

# REE content of volcanic rocks and their weathered horizons in the Muria Volcanic Complex, Central Java, Indonesia

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**Submission date:** 07-Sep-2022 03:41PM (UTC+0700)

**Submission ID:** 1894268388

**File name:** REE\_in\_the\_Muria\_Volcanic\_Complex.pdf (7.75M)

**Word count:** 5208

**Character count:** 24221

# REE content of volcanic rocks and their weathered horizons in the Muria Volcanic Complex, Central Java, Indonesia

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SUTARTO S., SULAKSONO A., LAKSANA DT., MAHYUDANI A., SETIAHADIMBOWO AP, NURCHOLIS M (2022) REE content of volcanic rocks and their weathered horizons in the Muria Volcanic Complex, Central Java, Indonesia. Bull Mineral Petrolog 30(1): 28-37 ISSN: 2570-7337

## Abstract

We investigated bedrock samples and their weathered horizons collected from the Muria Volcanic Complex (MVC), Central Java, Indonesia. In addition to petrographic study, samples were analysed using X-ray diffraction (XRD), inductively coupled plasma-atomic emission spectroscopy (ICP-AES), and inductively coupled plasma-mass spectrometry (ICP-MS) for mineral composition, major elements, and trace elements, respectively. Bedrock samples ( $n = 10$ ) from the MVC have ZREE ranging from 364 to 739 ppm (avg. 579 ppm). Basaltic ( $n = 2$ ) and phonotephrite ( $n = 2$ ) are consistently high in ZREE (659–739 ppm) compared with basaltic trachyandesite, trachyandesite, and trachyte. Apatite is the only REE-bearing mineral observed in basaltic and phonotephrite (up to ~1 vol.%). The ZREE is positively correlated with  $P_2O_5$ , which inversely correlates with  $SiO_2$ . The weathered horizons contain clay minerals that consist primarily of kaolinite + halloysite. The REE content of the weathered horizons ( $n = 7$ ) is up to 183 ppm higher than those of the bedrocks. The decrease in CaO and  $P_2O_5$  indicates a fractionation of apatite at early stage of magma evolution, resulting in the depletion in the ZREE content in the residual melt. We suggest that apatite is the major host of REE in the MVC alkali-rich, silica-undersaturated volcanic rocks, as evidenced by our petrographic and geochemical data. We also suggest that the increase in ZREE in the weathered horizon is due to the presence of clay minerals, particularly kaolinite and halloysite.

**Keywords:** apatite, REE, volcanic rocks, weathered horizons, clay minerals

Received 20. 1. 2022; accepted 10. 3. 2022

## Introduction

Rare earth elements (REEs) are of paramount importance in a modern society and are among the most critical of all raw materials (Wang et al. 2020). However, major supply of REEs is currently restricted to China, Brazil, Australia, United States, Canada, and India (Li et al. 2017; Zheng et al. 2020).

A number of weathering crust ion-adsorption type REE deposits has been discovered in South China. They are the main source of global HREEs and provide nearly the total global HREEs demand (Hoehne et al. 2016; Li et al. 2016; Li et al. 2017; Goodenough et al. 2018). Ion-adsorption type REE deposits have also been discovered in Madagascar (Berger et al. 2014), Malawi (Le Cousteur 2011), Brazil (Rocha et al. 2013), and Southeast Asia (Sanematsu et al. 2009). Most ion-adsorption type REE deposits are hosted in the weathered granite and felsic volcanic rocks (Bao, Zhao 2008; Sanematsu, Watanabe 2016; Qin et al. 2019), in which REEs are primarily hosted in less weather-resistant minerals (Chi et al. 2012; Li et al. 2017).

Exploration targets of REE in Indonesia include primary REE deposits associated with alkaline-peralkaline granitoids, secondary lateritic deposits, and monazite-xenotime by-products of placer-type tin mining. Granitoids

and their weathered crusts are currently the main source of REEs in Indonesia (Setiawan et al. 2017). This paper presents the REE content in various alkali-rich, silica-undersaturated volcanic rocks in the Muria Volcanic Complex (MVC), Central Java, Indonesia, and their weathered horizons. Four weathering profiles of such volcanic rocks were carefully sampled, followed by detailed petrographic and geochemical studies.

## Geological framework

The present day subduction of the Indian oceanic crust beneath the Sunda-Banda arc is well-documented in Hamilton (1977). This arc extends from the northern tip of the island of Sumatra to the southeast, continues eastward to the island of Java, Bali, Lombok, Sumbawa, Sumba, and Flores. In Central and East Java, the axis of the volcanic arc corresponds to a set of active volcanoes, mainly calc-alkaline in nature with some low-K (tholeiitic) varieties (Hutchison 1981, 1982). They correspond to an approximately 200 km deep Benioff plane.

The MVC is situated behind the Pleistocene-Recent Sunda-Banda arc (Fig. 1). It is a complex of Pleistocene volcanoes that form a large peninsula in the northern part of Central Java. Most of the back arc volcanic centres in Central Java that include the MVC lie close to a major

dimensional submarine geodynamic structure of which the MVC is oblique to the arc (Letterier et al. 1990; the axis is indicated by dotted line on Figure 1). K-rich lavas have been erupted from the extinct MVC (van Bemmelin 1949); this composition is not consistent with the calc-alkaline affinity of the Pleistocene-Recent Sunda-Banda volcanic arc. The lower  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of leucite-bearing lavas of the MVC also suggest that they are genetically related to rifting and represent a back-arc volcanism (Cundari 1980). The MVC K-rich volcanic rocks were generated by melting of mantle sources enriched in incompatible elements during previous subduction events, and possibly involving a contribution of subcontinental mantle (Letterier et al. 1990).

### Local geology

The MVC volcanic activities can be divided into two main products i.e., Mount Genuk (2.00 - 0.49 Ma) in the north and Mount Muria (0.84 - 0.32 Ma) in the south (McBimney et al. 2003; Fig. 2). These volcanoes lie on the Middle Miocene calcareous sedimentary sequence of the Buku Formation. Our geological mapping shows that Mount Genuk is composed of basaltic trachyandesite in the center (main volcanic vent) surrounded by volcaniclastic deposits of the Ujungwatu Formation and pyroclastic deposits. Trachyte and basaltic trachyandesite are also observed in the distal facies (possibly secondary vent; Fig. 2). Mount Muria is composed of more varied volcanic rocks i.e., basaltite, phonolephrite, trachyandesite and basaltic trachyandesite (Fig. 2). These volcanic rocks are surrounded by widespread pyroclastic deposits in the distal facies.

### Sampling and analytical methods

A total of 10 samples from bedrocks and their weathered horizons were collected from the MVC. The most complete weathering profile in the MVC consists of trachyan-

desite bedrock (TA-Bed), horizon C (a layer of partially altered bedrock; TA-With-C), horizon B (where soluble minerals and clays accumulate; TA-With-B) and horizon A (near-surface horizon containing humified organic matter; TA-With-A). A basaltite outcrop (B-1-Bed) is associated only with horizon C (B-1-With), whereas trachyte bedrocks T-1-Bed and T-2-Bed have only horizon C (T-1-With) and horizon A (T-2-With), respectively. Six unweathered samples such as basaltite (B-1), phonolephrite (PT-1, PT-2) and basaltite trachyandesite (BTA-1, BTA-2, BTA-3) were also collected.

All samples were air-dried at 20 - 30 °C for four weeks, then were quartered and powdered using mortar and pestle. Four polished thin sections of bedrocks were prepared. The abundances of rock-forming minerals in the bedrock were determined under optical microscope. The bulk mineralogy of the samples was analysed using XRD at UPN Veteran Yogyakarta. Mineral identification was accomplished using the COD reference database of MATCH! software. The bulk rock geochemical analyses for both major and trace elements were carried out at ALS Geochemistry, Brisbane, Australia. Major elements have been analysed by ICP-AES (preceded by peroxide fusion), whereas trace elements were measured using ICP-MS (preceded by lithium borate fusion).

## Results

### Petrography of volcanic rocks

A total of 10 volcanic rock samples in this study include basaltite ( $n = 2$ ), phonolephrite ( $n = 2$ ), basaltic trachyandesite ( $n = 3$ ), trachyandesite ( $n = 1$ ), and trachyte ( $n = 2$ ). Two basaltite samples (B-1-Bed and B-2; Fig. 3A, B) contain olivine, pyroxene, plagioclase, and feldspathoid phenocrysts up to 30 vol.%, generally from 0.5 to 4 mm in size, in a groundmass that consists of mainly plagioclase, feldspathoid, apatite, and opaque minerals (magne-

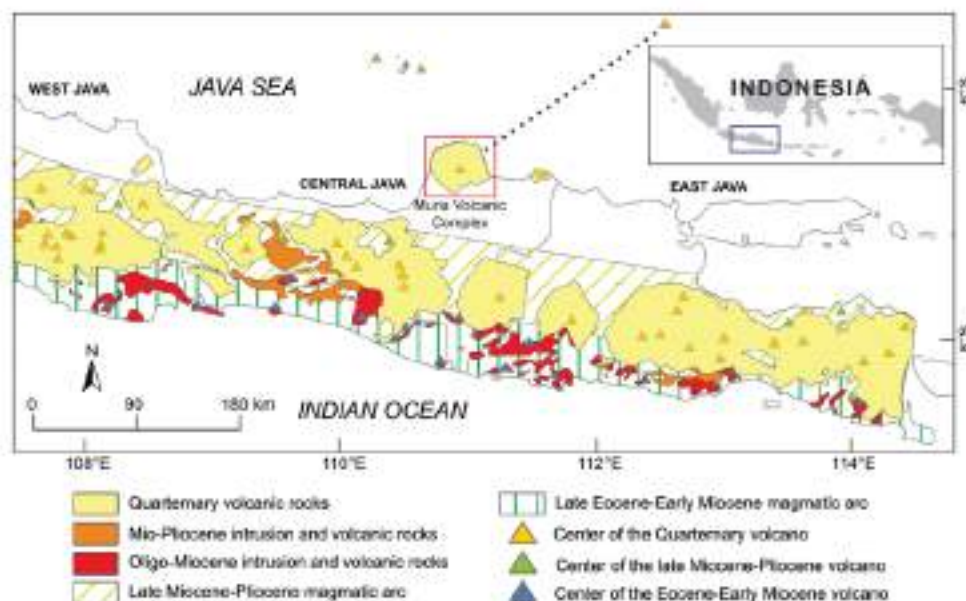


Fig. 1 The distribution of magmatic-volcanic arcs in Java island, Indonesia. The MVC (red square) is situated behind the Pleistocene-Recent Sunda-Banda arc, forming a large peninsula in the northern part of the island.



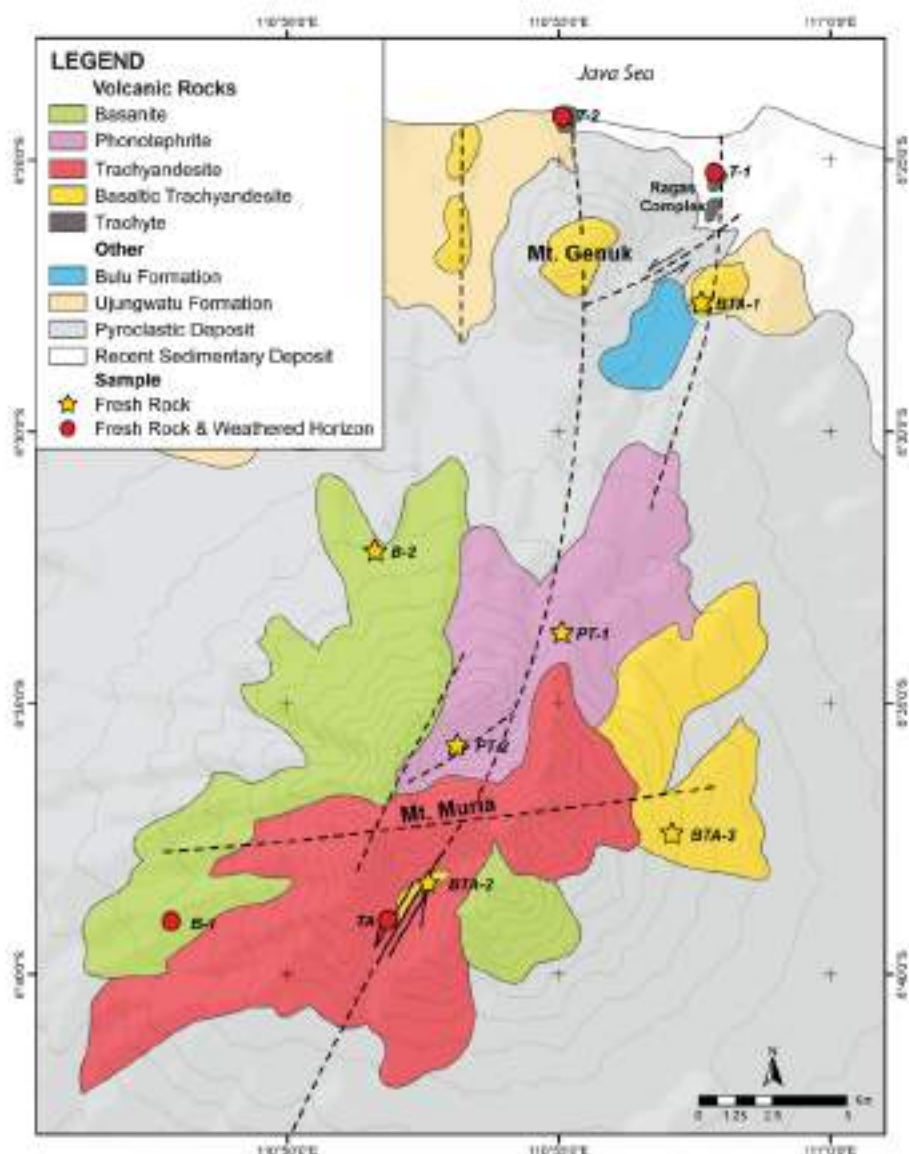
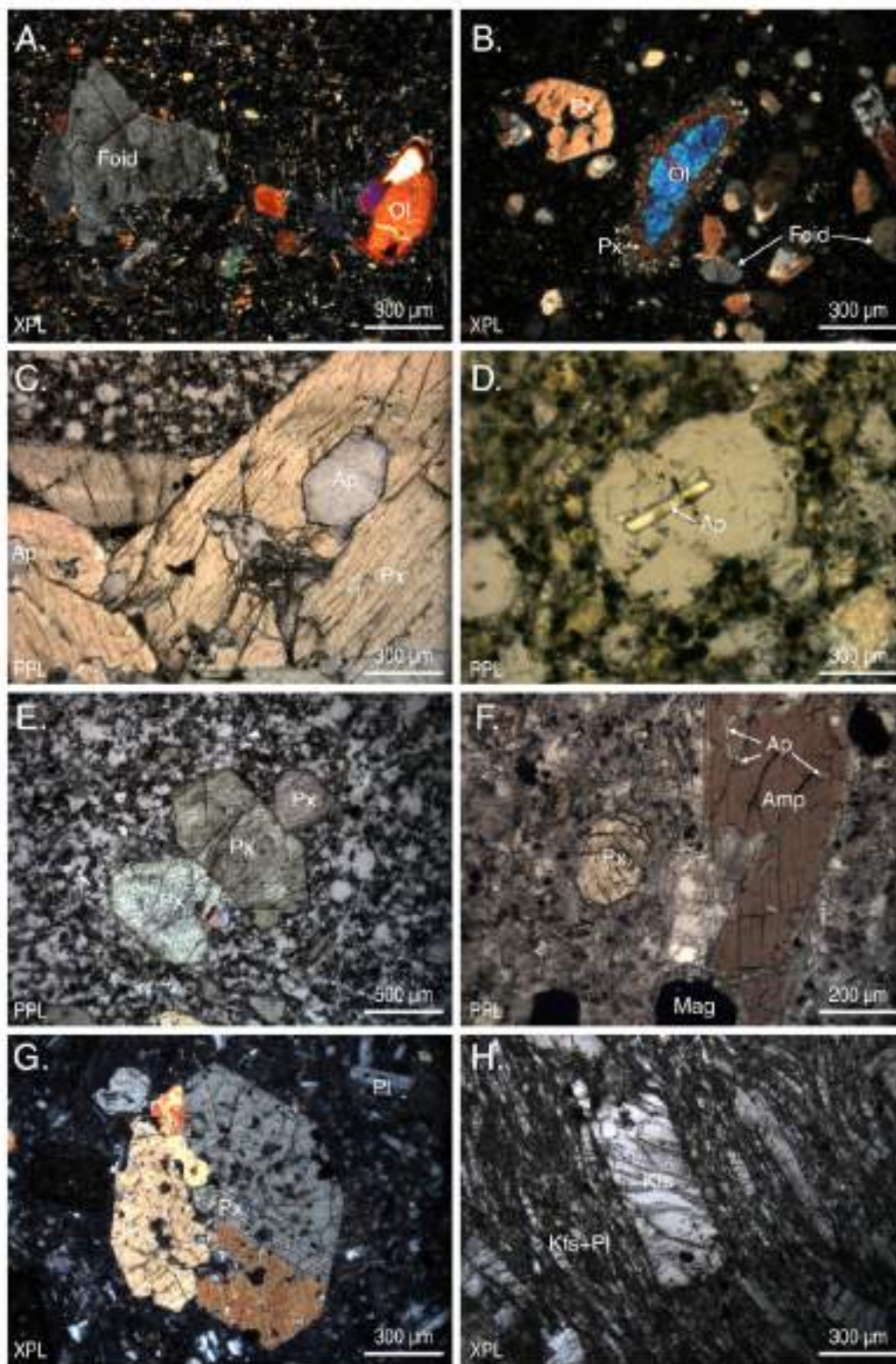
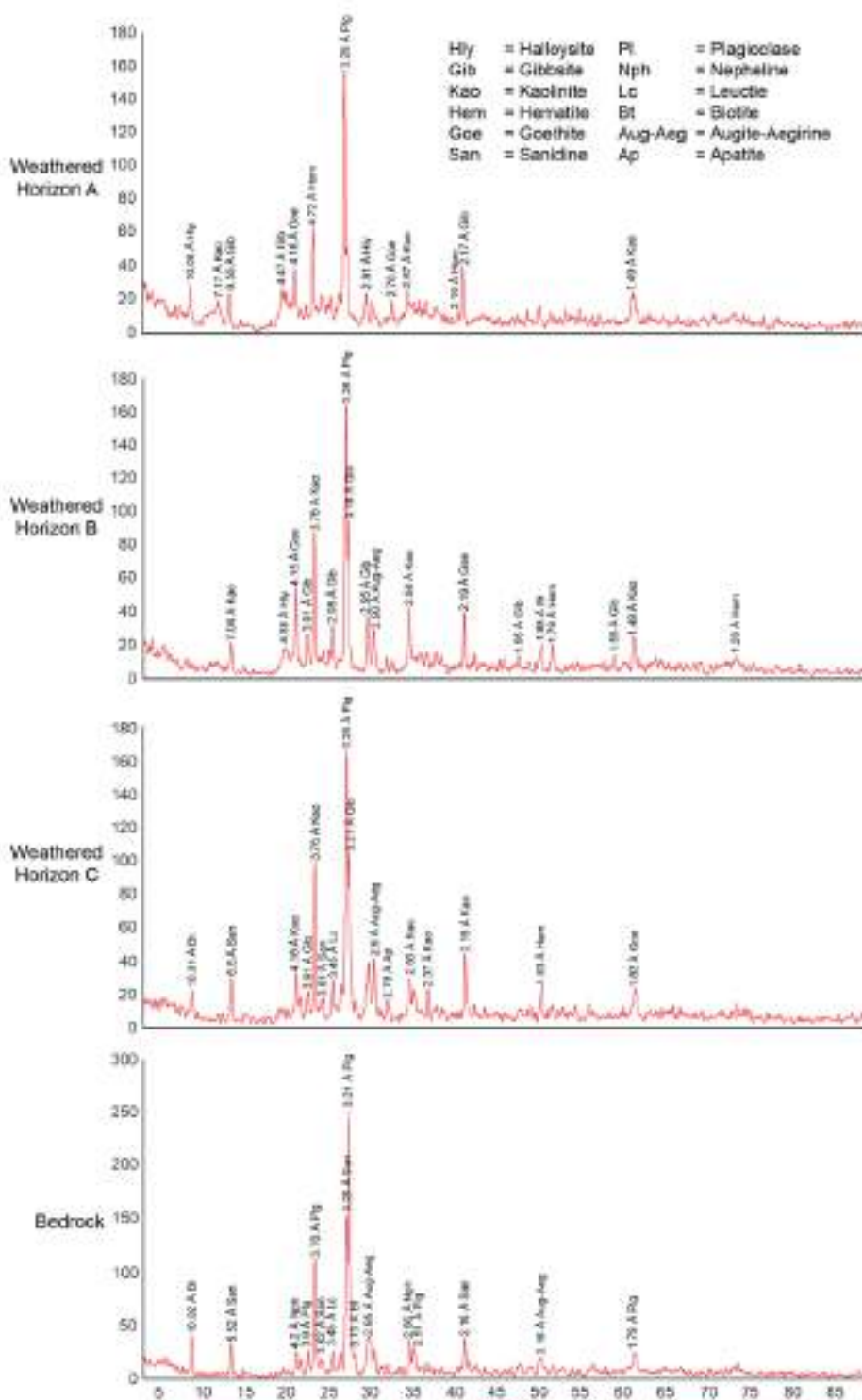


Fig. 2 Geological map of the Muria Volcanic Complex (MVC).

Fig. 3 Representative photomicrographs of the MVC volcanic rock samples. A. Basanite (sample B-1-Bed) with olivine and feldspathoid phenocrysts, set in the groundmass composed of plagioclase, feldspathoid, apatite, and opaque minerals. B. Basanite (sample B-2), showing phenocrysts of olivine, pyroxene, and feldspathoid. Also shown is the pyroxene corona on olivine. C. Apatite inclusions in pyroxene (basanite; sample B-1-Bed). D. Apatite inclusion in feldspathoid (basanite; sample B-2). E. Phonotephrite of sample PT-1, showing phenocryst crystals of pyroxene. The phenocrysts are set in the fine-grained plagioclase, feldspathoid, opaque minerals (magnetite and ilmenite), apatite, and glass groundmass. F. Phonotephrite of sample PT-2, showing phenocrysts of amphibole, pyroxene, and plagioclase. These phenocrysts are set in the fine-grained plagioclase, feldspathoid, opaque minerals (magnetite and ilmenite), apatite, and glass groundmass. G. Trachyandesite of sample TA-Bed, showing a porphyritic texture with pyroxene phenocrysts. The phenocrysts are set in a crystal groundmass that contains mainly plagioclase, K-feldspar, and opaque minerals (magnetite and ilmenite). H. Trachyte (sample T-2-Bed), which shows a typical trachytic texture, where acicular to tabular feldspar of groundmass shows flow structure. Abbreviations: Ap, apatite; Amp, amphibole; Foid, feldspathoid; Kfs, K-feldspar; Mag, magnetite; Ol, olivine; Pl, plagioclase; Px, pyroxene; PPL, Plane-polarized light; XPL, Crossed polars.





**Fig. 4** XRD patterns of trachyandesite bedrock and its weathered horizons A, B, and C. The dominant minerals in the bedrock are plagioclase, sanidine, and augite, whereas kaolinite and Fe-oxides are observed mostly in the weathered horizon A, B, and C. Halloysite is observed in the weathered horizon A and C.



site and ilmenite). The olivine, pyroxene, plagioclase, and feldspathoid phenocrysts are euhedral to anhedral, and commonly host apatite inclusions (Fig. 3C, D). Pyroxene corona on olivine is common (Fig. 3B). Sample B-1-Bed shows that groundmass crystals have fluidal texture.

Phenocrysts of sample PT-1 is characterized by a strong porphyritic texture (Fig. 3E). Phenocryst crystals (~30 vol%) are up to 2 mm long and consist of olivine, pyroxene, amphibole, plagioclase, and feldspathoid. The phenocrysts are set in the fine-grained matrix composed of plagioclase, feldspathoid, opaque minerals (magnetite and ilmenite), apatite, and less commonly glass. Sample PT-2 is characterized by a weak porphyritic texture (Fig. 3F). Phenocrysts are up to 4 mm long and comprise up

to ~20 vol.% of rock. Phenocryst crystals consist mainly of amphibole and less commonly pyroxene, biotite, plagioclase and feldspathoid. These phenocrysts are set in the fine-grained groundmass formed by plagioclase, feldspathoid, opaque minerals (magnetite and ilmenite), apatite, and less commonly glass. Apatite inclusions in phenocryst crystals are common in both samples PT-1 and PT-2 (Fig. 3F).

Basaltic trachyandesites (BTA-1, BTA-2, BTA-3) are characterized by a weak porphyritic texture. Phenocryst crystals are up to 2.5 mm long and consist of pyroxene, amphibole, biotite, plagioclase, and less commonly K-feldspar. These phenocrysts are set in the fine-grained matrix composed of plagioclase, K-feldspar, magnetite, il-

**Table 1** Whole-rock major and trace element concentrations for the MVC samples. Abbreviations (sample codes): B, basaltite; T, trachyte; TA, trachyandesite; PT, phonotephrite; BTA, basaltic trachyandesite; Bed, bedrock; Wh, weathered horizon

Sample	B-1-Bed	B-1-Wh	B-2	T-1-Bed	T-1-Wh	T-2-Bed	T-2-Wh	TA-Bed	TA-Wh	TA-Wh-B	TA-Wh-A	PT-1	PT-2	BTA-1	BTA-2	BTA-3
SiO <sub>2</sub> (wt%)	44.70	52.10	45.30	60.90	56.60	65.10	52.10	53.60	54.20	53.90	45.10	45.30	50.30	50.90	52.00	50.30
Al <sub>2</sub> O <sub>3</sub>	14.65	27.20	16.35	20.80	21.00	20.20	24.60	17.60	18.25	20.70	24.00	15.65	16.75	17.65	19.05	17.65
Fe <sub>2</sub> O <sub>3</sub>	10.15	15.50	11.15	3.42	4.05	1.87	3.61	8.88	6.96	6.39	12.25	9.74	7.66	7.64	6.30	8.24
CaO	12.35	0.35	12.70	1.48	1.06	0.61	0.65	5.83	6.17	2.22	0.80	10.80	7.20	6.75	7.14	7.65
MgO	6.32	0.51	5.90	0.24	0.31	0.04	0.36	2.33	2.00	1.03	1.00	5.29	3.05	2.46	2.24	3.08
Na <sub>2</sub> O	2.97	0.15	1.83	3.97	3.52	5.80	2.79	3.24	2.69	2.40	1.44	3.13	3.40	3.05	3.76	3.27
K <sub>2</sub> O	4.72	0.34	3.91	7.24	6.83	6.74	4.07	4.95	4.83	5.40	3.40	5.55	5.66	2.42	2.78	4.56
TiO <sub>2</sub>	1.08	1.67	1.21	0.25	0.33	0.18	0.38	0.85	0.90	1.02	1.22	1.05	0.88	0.73	0.70	0.78
MnO	0.20	0.42	0.22	0.13	0.18	0.15	0.25	0.13	0.15	0.08	0.20	0.19	0.19	0.17	0.17	0.20
P <sub>2</sub> O <sub>5</sub>	0.98	0.74	1.06	0.07	0.05	0.01	0.07	0.61	0.57	0.65	0.45	1.05	0.53	0.60	0.67	0.65
SrO	0.10	0.00	0.19	0.16	0.12	0.02	0.02	0.11	0.00	0.07	0.05	0.18	0.22	0.17	0.18	0.22
BaO	0.17	0.36	0.12	0.24	0.25	0.03	0.03	0.13	0.12	0.13	0.14	0.27	0.14	0.17	0.17	0.13
Total	86.48	79.43	100.02	88.90	95.30	100.75	88.94	98.26	97.73	93.69	90.05	101.20	98.16	92.73	97.25	96.93
La (ppm)	176	213	159	134	138	90	135	106	111	124	150	188	167	106	117	171
Ce	314	418	288	281	287	159	273	185	198	188	262	286	289	185	207	294
Pr	33.4	38.6	32.2	20.3	20.6	14.9	20.7	20.5	21.8	23.7	28.7	27.5	30.3	20.5	21.9	31.0
Nd	121	138	119	62.6	65.6	43.3	65.7	75.3	77.5	85.5	103	90.9	110	75.9	78.5	108
Sm	20.70	23.50	21.20	9.05	9.72	6.36	9.51	13.00	13.60	14.65	18.10	14.20	18.35	13.10	13.55	18.30
Eu	6.75	6.48	5.85	2.91	2.95	1.58	2.10	3.55	3.53	3.79	4.74	3.79	5.17	3.52	3.64	4.81
Gd	13.60	17.85	16.65	6.15	6.79	4.94	7.25	10.05	10.50	11.30	13.75	10.15	13.75	9.94	9.93	13.50
Tb	1.83	2.10	1.96	0.84	0.85	0.74	1.02	1.28	1.33	1.41	1.66	1.21	1.66	1.23	1.29	1.62
Dy	6.15	9.28	9.02	4.35	4.46	4.42	5.80	6.34	6.60	6.81	8.31	5.78	7.82	6.18	6.52	7.78
Ho	1.32	1.48	1.45	0.83	0.84	0.98	1.24	1.13	1.18	1.21	1.51	0.98	1.34	1.13	1.18	1.32
Er	3.05	3.45	3.49	2.29	2.27	3.07	4.00	3.06	3.11	3.14	3.90	2.42	3.36	2.94	3.20	3.18
Tm	0.40	0.45	0.45	0.35	0.34	0.54	0.67	0.43	0.45	0.45	0.54	0.31	0.46	0.44	0.46	0.44
Yb	2.22	2.83	2.58	2.20	2.22	3.86	4.75	2.61	2.66	2.74	3.39	1.99	2.76	2.51	2.93	2.78
Lu	0.35	0.45	0.39	0.35	0.34	0.64	0.81	0.40	0.41	0.42	0.51	0.29	0.42	0.40	0.46	0.43
Y	35.0	37.8	40.3	22.6	23.8	29.8	39.0	30.6	32.7	32.9	41.1	26.1	36.3	29.5	33.0	36.0
ΣREE	739	913	701	530	566	364	570	458	484	500	641	659	687	457	501	656
Th	29.8	48.2	29.6	38.1	37.2	40.5	47.1	25.6	29.0	32.9	38.2	44.8	37.2	23.7	31.3	42.2
U	5.07	7.24	4.87	1.82	3.08	4.82	11.05	5.11	6.35	7.41	7.95	9.00	7.8	4.20	6.20	6.77
Zr	272	435	296	285	291	515	637	234	253	310	381	240	336	218	276	337
Hf	5.5	8.6	6.0	5.2	5.3	9.4	11.6	5.1	5.4	6.4	7.4	4.5	6.3	4.5	5.7	6.3
Sn	1	2	2	1	1	1	2	1	2	1	3	1	1	2	2	1
Nb	84.0	136	62.2	40.8	43.4	39.1	50.2	41.0	38.4	43.3	55.0	205	75.0	39.7	53.9	89.7
Be	1.630	3.390	1.060	2.230	2.260	261	278	1.220	1.090	1.220	1.250	2.500	1.290	1.650	1.570	1.290
Cr	160	150	120	<10	10	<10	10	30	50	70	50	90	50	40	10	20
Cs	5.29	1.90	7.83	10.8	6.19	8.84	8.60	9.66	7.90	6.49	8.37	5.67	9.23	4.27	3.77	9.45
Ge	18.4	31.0	20.3	20.2	20.9	24.1	30.4	20.9	21.3	24.5	28.5	17.5	21.4	20.6	22.1	21.2
Rb	186	14.9	261	200	187	269	179	187	173	196	144	218	167	49.3	56.8	272
Sr	1.610	786	1.610	1.390	1.030	160	141	945	765	606	456	1,540	1,910	1,420	1,520	1,930
Ta	3.1	4.7	2.5	1.9	1.7	1.3	1.6	1.6	1.8	1.8	2.2	7.7	3.1	1.4	1.9	3.8
V	355	244	371	39	86	20	68	242	269	270	352	330	226	216	207	248
Rb/Sr	0.12	0.02	0.16	0.14	0.16	1.66	1.25	0.20	0.23	0.32	0.32	0.14	0.09	0.03	0.04	0.14

merite, apatite, and glass. The rutile-magnetite assemblage occurs as a reaction rim on biotite phenocrysts. Apatite is common inclusion mineral in silicate phenocrysts.

A trachyandesite sample (TA-Bed) is characterized by a porphyritic texture of pyroxene, amphibole, and biotite phenocrysts (up to 60 vol.%; Fig. 3G). These phenocrysts are 0.5 to 2 mm in length. The plagioclase phenocrysts particularly host zircon inclusions. The phenocrysts are set in a crystal groundmass that contains mainly plagioclase, K-feldspar, and opaque minerals (magnetite and ilmenite). Apatite crystals are observed as inclusion in the phenocryst crystals as well as in the groundmass.

Trachyte samples (T-1-Bed, T-2-Bed) contain plagioclase, K-feldspar, pyroxene, olivine, glass, and accessory magnetite (Fig. 3H). This rock shows a weak porphyritic texture with mainly plagioclase and K-feldspar phenocrysts (less commonly olivine and pyroxene), set in the fine-grained groundmass composed of plagioclase, K-feldspar and glass. Phenocrysts are generally 0.2 to 2 mm in size. Plagioclase and K-feldspar comprise up to 75 vol.% of rocks. These trachyte samples show a typical trachytic texture, where acicular to tabular feldspar groundmass shows fluidal texture.

### Bulk rock mineralogy

Bedrocks and their weathered horizons A, B, and C from trachyandesite were analysed for their mineralogy by XRD (Fig. 4). K-feldspar and plagioclase are the dominant minerals in the trachyandesite bedrock. Clay minerals are observed in the weathered horizons A, B, and C. Kaolinite is preserved in all horizons, whereas halloysite occurs preferentially in horizon A.

### Whole-rock geochemistry

Results of bulk rock geochemical analyses are presented in Table 1. The bedrock samples contain  $\text{SiO}_2$  and  $\text{K}_2\text{O}$  ranging 44.70 - 65.10 wt.% and 2.42 - 7.24 wt.%, respectively. Silica content generally increases with decreasing  $\text{TiO}_2$  content. Trachyte, trachyandesite, and basaltic trachyandesite samples are classified into shoshonite series in the  $\text{SiO}_2$  vs.  $\text{K}_2\text{O}$  diagram, whereas basanite and phonotephrite fall into the leucitic series (Fig. 5). The Harker diagrams indicate that the  $\text{TiO}_2$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{MnO}$ ,  $\text{MgO}$ ,  $\text{CaO}$ , and  $\text{P}_2\text{O}_5$  decrease with increasing of  $\text{SiO}_2$  content, whereas  $\text{K}_2\text{O}$ ,  $\text{Na}_2\text{O}$ , and  $\text{Al}_2\text{O}_3$  are positively correlated with the  $\text{SiO}_2$  content (Fig. 6). Weathered horizons were not plotted in the Harker diagrams.

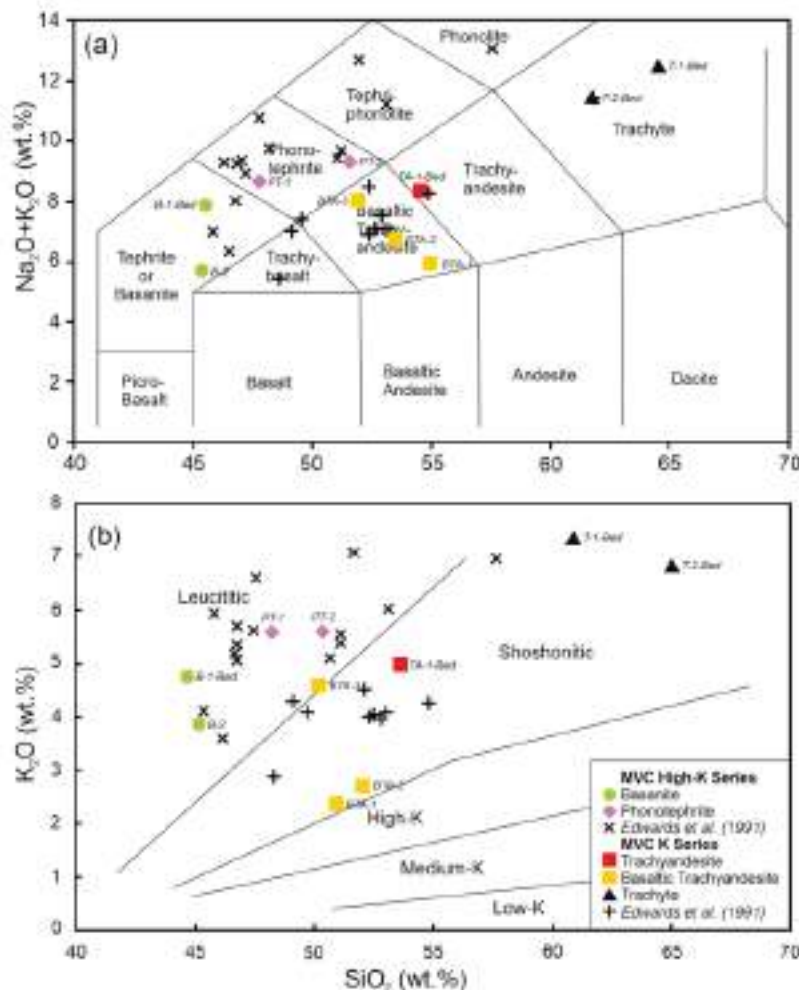


Fig. 5 A. Total alkalis ( $\text{Na}_2\text{O} + \text{K}_2\text{O}$ ) vs. silica ( $\text{SiO}_2$ ) diagram of the volcanic rocks from the MVC. B.  $\text{K}_2\text{O}$  vs.  $\text{SiO}_2$  diagram of the volcanic rocks from the MVC. Our data are fit with those from Edwards et al. (1991). Basanite and phonotephrite are classified into the MVC High-K series, whereas trachyandesite, basaltic trachyandesite and trachyte belong to the MVC K series (see Edwards et al. 1991).



The whole-rock REE concentrations in both bedrock and weathered horizon were analysed. The  $P_2O_5$  and CaO contents in the bedrocks are positively correlated with ZREE (Fig. 7). Bedrock samples from the MVC have REE contents ranging from 364 to 739 ppm, whereas the weathered horizons are more enriched in REE (484 to 913 ppm). Basanite and phonotephrite samples have highest ZREE ranging from 659 to 739 ppm. Chondrite-normalized REE patterns show that both bedrock and weathered horizon samples show a systematic minor HREE-enriched U-shaped patterns (Fig. 8). Small positive Eu anomaly is observed in trachyte, whereas the other three bedrock samples show negligible Eu anomalies.

**Discussion**

**Fractional crystallization**

The  $SiO_2$  contents of samples studied are very low to intermediate, ranging from 44.70 to 65.10 wt%. These samples have Rb/Sr ratios of 0.03 - 1.88. Such low to intermediate  $SiO_2$  and low Rb/Sr ratios suggest that the magmas were weakly differentiated. Negative correlations between  $TiO_2$ ,  $Fe_2O_3$ , MnO, MgO, CaO,  $P_2O_5$ , and  $SiO_2$  content suggest that the magmas likely underwent fractional crystallization during magmatic differentiation. The decrease in  $Fe_2O_3$ , MgO, CaO, and  $P_2O_5$  indicates

removal of mafic minerals and apatite. The ZREE content decreases with decrease of CaO and  $P_2O_5$ , indicating that the fractionation of apatite enriched REE from the crystallizing melt significantly. Thus apatite is likely the major host for REE in the fresh volcanic rock in the MVC. This is supported by the abundant presence of apatite in basanite and phonotephrite (Fig. 3).

Silica is positively correlated with some major oxides such as  $K_2O$ ,  $Na_2O$ , and  $Al_2O_3$ , indicating that these elements were not fractionated in the early stage of magma evolution. They are mainly partitioned in minerals observed in the samples such as plagioclase and K-feldspar. The absence of an early plagioclase fractionation is evidenced by the lack of negative Eu anomalies in the chondrite-normalized diagram (Fig. 8).

**Mineralogical and geochemical evolution of the late-rift profiles**

Bedrocks are the primary source of REEs in the weathering horizons. To form ion-adsorption type REE deposits, the parent rocks must have a sufficient amount of REEs, which are hosted in weatherable minerals e.g., fluorocarbonates, allanite, titanite (Chi et al. 2012) and possibly apatite. Apatite is absent in REE-enriched weathered horizons (Fig. 4, horizons A and B). Therefore, REEs were likely bound to the clay minerals during weathering

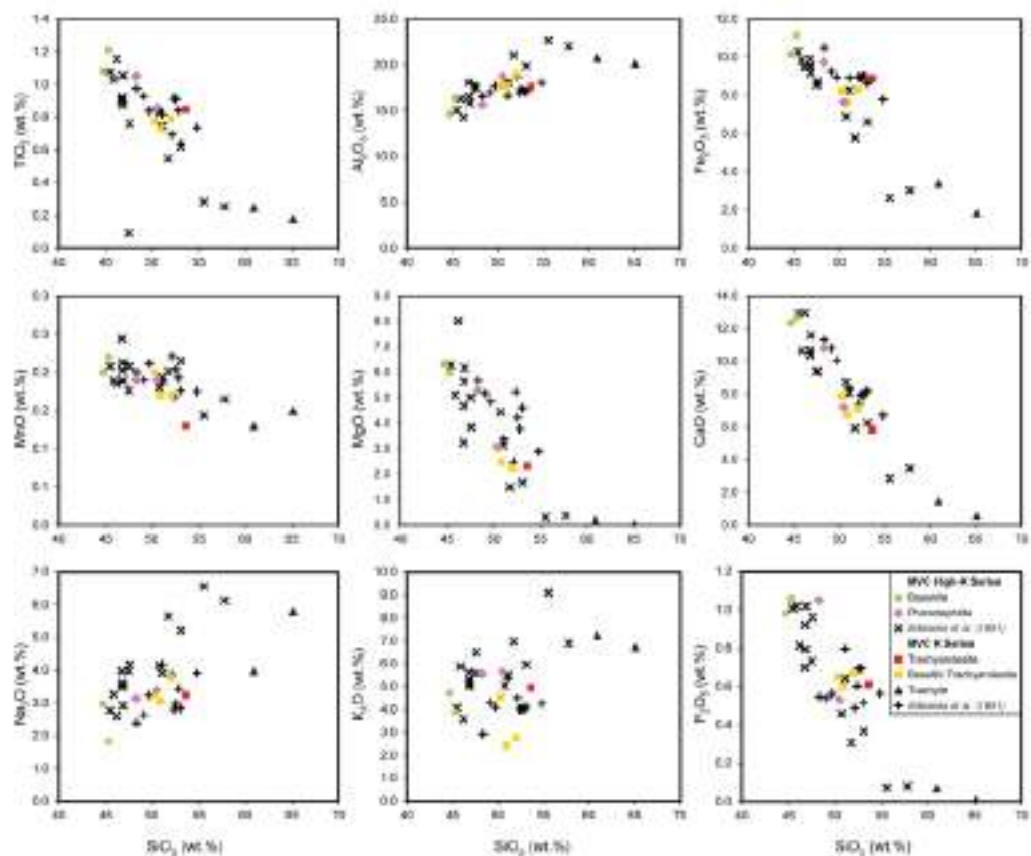


Fig. 6 Harker diagrams of major elements oxides of the MVC rock samples. Our data are generally consistent with the data from Edwards et al. (1991).

rather than to residual REE-bearing apatite. We suggest that apatite was decomposed during weathering, providing REEs to be deposited in weathered horizons.

Kaolinite and halloysite formed during the weathering of mainly plagioclase and K-feldspar in the samples studied. The results of XRD measurements on trachyandesite profile show that kaolinite is preserved in all horizons. Halloysite occurs preferentially in horizon A, in which  $\Sigma$ REE is significantly enriched. The sorption ability of halloysite for REEs is presumably not very different from that of kaolinite (Mukai [2020](#)). Thus we interpret that in addition to kaolinite, halloysite in the partides possibly plays a role in the enrichment of REEs in the weathered horizons.

## Conclusions

The REE content of volcanic rocks samples collected from the MVC varies from 354 to 739 ppm. Alkali-rich, silica-undersaturated rocks such as basanite and phonotephrite samples have highest  $\Sigma$ REE ranging from 659 to 739 ppm. Apatite is likely the major host for REE in this type of rock as evidenced by our petrographic and chemical data. The depletion in CaO and  $P_2O_5$  indicates preferential crystallization of apatite at early stage of magma evolution, resulting in the depletion in the  $\Sigma$ REE content of the MVC differentiated volcanic rock. The  $\Sigma$ REE increases in the weathered horizon, thus we suggest that in the MVC the increase in  $\Sigma$ REE in the weathered horizon is due to the presence of clay minerals, particularly kaolinite and halloysite.

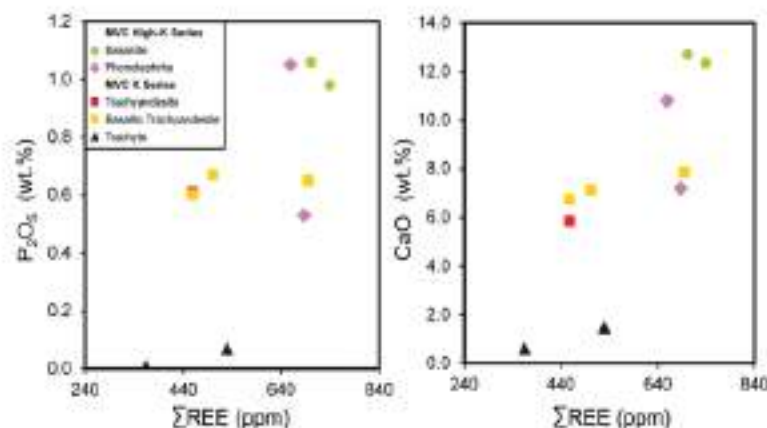


Fig. 7 A. The  $P_2O_5$  vs.  $\Sigma$ REE diagram. B. The CaO vs.  $\Sigma$ REE diagram. Both  $P_2O_5$  and CaO contents in the bedrocks are possibly correlated with  $\Sigma$ REE.

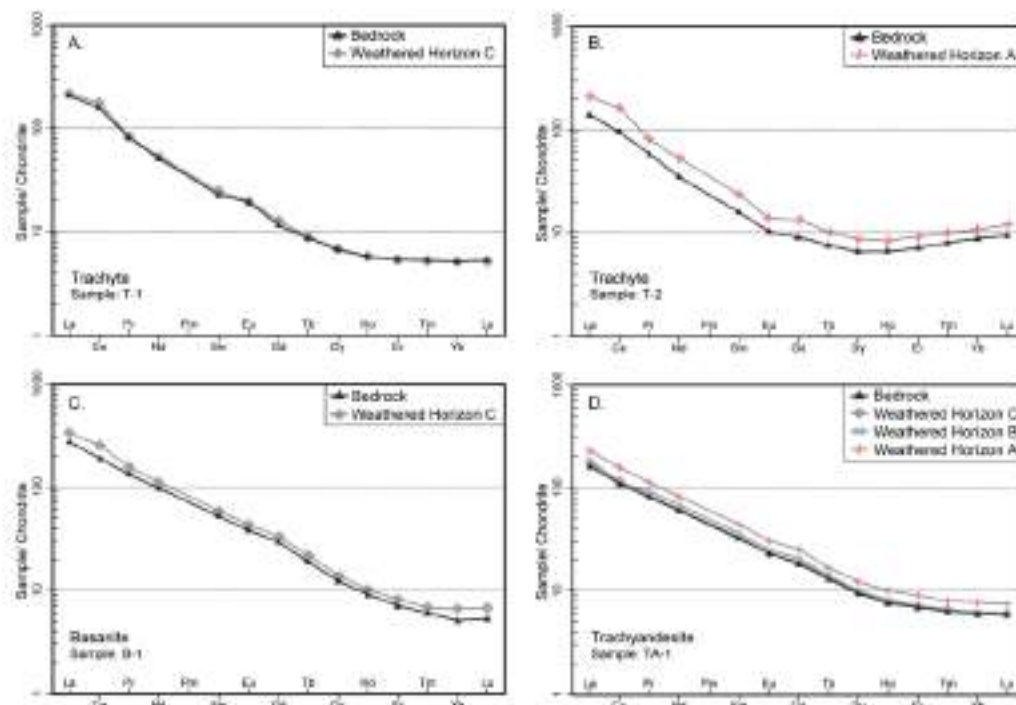


Fig. 8 Chondrite-normalized REE patterns for both bedrocks and weathered horizons.

### Acknowledgement

This project was funded by the Ministry of Education, Culture, Research, and Technology, Indonesia. We acknowledge Mr. Agus for his support during the fieldwork.

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