibity granite, relative depletion of

Sr and Ba with the Eu negative anomalies indicates feldspar fractionation, that of P indicates apatite fractionation, and the decrease of Ti with the increase of silica content can be caused by crystal fractionation of Fe-Ti oxides (Figure 9, Figure 10 and Figure 14). The Tsarasaotra monzonitic rocks display zircon fractionation (Zr depletion), low feldspar fractionation (Ba enrichment), and the absence of apatite and Fe-Ti oxide minerals fractionation (P enrichment, and normal variation of Ti, respectively) (Figure 10 and Figure 11). In the Tsarasaotra granitic dykes, sample TS-2 evolved with an accumulation of K-feldspar (high Eu positive anomaly, $Eu/Eu^*=5.2$), thus no feldspar fractionation signature (Figure 16).

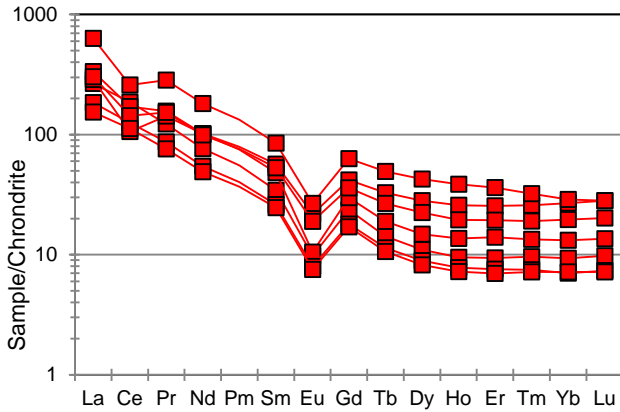


Figure 14. Chondrite-normalized REE patterns of the Ibity granite.

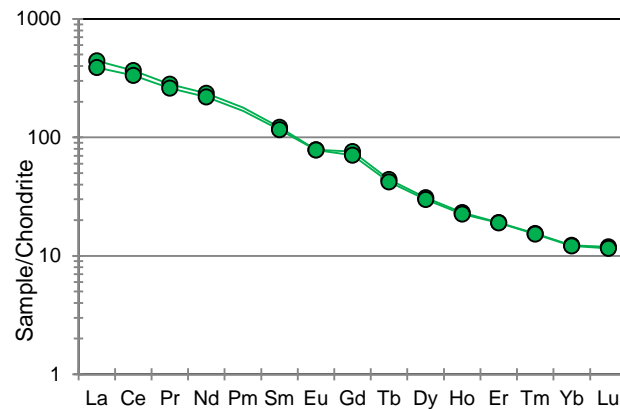


Figure 15. Chondrite-normalized REE patterns of the Tsarasaotra monzonitic rocks.

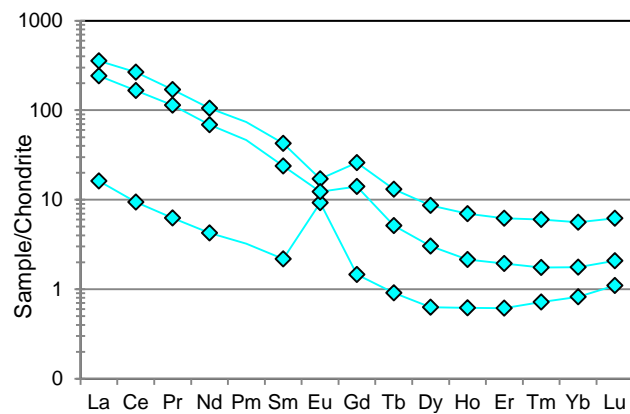


Figure 16. Chondrite-normalized REE patterns of the Tsarasaotra granitic dykes.

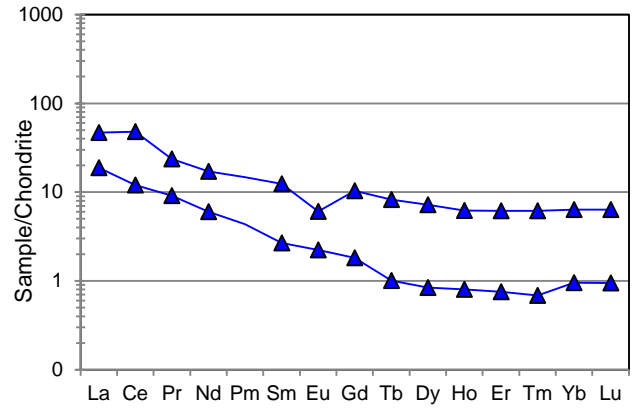


Figure 17. Chondrite-normalized REE patterns of the Ambatofinandrahana granitic rocks.

The La/Sm versus La(ppm) diagram of these granitic rocks points to the crystal fractionation involvement with different degrees of partial melting during their evolution (Figure 18).

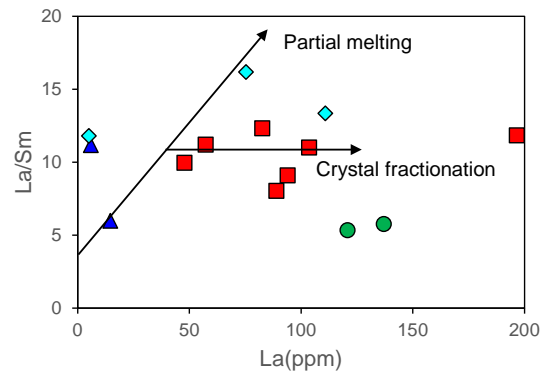


Figure 18. La/Sm versus La (ppm) diagram after [48]. Designations follow Figure 3.

6.2. Geochemical Constraints and Petrogenetic Interpretation

High potassium calc-alkaline and shoshonitic series, metaluminous, rarely peraluminous, are observed in the studied rocks (Figure 8). Those characteristics indicate igneous source or I-type granitic rocks rather than sedimentary source granitic rocks after the [45] classification scheme. The classification diagrams after Whalen, et al. [46] confirm that the origins of the studied rocks are not alkaline (anorogenic), not as [47] reported about post-collisional granitoids in the East African Orogen (EAO) and many other orogenic belts (Figure 19). However, it is obvious that the studied rocks are divided into two geochemical groups: the first is composed of the Tsarasaotra monzonitic rocks with the Ifasina granite, and the second one comprises the Ibity granite, the Tsarasaotra granite dykes, and the Antsahakely granite.

Based on geochemical characteristics, the Ifasina granite has a strong similarity to the Tsarasaotra monzonitic with their common lack or absence of negative Eu, Ba, Nb, P, and Ti anomalies (Figure 11, Figure 13, Figure 15 and Figure 17) as well as their Th/Yb and Nb/Yb ratio behaviors (Figure 20). The Tsarasaotra monzonitic rocks and the Ifasina granite display almost

similar characteristics to the Oceanic Island Basalt (OIB); they have most likely evolved from enriched-MORB sources by within-plate enrichment to approach the OIB compositions as they stay in the MORB-OIB array (Figure 20). In addition, the lack of an Nb anomaly and a Ba negative anomaly for Tsarasaotra monzonitic rocks implies that they are not subduction-related (Figure 11 and Figure 13). The absence of Ba negative anomaly and very low Nb negative anomaly observed in the Ifasina granite might have originated from mixing with different sources (Figure 11 and Figure 13). Therefore, although the drawback regarding lack of examination of the entire suite was announced by [17], the Tsarasaotra monzonitic rocks and the Ifasina granite most likely belong to the Imorona-Itsindro suite, which has been recently reported to be intra-plate origin related [29,49].

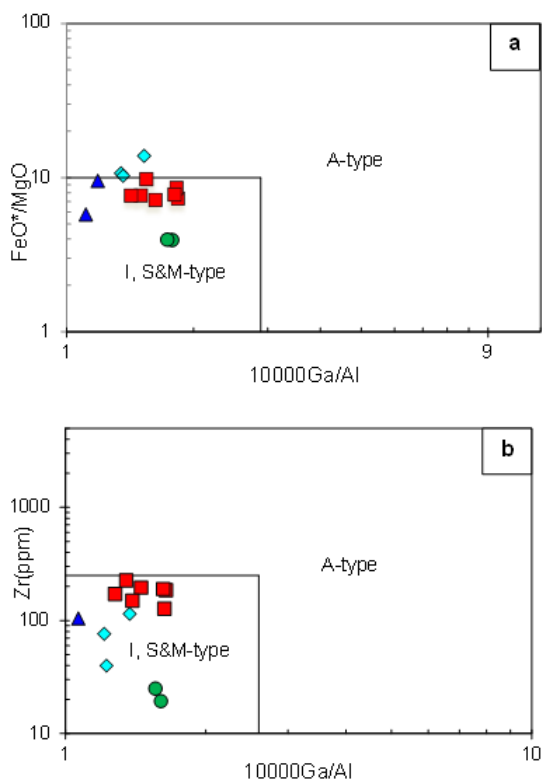


Figure 19. Discrimination diagrams of A-type and I, S, and M types after [46]. a) FeO^*/MgO versus Ga/Al ; b) $\text{Zr}(\text{ppm})$ versus Ga/Al . Designations follow Figure 3.

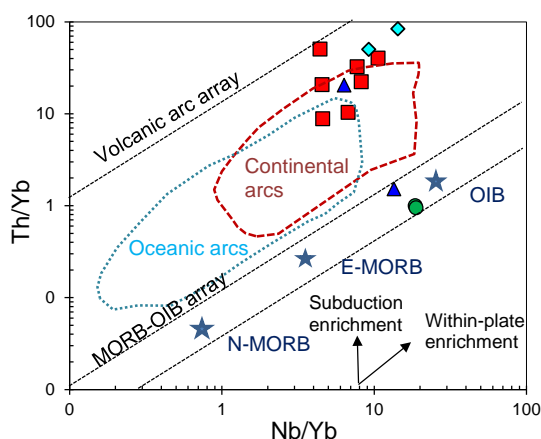


Figure 20. Th/Yb ratio versus Nb/Yb ratio discrimination diagram after [50]. Designations follow Figure 3.

On the other hand, behaviors of major, trace elements and REE chondrite-normalized patterns display similarity among the Tsarasaotra granite dykes and the Ibity granite (REE of samples TS-3 and TS-4 of the Tsarasaotra granite dykes with samples IB-6, IB-8, and IB-16 of the Ibity granite show very strong correlation ($R^2=1$; Figure 9, Figure 10, Figure 12, Figure 14 and Figure 16). Those similarities with the strong correlations obviously indicate that the Tsarasaotra granite dykes (including the pegmatite dyke) and the Ibity granite magma sources have an intimate relationship. Furthermore, for the Ibity granite, the Tsarasaotra granitic dykes, and the Antsahakely granite, there is a strong enrichment of LILES (especially Rb and Th) (○) and LREEs with a depletion of HFSEs (Figure 9, Figure 12 and Figure 13; Figure 14, Figure 16 and Figure 17), indicating partial melting of the upper crust caused by dehydration of the sinking oceanic slab during the subduction process [51]. Therefore, the Th/Yb versus Nb/Yb diagram displays an enriched-MORB source origin and evolution mostly by subduction enrichment in the continental arc setting, followed or mixed with a small part of within-plate enrichment for these rocks (Figure 20). Their relative Nb negative anomalies and Ba negative anomalies support their possible subduction relationship (Figure 9, Figure 12 and Figure 13). Although [1] classified the Antsahakely granite as “intrusive rocks” other than the Imorona-Itsindro, and [5] indicated granitic facies of the Ambalavao suite, these geochemical characteristics reveal that the Ibity granite, the Tsarasaotra granitic dykes, and the Antsahakely granite belong to the second phase of the Imorona-Itsindro suite emplacement, which is subduction-related as [16] reported about the Antsakoamamy granite. It is to be noted that the sample location of this study at Ibity is not far from the [16]’ investigation site of the Imorona-Itsindro suite at Ibity (although geochemical data is not published for comparison). The arc-magmatism signatures caused by the Precambrian basement assimilation proposed by [33] unlikely happened to the Ibity granite, the Tsarasaotra granitic dykes, and the Antsahakely granite.

Based on the explanation of [52] regarding the generation of the calc-alkaline trend, the abundance of the hydrous minerals such as hornblende and biotite especially in the Tsarasaotra monzonitic, as well as the relative abundance of spinel phases, indicates water saturation of the magma during the crystallization. Their relative depletion in the Ibity granite, the Tsarasaotra granite dyke, and the Antsahakely granite could indicate the decrease of H_2O content in the melt, probably due to their emplacement in a shallow environment. This is consistent with the high and moderately high Eu negative anomalies in the Ibity granite and the Antsahakely granite relative to low Eu anomalies in the Tsarasaotra monzonitic and the Ifasina granite; the formers display plagioclase activity whereas the latter exhibit more hydrous mineral activity.

6.3. Adakitic Signatures

Tsarasaotra granite dykes, Ambatofinandrahana granitic rocks (Antsahakely and Ifasina granites), and some samples of Ibity granite are plotted in the adakitic field,

while Tsarasaotra monzonitic rocks are plotted in the field of non adakitic rocks (Figure 21a). On the other hand, the Sr/Y versus Y (ppm) diagram displays that Tsarasaotra granite dykes and Antsahakely granite are among adakitic rocks, whereas Ibity granite, Tsarasaotra monzonitic rocks, and Ifasina granite are among “ordinary rocks” (Figure 21b). The proposition that Antsahakely granite is subduction-related is coherent with its adakitic characteristics. Similarly, Tsarasaotra granite dykes plot within the field of adakitic rocks and their geochemical characteristics fit those of adakite according to [53,54] and [55]’s definition.

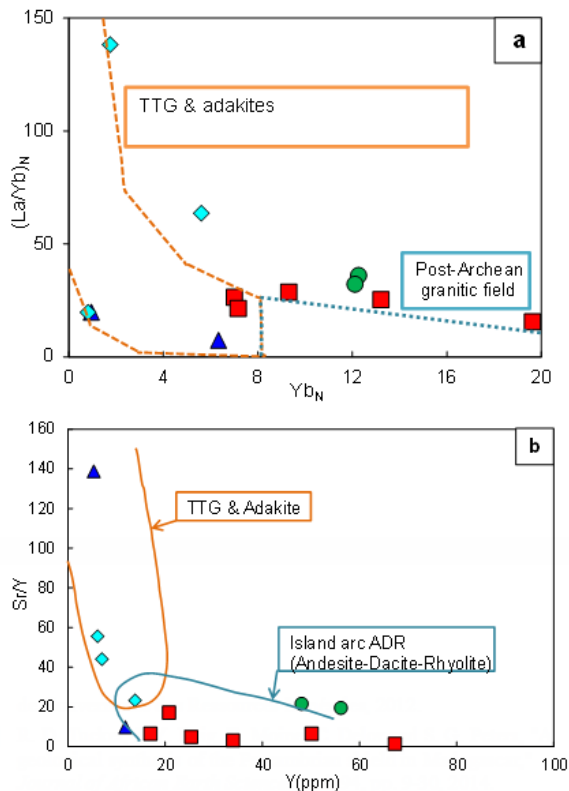


Figure 21. Trace elements ratio diagrams: (a) Normalized La/Yb ratio versus Yb diagram after [59]; (b) Sr/Y versus Y (ppm) diagram after [53]. TTG stands for Trochjemitite-Tonalite-granodiorite defined after [60]. Designations follow Figure 3.

Nonetheless, given that Tsarasaotra granite dykes lack hydrous minerals, their high Sr/Y (and La/Yb) characteristics might have originated from other possibilities than slab melting. As Tsarasaotra granite dykes and Ibity granite belong to one subduction-related magmatic unit, the fact that Ibity granite does not show adakitic signatures reveals that both rocks are not slabs melting-related. According to [56], high Sr/Y (and La/Yb) rocks can be attributed to high Sr/Y (and La/Yb) ratios resulting from deep melting with ample residual garnet, fractional crystallization combined or not with assimilation, and mantle interaction of felsic melts. For example, the possibility of evolution through magmatic differentiation from an “ordinary rock” field to an adakitic field, in particular caused by amphibole fractionation, has been reported [57]. Subsequently, [58] indicated the origin of high Sr/Y rocks in the Qinling orogenic belt, Central China to be related to a high Sr/Y ratio magma source. Accordingly, the lack of hydrous minerals like hornblendes in the Antsahakely

granite and Tsarasaotra granite dykes indicates that they do not necessarily relate to slab melting.

7. Conclusion

Field investigation, petrographic and geochemical characterization indicate that the granitic rocks in the Itremo domain consist of intermediate to felsic, ferroan, calc-alkalic to alkalic, metaluminous, rarely peraluminous I-type granitic rocks. Granitic rocks of the Ibity, Tsarasaotra, and Ambatofinandrahana areas display signatures of magmatic differentiation processes related to crystal fractionation with different degrees of partial melting. Based on geochemical characteristics, these rocks most likely originated from an enriched MORB source. The Tsarasaotra monzonitic rocks and the Ifasina granite have evolved by a within-plate enrichment process, while the Ibity granite, the Tsarasaotra granite dykes, and the Antsahakely granite have evolved by subduction enrichment. This study confirms that the Imorona-Itsindro suite was formed by (i) intraplate enrichment followed by (ii) lithospheric subduction and arc-magmatism, as previously reported; the Tsarasaotra granite dykes that intrude the Tsarasaotra monzonitic rocks were most likely formed during the second phase. The adakitic characteristics observed on some rocks are quite possibly the result of magmatic differentiation rather than slab melting signatures.

Acknowledgements

This work was financially supported by the Japan International Cooperation Agency (JICA) through the KIZUNA program. We gratefully acknowledge Professor Daizo Ishiyama for his guidance during the fieldwork in Madagascar and for his supervision during the laboratory work at the Faculty of International Resource Sciences, Akita University, Japan. We are also thankful to anonymous reviewers who contributed to improving the quality of the manuscript through their relevant comments.

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