Magma Genesis in Kabanjahe Region Continental Margin Arc of Sumatra

Genesis Magma di Daerah Kabanjahe Busur Tepi Benua Sumatra

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Abstract

Volcanic rocks in Kabanjahe region, Karo Regency, North Sumatra Province, are products of old Toba Caldera, Sibayak Volcano, and Sipiso-piso Volcano. Rhyolitic tuff is the main lithology distributed over a large area in this region. Others are basaltic, basaltic andesitic, andesitic, dacitic, and rhyolitic lavas. Data show that the rock was originated from magma of a continental origin formed at a subduction zone environment. Petrogenetic modelling suggests that the range in composition was mainly controlled by a fractional crystallization of plagioclase, clinopyroxene, hornblende, and biotite. Harker's variation diagram of major and trace elements show a continuous range that indicates they are cognate. The lava in this area belongs to a high-K, calc-alkaline series, with particular high Nb concentrations. The composition of these high-Nb lavas is more similar to those of intra plate basalts rather than those of calc-alkaline or arc-tholeiitic basalt. The high anomaly of Nb which is accompanied by high Th, Rb, and normative corundum suggests that the source may also be enriched in incompatible elements, a characteristic feature of alkali magmatism. The similarity of the trace element of volcanic rocks to the within-plate basalts indicates that the convecting mantle wedge above subducted slabs contains variable proportions of MORB-source and OIB-source components; fluids added were derived from the subducted slab. Hence, it is interpreted that the high Nb concentration of volcanic rocks from Kabanjahe region were generated from subduction modified OIB source components. Alternatively, a deep seated faulting conduit magma from the lower mantle resulted in the alkaline enrichment of the volcanics. This article performs a petrological aspect, especially based on geochemical analysis including major elements, trace elements, and rare earth elements. The results are plotted into a general and specific classification used in petrology.

Keywords: petrology, geochemistry, Kabanjahe, continental margin arc, tectonic

Sari

Batuan vulkanik di daerah Kabanjahe, Kabupaten Karo, Provinsi Sumatra Utara terutama dihasilkan oleh Kaldera Toba Tua, Gunung Api Sibayak, dan Gunung Api Sipiso-piso. Tuf riolitis (Tuf Toba) melampar luas di daerah ini. Produk magma lainnya adalah lava yang terdiri atas basal, andesit basalan, andesit, dasit, dan riolit. Data menunjukkan bahwa batuan ini berasal dari magma asal kontinen yang terbentuk di daerah penunjaman. Model petrogenesis menunjukkan bahwa tingkatan komposisi terutama dikontrol oleh fraksinasi klinopiroksen, plagioklas, horenblenda, dan biotit. Diagram variasi Harker unsur utama dan unsur jejak yang menunjukkan komposisi menerus menandakan bahwa mereka berasal dari satu sumber. Lava di daerah ini termasuk seri kalk-alkali K-tinggi, dengan kandungan Nb yang tinggi. Komposisi unsur Nb yang tinggi ini menunjukkan bahwa batuan ini lebih mirip dengan basal intra lempeng daripada tipe kalk-alkalin atau basal toleit busur kepulauan. Pengayaan unsur Nb yang diikuti oleh Th, Rb, dan normatif korundum menandakan magma sumber kaya akan unsur-unsur inkompatibel, dan merupakan ciri khas magma alkali. Kemiripan unsur jejak batuan vulkanik terhadap basal intra lempeng mengindikasikan konveksi baji mantel di atas slab subduksi mengandung komponen sumber berasal dari MORB dan OIB yang bervariasi, penambahan fluida berasal dari slab subduksi. Dengan demikian, diperkirakan bahwa konsentrasi Nb tinggi pada batuan vulkanik dari daerah Kabanjahe tergenerasi dari subduksi yang termodifikasi komponen OIB. Sebagai alternatif, suatu sesar dalam yang menyalurkan magma dari mantel bawah menghasilkan pengayaan alkalin pada batuan vulkanik. Makalah ini ditampilkan dengan menggunakan pendekatan aspek petrologi, khususnya berdasarkan geokimia termasuk unsur-unsur utama, jejak, dan unsur tanah jarang. Hasilnya diplot dengan menggunakan klasifikasi-klasifikasi yang umum dan khusus dalam pembahasan petrologi.

***Kata kunci**: petrologi, geokimia, Kabanjahe, busur tepi benua, tektonik*

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Introduction

The location of the researched area is shown on Figures 1 dan 2. The volcanic rocks from Kabanjahe Region, Karo Regency, North Sumatra Province is a product of Sibayak, Sipiso-piso, and Toba eruption which give an age of <0.074 Ma (Chesner and Rose, 1991) and display a wide range in chemical compositions, from basic to acid where basaltic andesite and andesite lavas are the main product. The distinctive rocks of arcs and orogenic zones are an association which on petrographic criteria would be called basalt, andesite, dacite, and rhyolite, in which intermediate members are more common than basic ones. Such an association is usually called the calc-alkaline series. The Quaternary to Neogene volcanic rocks found in this region define the northeastern part of Sumatra Continental Margin, and have response to the northeastward subduction of the Indian Ocean Plate beneath the Sumatra Island and an east-west strike-slip fault of the Sumatran Fault System (SFS) (Semangko Fault Zone or Barisan Fault Zone of some authors). The region is situated near an intersection between the NW-SE great Sumatran Fault System and the SW-NE Investigator Ridge (Page *et al.*, 1979).

Previous studies on magmatic rocks were briefly reported by Aldiss *et al*. (1983) and Cameron *et al*. (1982) during regional geological mapping of northern Sumatra. They further reported that the Tertiary and Quaternary magmatism in Sumatra has a wide spectrum of magma composition ranging from basic to acid, where the volcanism involved large volumes of felsic eruption such as Toba Tuff. There is no detailed petrological and geochemical study on the volcanic rocks from Kabanjahe region which has been reported. This paper presents new geochemical data on Quaternary volcanic rocks obtained from the particular area of Kabanjahe Region, and discusses the geochemistry and other important petrological aspects which then relates them to the plate tectonic theory, a model for its magmatic petrogenesis.

Nineteen samples were collected from Kabanjahe Region, eleven samples are derived from Sibayak Mount and Berastagi areas, six samples derived from Sipiso-piso Mount, area and two samples from northeast coast of Lake Toba. The Global Positioning System coordinates of the samples are plotted on Figure 3. The Sibayak and Berastagi samples

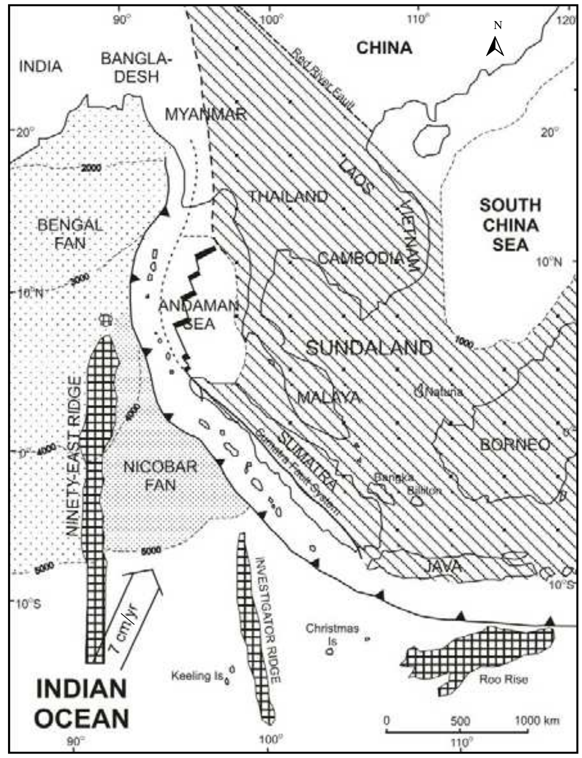

Figure 1. Tectonic setting map of Sumatra with the floor of the Indian Ocean subducting beneath the southwestern margin of the Sundaland Craton. The deformation front of the Sumatran subduction system is indicated by the tool bed line; spreading centers and transform faults are shown in the Andaman Sea (after Curray *et al.*, 1979).

consist of volcanics (lava and breccia) represented by samples 07BH01A - 07BH10A. The Sipiso-piso Mount area samples consist of lava flows represented by samples 07BH11A - 07BH15A, and the northeast coast represented by samples 07BH17AB. The samples labelled 07BH01A - 10A belong to the Singkut Unit (Quaternary), samples 07BH11A - 15A represent Sipiso-piso Centre (Quaternary), and sample 07BH17AB represents the Haranggaol Volcanic Formation (Quaternary). Seventeen samples have been selected for petrology includes petrography, geochemistry (major, trace, and rare earth elements). All of them are lavas. Analyses have been conducted at Geol-Lab in the Centre for Geological Survey Bandung. All samples were crushed in a WC crusher after removal of weathered rims and were cleaned then in an ultrasonic bath. Samples were dissolved in sealed Teflon beakers with HF-HNO_3 mixture, evaporated, dried down with 6 N HNO_3 and subse-

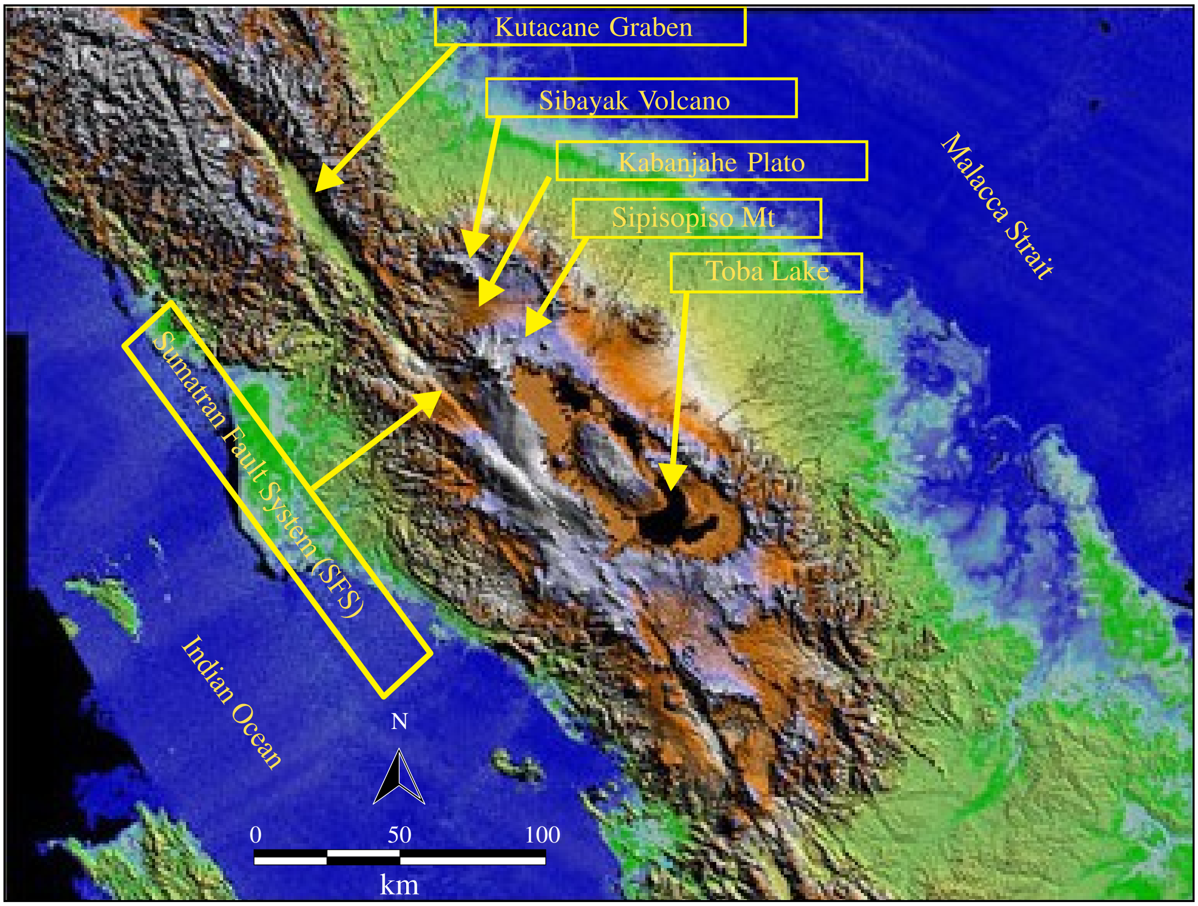

Figure 2. Satelite imagery of the northern part of Sumatra. Kabanjahe lies just to the northwest of Lake Toba and on the northeast of Sumatran Fault System (SFS).

quently taken up for analysis in 2% HNO_3. Analyzing rock samples for major elements (Na, Mg, Al, Si, P, K, Ca, Ti, Mn, Fe) is by using instrumental method XRF (X-ray Fluorescence Spectrometer Automatic, Phillips PW 1480). Trace elements (Rb, Ba, Nb, La, Ce, Sr, Nd, Zr, Sm, Dy, Y, Er, Yb, Ni, Ni, Th, U, V) and Rare Earth Element (REE) (La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Ho, Er, Tb, Yb) were determined on an ELA-ICP-MS (Excimer Laser Ablation Inductively Coupled Plasma Mass Spectrometer). In all cases, major elements are expressed as wt.% constituent oxides, while trace and Rare Earth Elements as parts per million, or ppm. Analysis of the total volatile content is approximately shown as the loss on ignition (LOI). The Fe content is presented as total Fe_2O_3. Rock classification and nomenclature is based on K_2O *versus* SiO_2 (Pecerillo and Taylor, 1976) and ($K_2O + Na_2O$) *versus* SiO_2 (Le Bas *et al*., 1986) diagrams. Most of the samples are basaltic andesite and andesite, minor basalt, dacite, and rhyolite that are arc calc-alkaline. They have been classified as Nb-enriched volcanic rocks.

Geology

Sumatra Island is the northwest oriented physiographic expression, lying on the western edge of Sundaland, a southern extension of the Eurasian Continental Plate (Figure 1). The main body of the island is composed of Paleozoic sediments and igneous rocks intruded by granitic plutons, and overlain extensively by Lower Tertiary sediments and Late Tertiary volcanics. The Kabanjahe Region is covered by various types of lithology and age (Figure 4). The oldest unit in this area is the Kluet

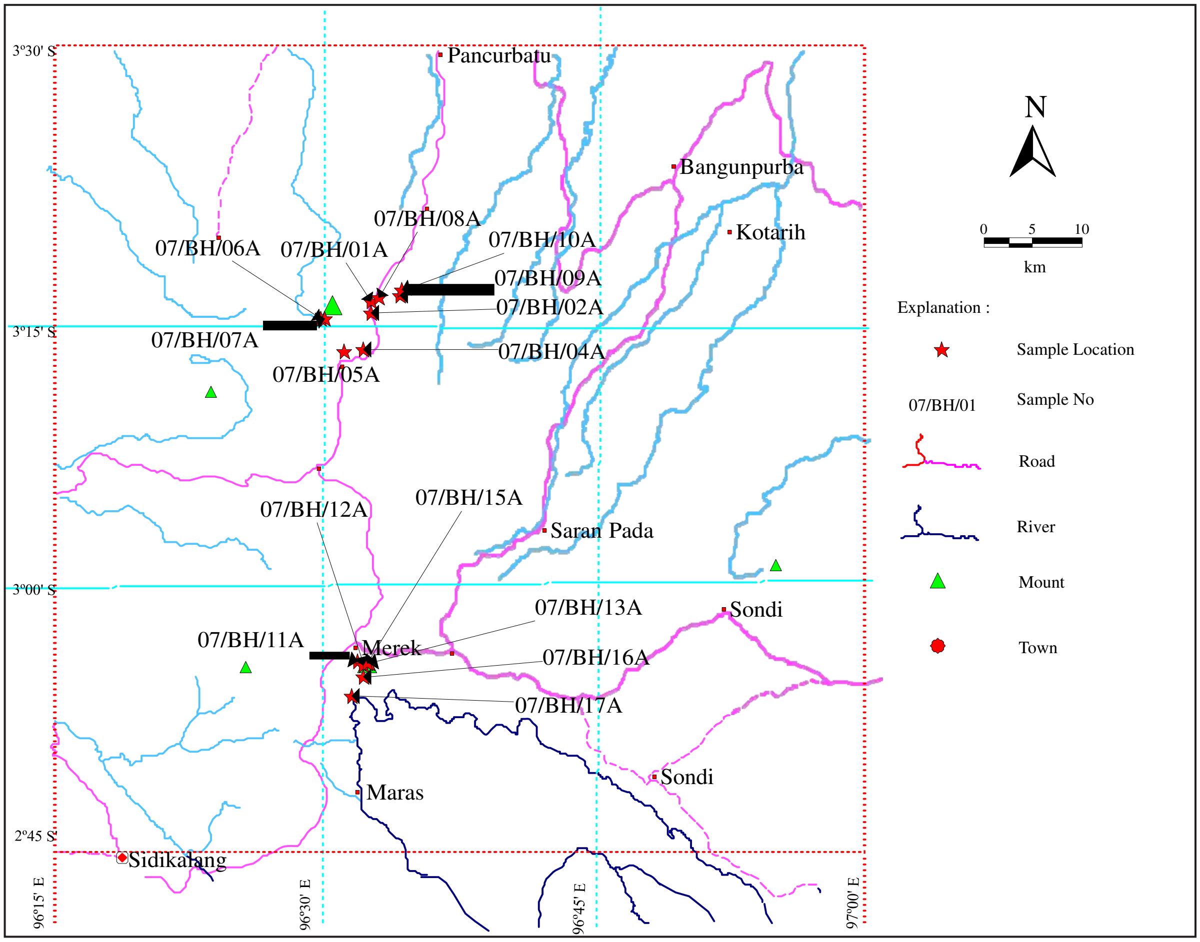

Figure 3. Locality map of the Kabanjahe Region showing sample locations.

and Bahorok Formations that are Late Carboniferous to Early Permian in age. The Kluet Formation consists of metaquartzose arenites, metawackes, slates and phyllites, while the Bahorok one comprises metawackes, metaconglomerate, and slate. They are comparable to the Kuantan Formation that belongs to the Tapanuli Group which crops out mostly in the central part of Sumatra. The Kluet Formation is unconformably overlain by the Oligocene Bruksah Formation comprising sandstone and conglomerate. Subsequently, the Bruksah Formation is overlain by the Middle Miocene Peutu Formation in turn overlain by the Late Miocene Haranggaol Volcanic Formation and in turn is overlain by the Mio-Pliocene Takur-takur and Simbolon units. The Peutu Formation crops out on the north coast of Lake Toba made up of sandstones, conglomerate, and calcareous mudstone. The Haranggaol Volcanic Formation cropping out along the coast of northwest of Lake Toba consists of andesites, dacite, and pyroclastics. Nishimura *et al*. (1977) reported a fission track age of 1.20 ± 0.16 Ma on zircon from the Haranggaol Volcanis. The Takur-takur unit mostly distributed around Mount Sibayak comprises andesite, dacite, and pyroclastics. All the above units are intruded by the Plio-Pleistocene Mendem Microdiorite. The Middle Pleistocene Toba Tuff sitting unconformably on the above units occupies a large area that composed of rhyodacitic tuffs, partly welded. Quaternary Volcanis continued during later Pleistocene to the present consisting of the Singkut Unit, Sibayak Unit, Sipisopiso Centre, Binjai Unit, Sibutan Unit, Sinabung Centre and Barus Centre. The Singkut Unit is distributed mainly to the south and northeast of Mount Sibayak and it consists of andesite, dacite, microdiorite, and tuff. The Sibayak Unit occupies

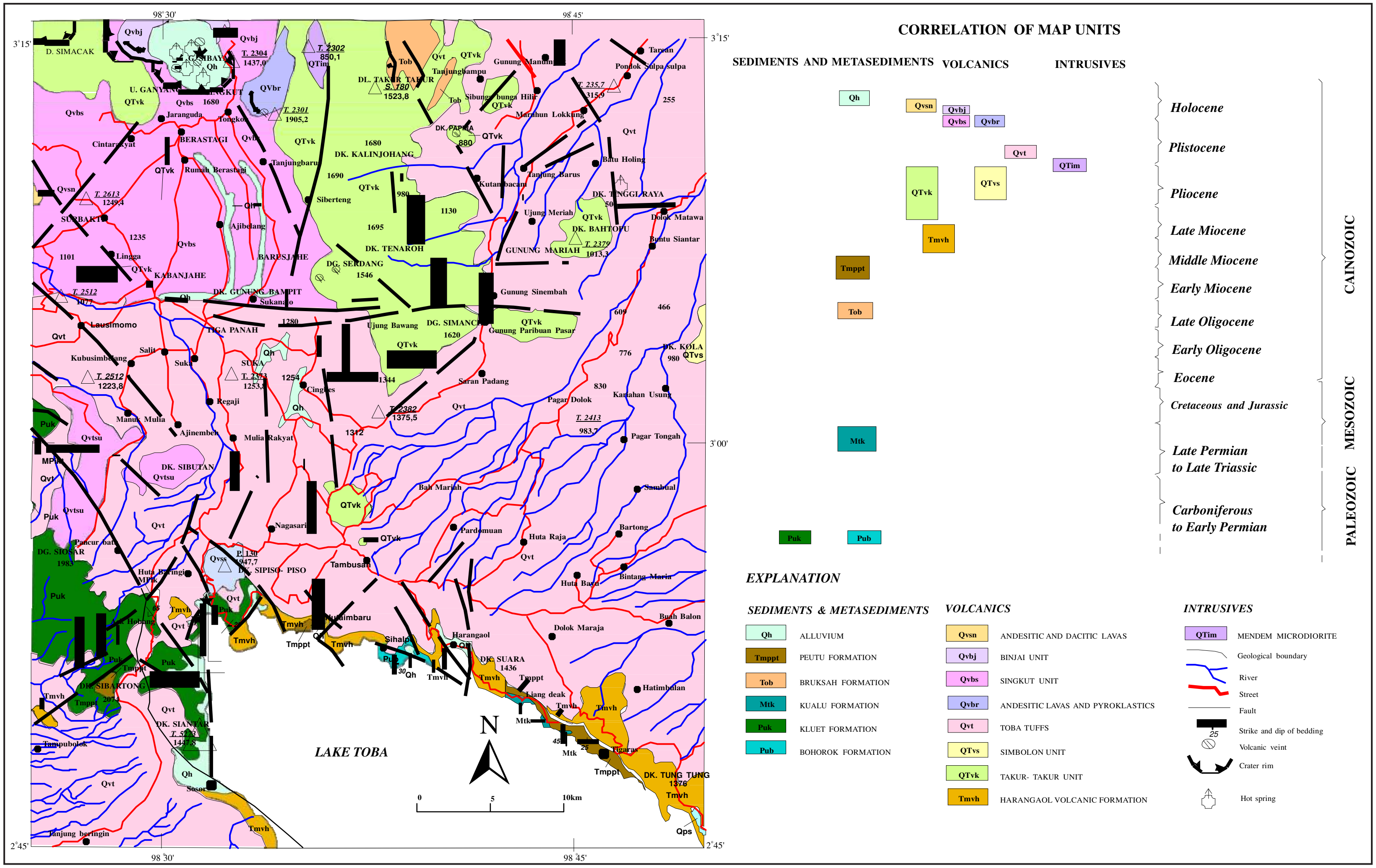

Figure 4. Geological map of the Kabanjahe Region, North Sumatra (source from Aldiss *et al.,* 1983 and Cameron *et al.,* 1982).

Sibayak Mount and is made up of andesite, dacites, and pyroclastics. The Sipiso-piso Unit occupying the Mount Sipiso-piso comprises dacite and andesite. The Binjai Unit occupies the northern part of Mount Sibayak and is distributed further north up to Binjai Town, consisting of andesitic to dacitic breccia flows. The Sibutan Unit distribution occupies right on the Mount Sibutan and surrounding this mount itself consists of rhyolitic lava and pyroclastics. The Sinabung Centre occupying the Mount Sinabung consists of andesitic and dacitic lavas. The Barus Centre spreading to the east of Mount Sibayak comprises andesitic lavas and pyroclastics. Alluvial deposits have been mapped along the coast of the Lake Toba, composed of gravels, sands, muds, fanglomerates, and diatomaceous earth.

Petrology

The petrographical determination of the volcanic rocks, i.e. basalt, andesite, dacite, and rhyolite have been based on the chemical nomenclature diagram proposed by Le Bas *et al*. (1986). This nomenclature has always been tested and verified by the microscopical observations using Leitz-pol type of binocular polarizing microscopy. The volcanic rocks from Kabanjahe Region are vesicular, amygdales, fine-grained, and porphyritic in textures. The groundmass is glass or pilotaxitic textures. Phases present as phenocrysts also occur in groundmass, which may also contain alkali feldspar. Apatite, zeolite, chlorite, and rare spinel are accessory phases. The most distinctive petrographic characteristic within the rocks is their richness in oxyhornblende and biotite. Pyroxene, hornblende, and biotite are the dominant mafic phenocryst. Hornblende and biotite are always brown to vermilion red in color. Geochemical signature of volcanic rocks from Kabanjahe Region will be determined by classification approached and composition of geochemical pattern on major elements, trace elements, and rare earth elements.

Petrography

Eleven samples from the Kabanjahe Region, of which eight samples (07BH01A, 02A, 03AB, 04A, 05A, 06A, and 07A) belong to the Sibayak Unit and three samples (07BH08A, 09A, and 10A) come from the Singkut Unit. Six samples (07BH11A, 12A, 13A, 14A, 15A, and 16A) collected from Sipiso-piso that belong to the Sipiso-piso Centre and two samples from north coast (07BH17AB) which are derived from the Haranggaol Volcanic Formation have been determined by using polarization microscope. Representative samples are shown on Figures 5 - 8.

The basaltic andesite and andesitic lavas of the Sibayak Unit are dark grey, vesicular, and amygdales, fine-grained, and strongly porphyritic in texture with phenocrysts of plagioclase, hornblende, clinopyroxene, and biotite. These phenocrysts are set on the groundmass of glass and plagioclase microlith and pyroxene or pilotaxitic textures (Figure 5). The plagioclase is anhedral to subhedral in form, up to 3 mm long in size, albit and carlsbad-albit twin, mainly unzoned plagioclase. A few plagioclase grains are weak to strongly zone, inclusions of other plagioclase and pyroxene, replacement of secondary minerals, holes, and rimmed by corrosion of iron oxide. The hornblende are brown in colour, oxidized, subhedral-euhedral in form, up to 3mm long in size, good parallel cleavage, high relief, a few grain rimmed by opaques (magnetite and ilmenite), and corrosion. A few hornblende grains have holes in the centre filled by plagioclase microlith and opaques. Some hornblendes are extremely altered indicating disequilibrium (Figure 5). The clinopyroxene is light grey in colour, anhedral in form, good cleavage, some minerals embayed and holes. The biotite is brown - oxy, subhedral - anhedral in form, up to 1mm long in size, oxidation, structure of bird eyes.The andesite lava from the Singkut Unit is strongly porphyritic in texture with phenocrysts of plagioclase and hornblende in groundmass of microlith of plagioclase and pyroxene and minor glass (Figure 6). The plagioclase phenocryst is anhedral in form, up to 2 mm long in size, strongly zoning with glass inclusion. The hornblende is brown in color, subhedral - anhedral in form, up to 2mm long in size, good cleavage, holes and corrosion in some parts. Some hornblende minerals are strongly altered indicating disequilibrium.

The basalt and basaltic andesite from Sipiso-piso has strongly porphyritic texture with phenocrysts of plagioclase and pyroxene in groundmass of glass and microlith of plagioclase and pyroxene (Figure 7). The plagioclase is subhedral - anhedral in form, up to 1mm long in size, carlsbad-albite twin,

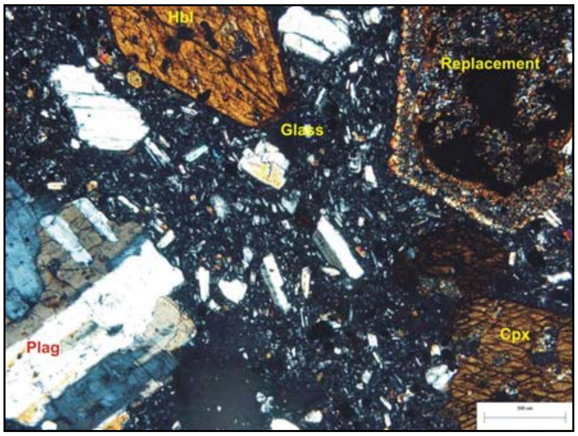

Figure 5. Basaltic andesite of the Sibayak Unit shows strongly porphyritic texture with phenocrysts of plagioclase, hornblende, and pyroxene in groundmass of microlith of plagioclase and pyroxene and minor glass (sample 07BH06A). Hornblende is strongly altered with replacement of secondary minerals (iron oxides), indicating disequilibrium. Plag = plagioclase, Cpx = clinopyroxene, Hbl = hornblende.

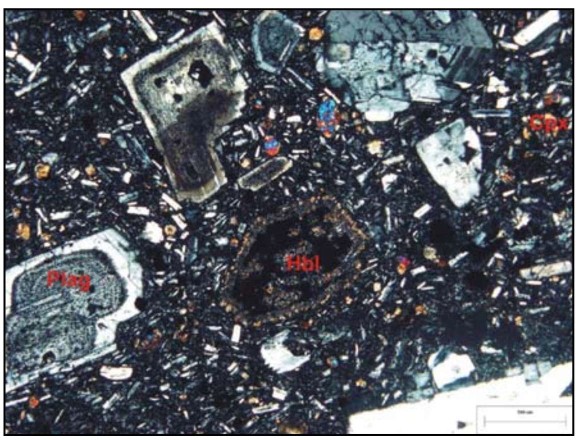

Figure 6. Andesite of the Singkut Unit shows strongly porphyritic texture with phenocrysts of plagioclase and amphibole in groundmass of microlith of plagioclase and pyroxene and minor glass (sample 07BH08A). Some plagioclases are strongly zoned with glass inclusions on the middle. Amphibole is strongly altered and replaced by glass and iron oxides.

zoned crystal (often with dusty core owing to glass inclusions). Pyroxene consists of clinopyroxene and orthopyroxene, light grey colour, subhedral - anhedral in form, simple twin.

The dacite from Sipiso-piso has strongly porphyritic texture with phenocrysts of plagioclase, K-feldspar, hornblende, and biotite in groundmass of microlith of plagioclase, K-feldspar and glass (Figure 8). The

Figure 7. Basalt of the Sipiso-piso Centre shows porphyritic texture with phenocrysts of plagioclase and pyroxene (clino- and ortho-pyroxene) in groundmass of glass and microlith of plagioclase and pyroxene (sample 07BH13A). Opx = orthopyroxene.

plagioclase is subhedral-anhedral in form, up to 2 mm long in size, carlsbad-albite twin, zoning, dirty surface, and fractures. K-feldspar (orthoclase and sanidine) is subhedral-anhedral in form, up to 2 mm long in size, dull and dusty surface. The hornblende is dark brown in colour, subhedral - anhedral in form, up to 2 mm long in size, high relief, and holes in some part. The biotite is brown in colour, subhedral-anhedral in form, good cleavage, and strongly oxidized in some parts.

The basaltic andesites of Haranggaol Volcanic Formation is strongly porphyritic in texture with

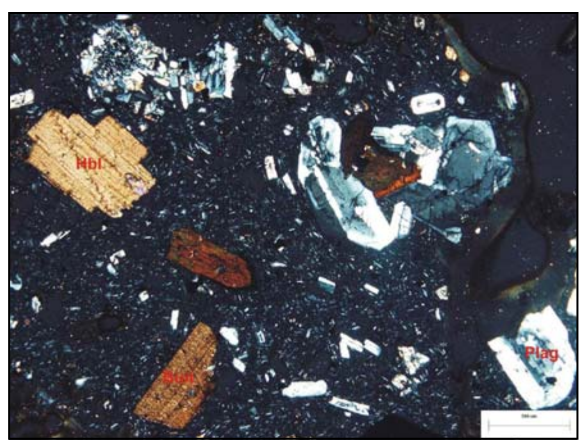

Figure 8. Dacite of the Sipiso-piso Centre shows strongly porphyriticc texture with phenocrysts of plagioclase, horblende, and biotite in groundmass of microlith of plagioclase and glass (sample 07BH11A).

phenocrysts of twin clinopyroxene and plagioclase in groundmass of glass and microlith of plagioclase and clinopyroxene. The rhyolite is porphyritic in texture with phenocrysts of quartz, K-feldspar, biotite, and hornblende in groundmass of glass and microlith of all the phenocrysts and plagioclase. The quartz is colourless, low relief, anhedral, up to 2 mm long in size. The K-feldspar is anhedral - subhedral, up to 2 mm long in size. Biotite is subhedral-anhedral, up to 1mm long in size, inclusion of opaques, holes. Opaques are black in colour, anhedral in form, up to 0.5 mm in maximum size.

Geochemistry

The volcanic rocks of Kabanjahe Region are characterized by a wide range in composition and their moderate to high-K calc-alkaline character. Representative bulk-rock major element analyses, C.I.P.W (Cross, Iddings, Pirsson, William) norms, trace-element abundances, and selected element ratios are shown in Tables 1 - 4. In terms of SiO_2 *versus* total alkalies (Le Bas *et al*., 1986) (Figure 9), most rocks are basaltic andesite and andesite, the rest are basalts, dacite, and rhyolites. They mostly fall on the calc-alkaline field on Figure 10 and calc-alkaline and tholeiitic field on Figure 11.

Major Element

Representative major elements analyses are given in Table 1. The volcanic rocks from Kabanjahe Region display a relatively wide range of silica (SiO_2) contents (50.80 - 74.35 wt.%). The rocks high alumina (Al_2O_3) contents, varying from 15.97 - 19.15 wt.% (except one sample 12.59 wt.%), low magnesium (MgO) content (1.81 - 4.56 wt.%), high in potassium (K_2O) (1.14 - 4.23 wt.%), and low in titanium (TiO_2) (< 0.8 wt.%). Half of the rock samples is high in loss on ignition (LOI) that up to 6.78 wt.%, mainly due to secondary minerals. The volcanic rocks are relatively potassium rich with K_2O/Na_2O values ranging from 0.71 - 1.82 and one sample (rhyolite) is 3.21. This value is typical of calc-alkaline volcanic rocks of continental margin (Jakes and White, 1972). Based on its major element content, the volcanic rocks are composed of basic-acid composition, ranging from basalt - rhyolite.

Plotting the rock samples on the Peccerillo and Taylor diagram shows that all the rocks from this area are high K-calc-alkaline volcanics except one sample (07BH03A) that is classified as medium-K calk-alkaline (Figure 12). The samples are mostly plotted near the border of the medium-K and high-K fields. To find out volcanic affinity, all samples have also been plotted by using correlation diagram of silica (SiO_2) *versus* Total Alkali ($K_2O + Na_2O$) based on Le Bas *et al*. (1986) (Figure 9). The result of this plot shows that most of the samples are basaltic andesite, and two samples from Sipiso-piso fall in basalt and rhyolite areas. The low medium-K calc-alkaline andesite sample (07BH03A; Table 1) is high quartz normative low normative orthoclase and albite.

The volcanic rocks from Kabanjahe Region have very low Mg value (Mg/Mg+Fe total) ranging from 24.00 to 42.00. If suggests that they are not in equilibrium with normal mantle (Cox, 1980). In high-K rocks, there is a fluctuation of Al_2O_3 between low (12.59 wt.%) and extremely high values (19.44 wt.%) (Jakes and White, 1972). Figure 13 presents Harker diagram showing major element concentrations plotted against SiO_2. Most major elements appear to increase in K_2O or decrease TiO_2, MgO, iron oxide (Fe_2O_3), calcium (CaO), and manganese (MnO) contents.

The CIPW norm calculations of the rocks are presented in Table 2. The rocks (basalt - rhyolite) are characteristically highly quartz-normative (9.91 - 28.53%). There is no olivine normative. The basalt (08BH13A) has a moderate normative feldspar content (~50%). Corundum appears in the norm of most rocks even in basalt up to 3%. The rhyolite is oversaturated and normative quartz is up to 47.63%. The rocks are moderate to highly orthoclase normative (6.74 - 18.44%) except one sample of 25.00% and high anorthite normative 12.33 - 35.2 %, except one sample (4.69%).

Trace Element

Trace element analyses of the volcanic rocks from Kabanjahe Region are represented in Table 3. Chrome (Cr) and nickel (Ni) are easily affected by removal or addition of ferromagnesian phases such as olivine. The abundances of vanadium (V) show an inverse correlation with SiO_2 (Figure 14h), but

Table 1. Results of the Major Element Analyses of the Rock Samples from Sibayak Unit, Singkut Unit, Sipioso-piso Unit and Haranggaol Volcanic Formation, in wt.%

Sample No	**07BH1A**	**07BH2A**	**07BH3A**	**07BH3B**	**07BH4A**	**07BH5A**	**07BH6A**	**07BH7A**	**07BH8A**	**07BH9A**	**07BH10A**	**07BH11A**	**07BH12A**	**07BH13A**	**07BH15A**	**07BH17A**	**07BH17B**
RockType / Elements	**Basaltic andesite**	**Basaltic andesite**	**Andesite**	**Andesite**	**Basaltic andesite**	**Andesite**	**Basaltic andesite**	**Andesite**	**Andesite**	**Andesite**	**Basaltic andesite**	**Dacite**	**Dacite**	**Basalt**	**Basaltic andesite**	**Ryolite**	**Basaltic andesite**
SiO_2	56.99	56.98	57.67	58.27	54.1	60.80	55.39	58.11	58.67	58.66	54.8	63.15	66.02	50.80	52.61	74.35	56.1
TiO_2	0.57	0.56	0.54	0.52	0.73	0.50	0.66	0.60	0.55	0.43	0.59	0.52	0.46	0.79	0.79	0.28	0.57
Al_2O_3	17.06	17.06	18.72	17.79	19.12	16.52	19.15	18.83	17.38	17.45	19.44	16.62	15.97	18.43	18.03	12.59	18.43
Fe_2O_3	7.64	7.4	7.46	6.63	7.58	6.23	6.83	6.00	8.11	5.60	6.05	4.71	4.57	9.64	10.27	1.42	7.35
MnO	0.15	0.14	0.16	0.14	0.16	0.13	0.15	0.11	0.19	0.14	0.13	0.10	0.09	0.16	0.18	0.03	0.15
CaO	6.6	5.03	4.02	3.93	5.68	5.13	6.41	2.71	6.76	6.63	4.78	4.35	3.86	6.59	7.08	0.94	7.34
MgO	3.45	2.92	3.35	3.67	3.29	2.49	3.09	2.18	3.39	4.73	2.49	1.81	2.27	4.17	4.56	0.00	3.71
Na_2O	2.02	1.64	1.08	1.31	2.5	1.83	2.92	1.9	1.93	1.83	2.54	3.34	1.97	1.50	1.55	1.32	2.10
K_2O	1.97	2.18	1.14	2.38	1.79	2.59	2.08	2.4	2.06	2.07	1.84	3.12	2.87	1.25	1.37	4.23	1.90
P_2O_5	0.11	0.11	0.06	0.08	0.23	0.00	0.19	0.18	0.04	0.16	0.20	0.20	0.00	0.18	0.17	0.01	0.06
LOI	1.77	4.46	6.36	6.15	4.41	1.82	2.57	6.62	1.36	3.30	6.78	1.69	3.33	4.89	2.64	3.48	0.93
Total	98.37	98.48	100.57	100.87	99.59	98.04	99.45	99.63	100.46	101.01	99.64	99.62	100.42	98.41	99.25	98.67	98.64
Mg# *	28.00	26.00	28.00	32.00	27.00	26.00	28.00	24.00	27.00	42.00	26.00	25.00	30.00	27.00	28.00	-	30.00

Tabel 2. CIPW Norm of the Rocks from Sibayak Unit, Singkut Unit, Sipioso-piso Unit, and Haranggaol Volcanic Formation

Minerals	**07BH1A**	**07BH2A**	**07BH3A**	**07BH3B**	**07BH4A**	**07BH5A**	**07BH6A**	**07BH7A**	**07BH8A**	**07BH9A**	**07BH10A**	**07BH11A**	**07BH12A**	**07BH13A**	**07BH15A**	**07BH17A**	**07BH17B**
Q	13.6	19.22	28.53	23.33	11.20	21.26	8.13	25.37	14.68	15.42	15.53	17.20	28.87	10.95	9.91	47.63	10.71
C	-	3.05	8.54	6.04	3.23	1.30	0.90	8.59	-	0.47	5.00	0.26	2.56	3.00	1.49	4.12	-
Or	11.64	12.88	6.74	14.06	10.58	15.31	12.29	14.18	12.17	12.23	10.87	18.44	16.96	7.39	8.10	25.00	11.23
Ab	17.09	13.88	9.14	11.08	21.15	15.48	24.71	16.08	16.33	15.48	21.49	28.26	16.67	12.69	13.12	11.17	17.77
An	31.66	24.42	19.55	19.17	26.85	25.66	30.56	12.33	32.18	32.01	22.57	20.43	19.27	31.69	34.13	4.69	35.25
Di	0.45	-	-	-	-	-	-	-	0.67	-	-	-	-	-	-	-	0.76
Hy	16.69	18.20	19.46	18.93	19.18	15.39	17.60	14.06	20.28	20.12	14.96	11.22	12.23	24.50	26.50	1.82	19.73
Mt	1.11	1.07	1.08	0.96	1.10	0.91	0.99	0.87	1.18	0.81	0.88	0.68	0.66	1.40	1.49	0.21	1.07
Il	1.08	1.06	1.03	0.99	1.39	0.95	1.25	1.14	1.04	0.82	1.12	0.99	0.87	1.50	1.50	0.53	1.08
Ap	0.26	0.26	0.14	0.19	0.54	-	0.45	0.43	0.09	0.38	0.47	0.47	-	0.43	0.43	0.02	14.00

Remarks:

Q : quartz

C : corundum

Or : orthoclase

Ab : albite

An : andesin

Di : diopside

Hy : hypersthene

Mt : magnetite

Il : ilmenite

Ap : apatite

Tabel 3. Results of the Trace Element Analyses of the Rock Samples from Sibayak Unit, Singkut Unit, Sipiosopiso Unit, and Haranggaol Volcanic Formation, in ppm

Elements \ Sample No	07BH1A	07BH2A	07BH3B	07BH4A	07BH5A	07BH7A	07BH8A	07BH9A	07BH10A	07BH11A	07BH12A	07BH13A	07BH15A	07BH17A	07BH17B
Rb	43.13	36.46	44.81	20.46	76.53	18.80	47.68	48.79	43.10	38.53	23.78	20.96	14.68	117.80	48.23
Ba	353.40	432.70	530.00	420.60	508.10	201.30	368.50	388.30	378.50	485.10	416.30	276.80	196.70	392.70	306.00
Nb	22.76	17.47	32.65	25.16	16.02	27.03	22.12	26.83	27.30	37.77	35.10	32.05	33.05	32.86	15.50
La	18.28	12.16	23.76	13.72	30.62	6.74	22.10	17.68	26.48	19.62	12.40	19.60	13.56	19.26	14.65
Ce	38.17	26.28	43.93	35.78	49.61	22.11	43.05	38.02	48.37	46.95	35.98	46.95	40.86	40.00	31.41
Sr	352.90	292.00	264.20	262.60	333.80	72.99	386.20	279.20	263.90	175.00	123.50	361.40	228.70	34.27	264.20
Nd	16.96	10.16	18.86	14.30	23.39	7.53	19.09	15.96	22.04	15.19	10.66	23.59	18.41	14.05	14.80
P	480.00	480.00	349.00	1,003.00	-	785.00	174.00	698.00	873.00	873.00	-	785.00	741.00	44.00	262.00
Zr	29.01	9.69	20.53	21.74	9.26	21.45	25.11	34.59	17.56	33.75	31.75	51.93	51.96	16.61	38.74
Sm	3.28	1.96	3.37	2.81	4.40	1.64	3.57	3.10	3.64	2.83	2.13	4.69	3.86	2.17	3.13
Y	14.58	11.77	15.58	12.44	29.43	7.95	15.79	14.29	16.92	13.12	8.67	18.76	13.62	9.74	18.41
Yb	1.62	1.48	1.80	1.54	2.40	1.12	1.77	1.62	1.77	1.53	1.70	2.00	1.50	1.23	2.06
Ni	1.73	0.10	0.10	0.10	0.10	0.10	0.45	0.10	0.10	0.10	0.10	0.10	0.01	0.10	0.10
Th	7.37	5.65	13.81	6.98	9.40	7.66	9.13	8.93	11.21	10.62	8.24	5.84	4.65	10.71	5.79
U	1.25	0.98	1.57	1.23	1.22	1.50	1.37	1.51	1.72	1.45	1.10	0.68	0.65	1.54	0.95
V	126.80	131.00	96.74	155.40	123.30	112.10	135.90	124.00	101.90	63.14	22.55	21.81	150.40	8.61	186.70
Cr	12.24	24.05	16.01	22.76	16.35	8.02	28.22	15.37	12.08	19.24	59.58	151.40	22.77	20.34	6.33
K	16,355.00	18,098.00	19,759.00	14,860.00	21,502.00	19,925.00	17,102.00	17,185.00	15,276.00	25,902.00	23,827.00	1,0377.00	11,374.00	35,117.00	15,774.00
Ti	3,417.00	3,357.00	3,117.00	4,376.00	2,997.00	3,597.00	3,297.00	2,578.00	3,537.00	3,117.00	2,758.00	4,736.00	4,736.00	1,679.00	3,417.00
Rb/Sr	0.12	0.13	0.17	0.08	0.23	0.26	0.12	0.18	0.16	0.22	0.19	0.60	0.06	0.44	0.18
K/Rb	379.00	496.00	440.00	726.00	280.00	1,059.00	357.00	352.00	354.00	672.00	1,002.00	495.00	775.00	298.00	327.00
Ba/Rb	8.20	11.90	11.80	20.50	6.60	10.70	7.70	7.90	8.80	12.60	17.50	13.20	3.40	3.30	6.30
La/Nb	0.80	0.70	0.73	0.55	1.91	0.25	1.00	0.66	0.97	0.52	0.34	0.61	0.41	0.59	0.95
La/Y	1.25	1.03	1.53	1.10	1.04	0.85	1.40	1.24	1.56	1.50	1.39	1.04	0.99	1.98	0.79
Zr/Nb	1.27	0.55	0.63	0.86	0.58	0.79	1.14	1.29	0.64	0.90	0.90	1.62	1.57	0.50	2.50
Ba/Nb	15.30	24.74	16.23	16.72	31.72	7.45	16.66	14.47	13.86	12.84	11.89	8.63	5.95	11.95	11.74
Ba/La	19.30	35.60	22.30	30.70	16.70	29.90	16.70	22.00	14.30	24.70	34.60	14.10	14.50	20.40	20.90
Zr/Y	1.99	0.82	1.32	1.75	0.31	2.70	1.59	2.42	1.40	2.57	3.66	2.77	3.81	1.71	2.10
Ce/Yb	23.56	17.76	24.40	23.23	20.67	19.74	24.32	23.47	27.33	30.69	33.63	23.47	27.24	32.52	15.25
(La/Sm)N	3.06	3.40	3.87	2.68	3.82	2.25	3.40	3.22	3.99	3.80	3.10	2.29	1.93	4.87	2.57
(La/Yb)N	6.84	04.98	8.00	5.40	7.73	3.65	7.57	6.61	9.70	7.77	6.82	5.94	5.48	9.49	4.31
(Tb/Yb)N	1.21	0.98	1.18	1.13	1.26	1.02	1.23	1.15	1.25	1.19	0.91	1.45	1.50	1.04	1.07

Tabel 4. Results of the REE Analyses of the Rock Samples from Sibayak Unit, Singkut Unit, Sipioso-piso Unit, and Haranggaol Volcanic Formation, in ppm.

Sample No / Elements	07BH1A	07BH2A	07BH3B	07BH4A	07BH5A	07BH7A	07BH8A	07BH9A	07BH10A	07BH11A	07BH12A	07BH13A	07BH15A	07BH17A	07BH17A
La	18.28	12.16	23.76	13.72	30.62	6.74	22.10	17.68	26.48	19.62	12.04	19.60	13.56	19.26	14.65
Ce	38.17	26.28	43.93	35.78	49.61	22.11	43.05	38.02	48.37	46.95	35.98	46.95	40.86	40.00	31.41
Pr	4.14	2.61	4.91	3.44	6.04	1.82	4.72	4.00	5.74	4.09	2.79	5.46	4.16	3.88	03.51
Nd	16.96	10.16	18.86	14.30	23.39	7.53	19.09	15.96	22.04	15.19	10.66	23.59	18.41	14.05	14.80
Sm	3.28	10.96	3.37	2.81	4.40	1.64	3.57	3.01	3.64	2.83	2.13	4.69	3.86	2.17	3.13
Eu	0.97	0.65	1.07	0.96	1.31	0.46	1.05	0.93	1.13	0.85	0.63	1.28	1.03	0.49	0.94
Gd	3.49	2.33	3.85	3.02	4.92	1.66	3.74	3.16	4.01	3.29	2.21	4.76	3.92	2.23	3.46
Tb	0.46	0.34	0.50	0.41	0.71	0.27	0.51	0.44	0.52	0.43	0.23	0.68	0.53	0.30	0.52
Dy	2.70	2.17	2.91	2.58	4.33	1.65	3.00	2.59	2.98	2.51	1.76	3.80	3.06	1.82	3.36
Ho	0.57	0.45	0.61	0.52	0.95	0.35	0.62	0.54	0.62	0.51	0.36	0.74	0.60	0.39	0.75
Er	1.63	1.42	1.81	1.54	2.74	1.02	1.79	1.62	1.78	1.55	1.08	2.13	1.67	1.23	2.11
Tm	0.24	0.21	0.27	0.23	0.37	0.15	0.27	0.24	0.26	0.22	0.15	0.30	0.23	0.19	0.30
Yb	1.62	1.48	1.80	1.54	2.40	1.12	1.77	1.62	1.77	1.53	1.07	2.00	1.50	1.23	2.06
Lu	0.25	0.22	0.29	0.23	0.35	0.17	0.27	0.26	0.27	0.23	0.17	0.30	0.23	0.19	0.34
Total REE	92.76	62.44	107.94	81.08	132.14	46.69	105.55	90.07	119.61	99.80	71.26	116.28	93.62	87.43	81.34

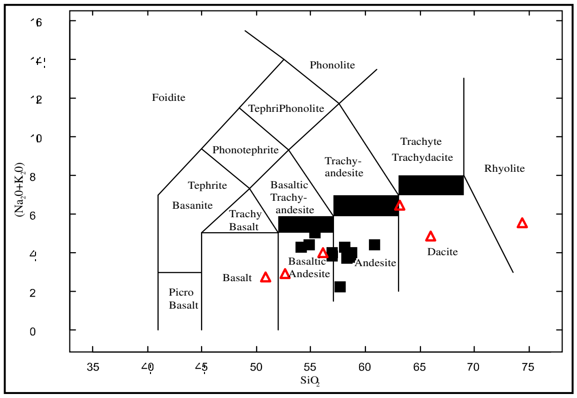

Figure 9. Diagram of SiO_2 *versus* alkali (K_2O+Na_2O) with field of rock nomenclature from Le Bas *et al*. (1986). Black square = Sibayak and Singkut Units, Triangle = Sipiso-piso

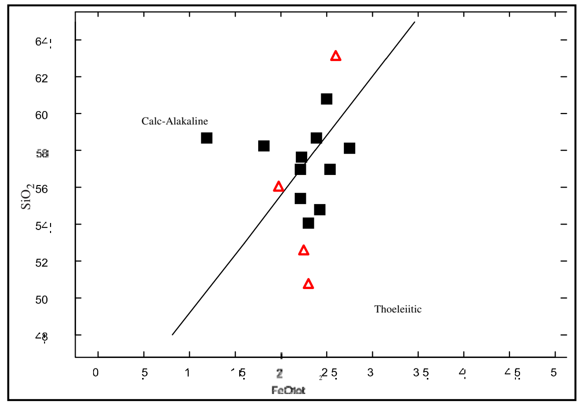

Figure 11. Diagram of SiO_2 *versus* FeO total / MgO of the lava from Sibayak - Sipiso-piso (after Myasiro 1974). Symbols as in Figure 9.

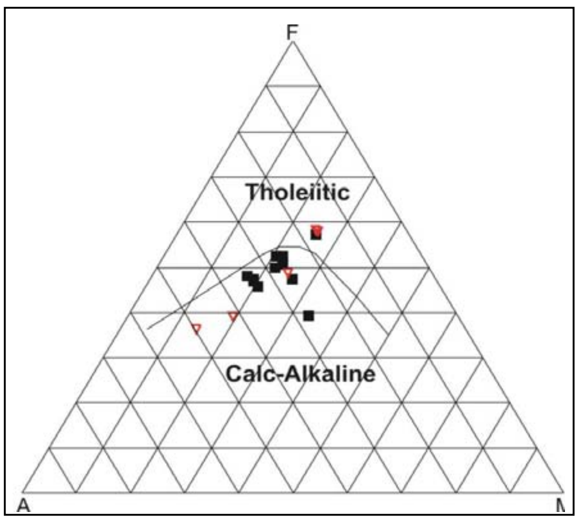

Figure 10. A (K_2O+Na_2O)-F (Fe_2O_3)-M (MgO) diagram (after Irvine and Bragar, 1971). Symbols as in Figure 9.

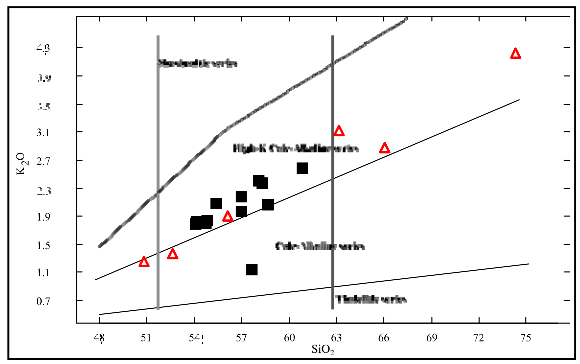

Figure 12. Chemical nomenclature diagram of SiO_2 *versus* K_2O with field for low-K (tholeiitic series) to alkaline (shoshonitic rocks) from Peccerillo and Taylor (1976). The Sipiso-piso samples are on average rich in potassium than the Sibayak and Singkut Units. Symbols as in Figure 9.

is not followed by Cr and Ni. The Ni content of the rocks is extremely low reflecting the evolved nature of the rocks, as shown by the very low Mg value (24.00 - 42.00). Similarly, the Cr contents are also very low. These data suggest fractionation of a chrome spinel (Hughes, 1982). V contents falls on a typical arc magma 120 - 175 ppm at SiO_2 58 wt.%. When compared with andesites of hypersthene rock series in Japan (Taylor and White, 1966), the rubidium (Rb) content in the andesites from this is are very high ranging from 18.80 - 117.80 ppm (average 19 ppm in Japan). This could be due to the higher potassium concentration in the rocks (K_2O=1.14 - 4.23 wt.%) than in Japan (0.9 wt.%). By comparing with orogenic andesite (Gill, 1981), the zirconium (Zr) contents of the rocks are low ranging from 9.26 - 51.96 ppm (average 110 ppm in orogenic andesite), and niobium (Nb) values (15.50 - 37.77 ppm) are extremely higher. Yttrium (Y) is moderate to high (7.95 - 29.43 ppm). High content of barium (Ba) (196.70 - 500.00 ppm) and low strontium (Sr) (13 samples 123.50 - 386.00 ppm, 2 samples 34.27 - 73.00 ppm) are present compared to calc-alkaline rocks (Jakes and White, 1972).

Figure 14 presents Harker diagram showing trace elements concentration plotted against SiO_2. Increase of the elements is shown by Rb, Ba, and thorium (Th), whereas decrease of element is shown

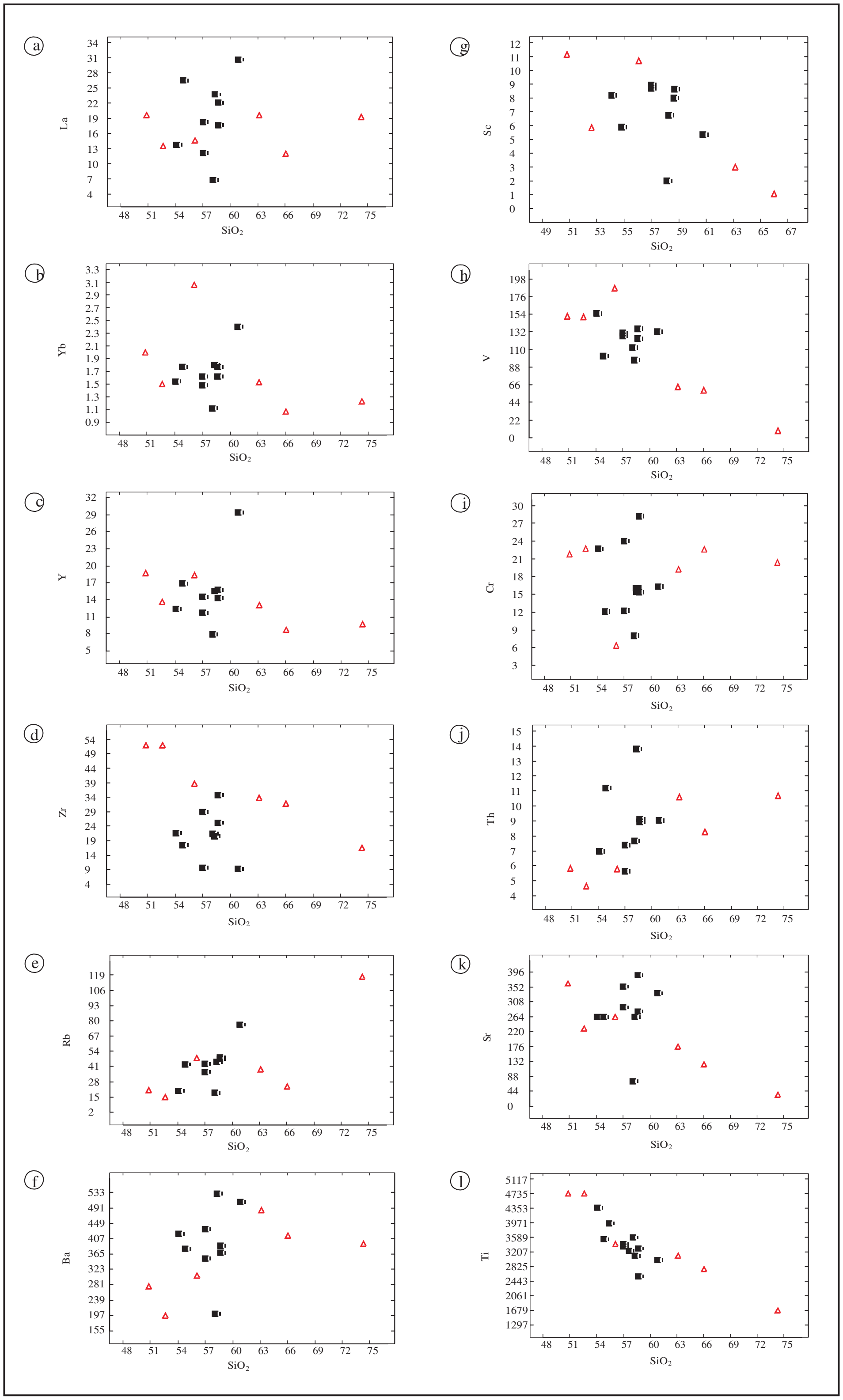

Figure 13. Harker diagram shows the major element variations. Symbols as in Figure 9.

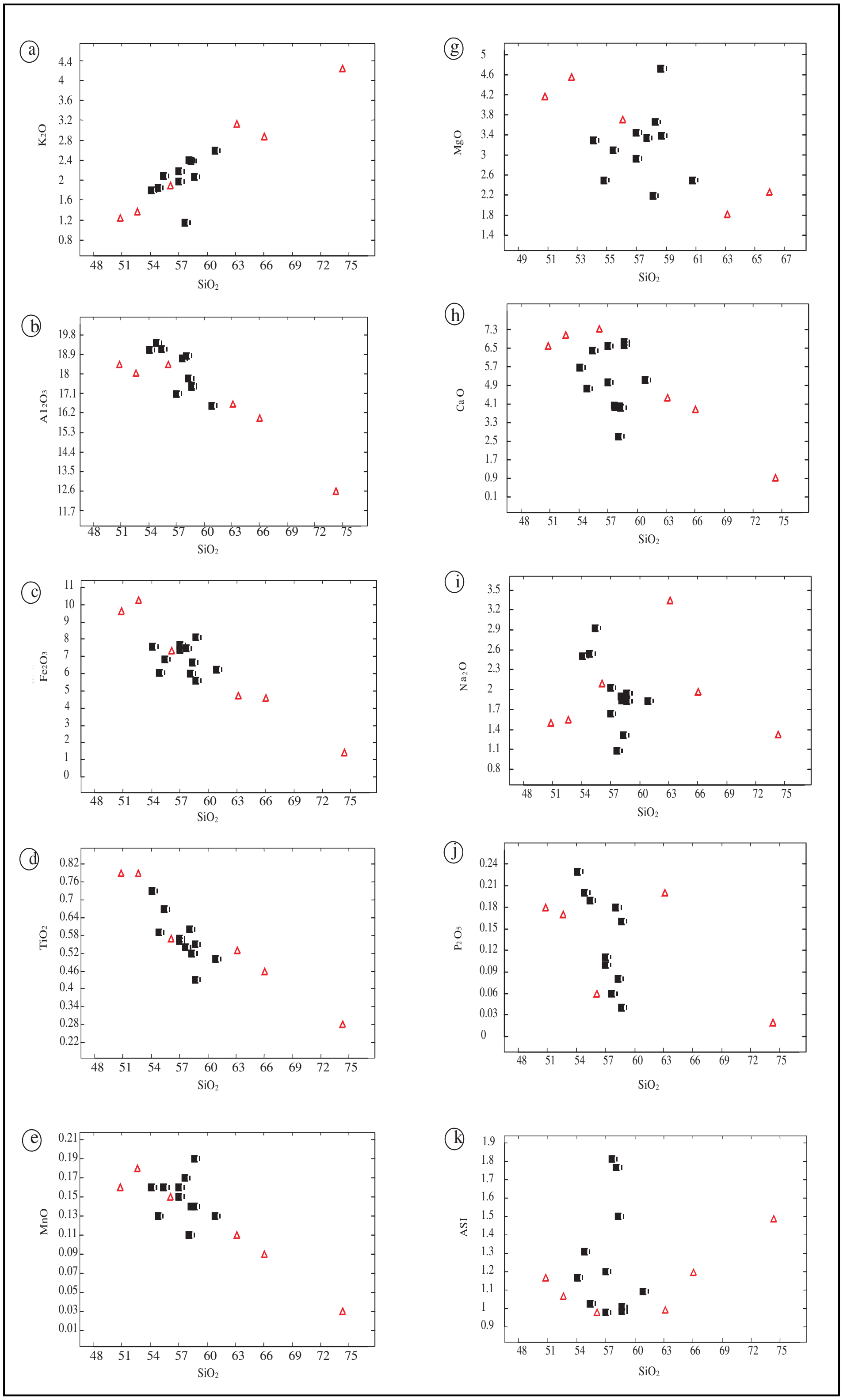

Figure 14. Harker diagram shows the trace element variations. Symbols as in Figure 9.

by Sr, titan (Ti), ytterbium (Yb), Y, Zr, and scandium (Sc), V. Decrease of V and Ti through a rocks series suggests Fe-Ti oxides (ilmenite or titaniferous magnetite) fractionation. The complexity of Sr variation and its abundances was due to the strong fractionation of Sr by feldspar. Kolbe and Taylor (1966), Hall (1967), and others found a decrease of Sr with increasing SiO_2 in calc-alkaline plutonic rocks. The similar trend is observed in island arc rock within the tholeiitic association. In high-K calc-alkaline rocks the converse is found; Sr increase with increasing SiO_2. On Figure 14k, the Sr contents of the volcanic rocks from the Kabanjahe Region decrease with increasing SiO_2 . High Nb of these rocks may have a source from tholeiite. Flat HFSE element is typical of MORB. Rb, Ba, and La are scattered but still showing a trend and have a similar behaviour to that of K_2O. In some high-K rocks (for example, in Eastern Papua), the crystallization of mica phase distorts the pattern of Ba as well as Rb variation, and even a decrease of Ba with increasing SiO_2 can be observed (Jakes and Smith, 1970). The rocks have high-Nb and low Sr and phosphor (P).

Figure 15 shows a MORB-normalized variation pattern for the rock samples from Kabanjahe Region. Element ordering and normalization values are from Bevins *et al*. (1984).The elements are ordered in a sequence of decreasing incompatibility, from the left to right.

The volcanic rocks from Kabanjahe, the part of the pattern from P to Cr (*i.e.* the immobile elements) lies parallel to but a lower level than MORB, which plots as a horizontal line at 1.0, as the data are MORB-normalized. In contrast, Rb, Ba, K, Th, and Nb (and to lesser extend La-Ce) are enriched above this level. A line drown through Nd-Cr and Sr should represent what the magma composition would have been without an element input from the subduction zone, assuming that it was derived by partial melting of MORB source mantle (depleted asthenosphere). The horizontal line may be displaced from the MORB line at 1.0 simply as a consequence of a different degree of partial melting, or subsequent crystal fractionation, than the MORB samples chosen for the normalization factor. The above line gives an indication of the contribution of the magma due to subduction-zone component added to the mantle wedge. The volcanic rocks from Kabanjahe Region are more akin to that of MORB

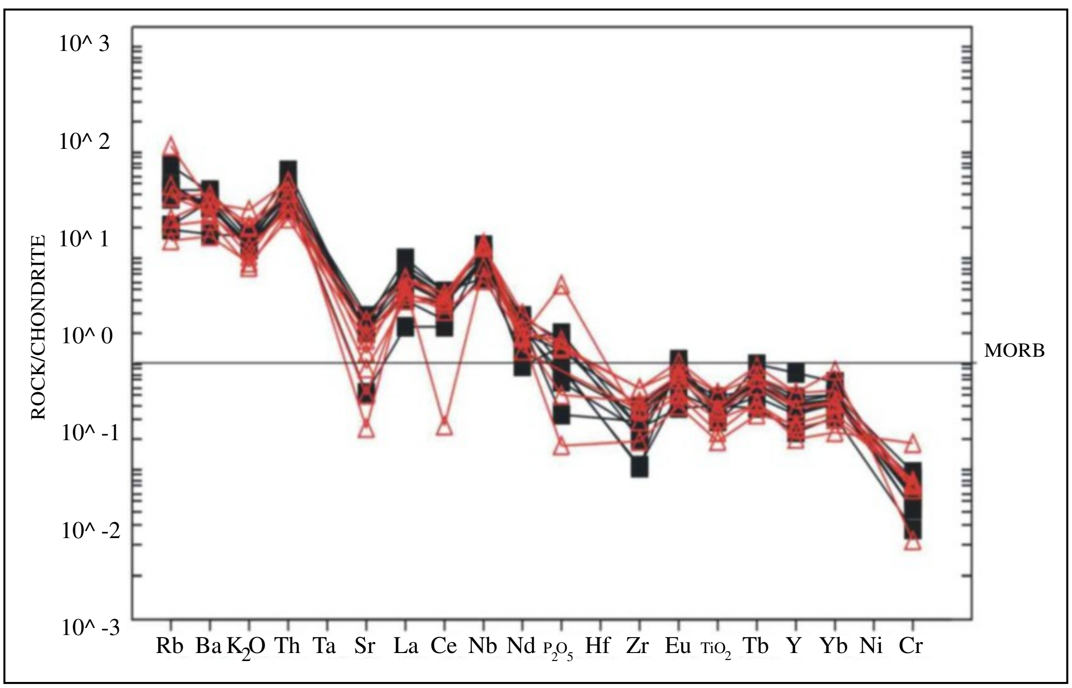

Figure 15. Plot of trace elements on spider diagram; the element values are divided by MORB (after Bevins *et al*., 1984). Black square = sample from Sibayak Unit and Singkut Unit, red triangle = Sipiso-piso Unit and Haranggaol Unit.

rather than to intraplate basal in which their immobile element patterns are slopping. In other words the mantle source of the intraplate basal magma was an enriched subcontinental lithosphere as defined by Pearce (1983, *in* Wilson, 1989). Therefore, it is suggested that crustal contamination does not appreciably add elements of the group P_2O5 –Yb – Ni - Cr, or indeed Sr. Ba and Th are the most enriched element in both cases. Contamination effects will obviously be easier to detect in basalts with originally flat MORB-normalized trace element pattern.

If the rocks are compared to the pattern for typical island arc calc-alkaline and tholeiitic basal (Wilson, 1989, p. 179), K, Rb, Ba, and Th show a typical calc-alkaline. In addition, La, Ce, Nb, and Nd are also enriched. However, the immobile elements (P-Cr ,and Sr) still define a relatively flat trend parallel to the MORB pattern, presumably reflecting the pre-subduction characteristic of the mantle wedge. Sr, Ce, and Nb are much more likely to be transported in a partial melt than an aqueous fluid, and this may reflect a fundamental difference in the petrogenesis of magma from this area to the normal tholeiitic and calc-alkaline series, in which Nb and Sr are low in tholeiitic and calc-alkaline series.

Although it is difficult to directly compare the samples due to their different fractionation state, there appear to be a trend from a more depleted to a more enriched pattern. MORB-normalized patterns for all samples are not typical of subduction-related magmas, with positive Nb anomalies, and negative spikes at K and Sr (Figure 15). The different fractionation stages of the samples make it difficult to directly compare with each other, but a general trend can be discerned.

Figure 16 shows chondrite normalized trace element abundances pattern (spider diagrams) for the volcanic rocks from Kabanjahe Region. Chondrite enrichment decreases successively from the low field strength element to the high field one, but a marked trough occurs at P. Compared to the equivalent diagram for Oceanic Island Arc basalts (Figure 17), they clearly show the same distinctive spike patterns with peak at Th and not for Nb. It is appropriate at this to consider the significance of the spiked spider diagram pattern in Figure 15b. From the above discussion it is clear that the trough at Nb may not actually reflect a real depletion in Nb. The apparent sharpness of the trough is in fact as a consequence of the marked enrichment of the adjacent elements Th and Ba in the spider diagram.

Incompatible enrichment element on Figure 15 with a peak at Nb, suggests that the source may also be enriched in incompatible elements. The trough at Sr probably results from the fractional crystallization of plagioclase from many basalts . A negative anomaly of Sr may correlate with the lack of plagioclase in the rocks. As plagioclase minerals are less abundant, it indicates the character of non-volcanic rocks (Wilson, 1989), as well as its (Y/Nb) ratio that less than 8 (Pearce and Can, 1973). A peak at Th and Rb combined with Nb may suggest uncontaminated of magma by lower continental crustal rocks.

ree

Rare Earth Element (REE) analyses of the lava basalt - rhyolite from Kabanjahe Region are presented in Table 4 and the result is summarized in spider diagrams (Figures 18a,b,c,d). La, Ce, and Nd contents range from 12 - 30.62 (except one sample 6.74), 22.11 - 49.61, and 7.53 - 23.59 ppm, respectively. Lutetium (Lu), samarium (Sm), gadolinium (Gd), erbium (Er), europium (Eu), terbium (Tb), dysporosium (Dy), thulium (Tm), and Yb contents range from 0.17 - 0.35, 1.64 - 4.69, 1.66 - 4.92, 1.8 - 2.74, 0.63 - 1.28, 0.15 - 0.37, and 1.07 - 2.40 ppm, respectively. The Ce content of these rocks is higher than that of orogenic andesite (Gill, 1981). The La content is equal to the average volcanic rocks from West Kalimantan (Harahap, 1990), and generally higher than the average in the SW Pacific (Ewart, 1979). The REE diagram presents the chondrite-normalized values of a number of rare-earth elements of the lavas that show an enrichment (rather strong fractionated) of light rare earth element and almost unfractionated heavy-REE (HREE) pattern. The REE pattern of basalt (Figure 18a) has a weak fractionated light-REE (LREE) [La- holmium (Ho) and almost unfractionated HREE pattern]. The REE pattern from andesite, dacite to rhyolite has a stronger LREE enrichment or steeper slope (Figures 18b-d), and the rhyolite has a very strong fractionated. REE patterns of volcanic rocks of the Kabanjahe Region have heavy REE (HREE) concentrations of 6 - 10 times chondritic suggesting that garnet is absent from the source. There is a marked enrichment

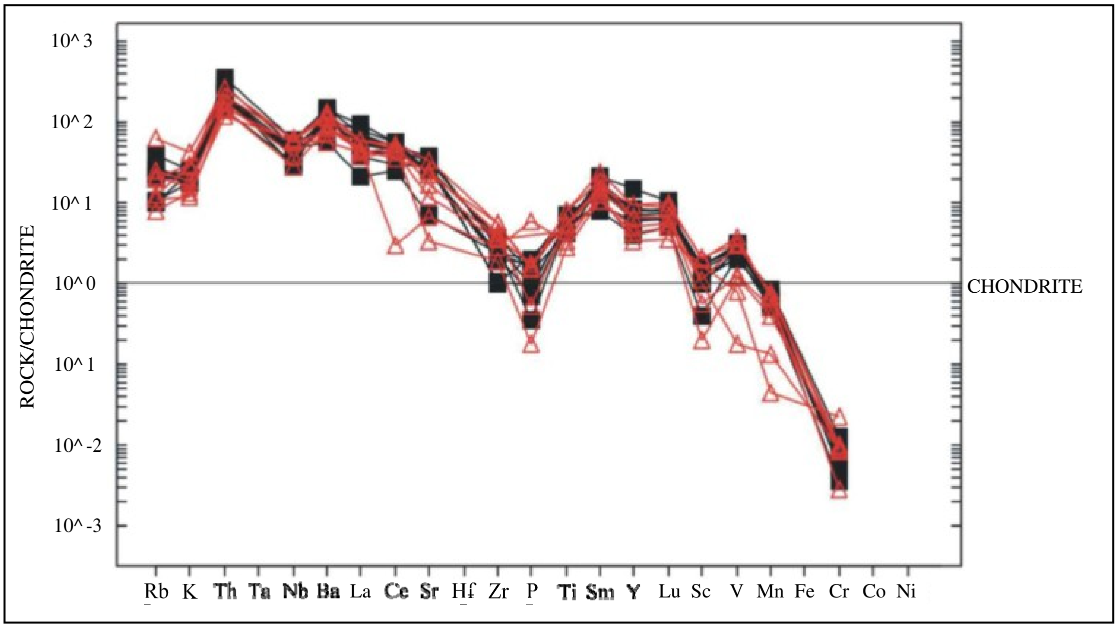

Figure 16. Plot of trace element on spider diagram, the element values are normalized to chondritic value (after Wood *et al*., 1979). Black square = sample from Sipiso-piso, red triangle = samples from Sibayak.

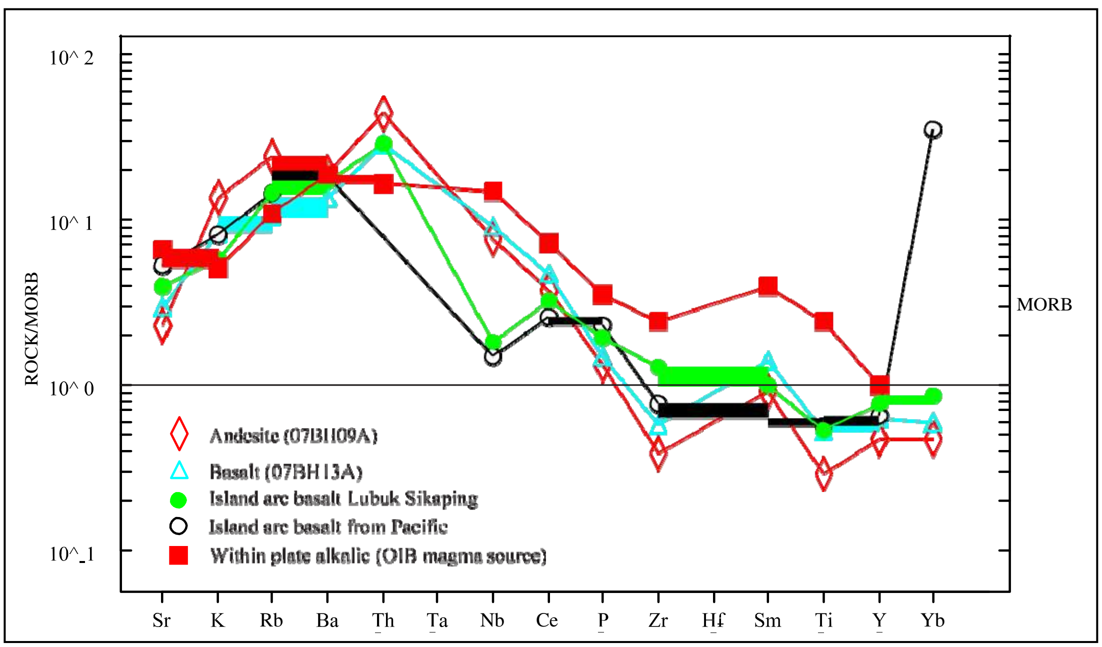

Figure 17. MORB normalized spider diagram of within plate alkalic (OIB source magma), island arc, and rocks samples from Kabanjahe Region. The element values are normalized to MORB values (after Pearce, 1983, in Wilson, 1989).

of La, Ce, Pr, Nd, and Sm concentrations, and it is flat heavy REE from Tm to Lu concentrations. The rocks are almost unfractionated HREE (Dy-Yb). No significant positive or negative Eu anomalies occur in the rocks which suggest that their Al_2O_3 contents are primary and not the accidental result of plagioclase accumulation. The plagioclase crystallization has not been sufficient to affect the REE distribution as is argued for abysal tholeiite (Kay *et al*., 1970). The lavas are characterized by enrichment in LREE with (La/Yb)N varying from 4 - 9.

dIscussIons And ImPlIcAtIons

Active continental margin and island arcs in the world have many features in common. They are accompanied usually by deep oceanic trenches and deep earthquakes. Sunda Arc of Sumatra where the studied area is located is an active continental margin in which oceanic crust flooring the Indian Ocean is moving northeasterly and being obliquely subducted at a Benioff zone along the western margin of Asian Plate. It is marked by the Sunda Trench in the west coast of Sumatra. This phenomenon was generated during Paleocene up to present day (Bellon *et al*., 2004; Sutanto inpress, 2011), leading to the origin of volcanic activities and to the origin of SFS. The formation of SFS two million years ago at the time was generally collinear with the volcanic belt (Nishimura *et al*., 1984) that is related to the Quaternary volcanic activity. The intersection of SFS and Investigator Ridge was interpreted by Page *et al*. (1979) as the central vent of the Toba volcanism which is located just to the south of the studied area. The data presented in this paper clearly confirm a well established concept that arc magmas have a complex multi source origin, including the subduction components and mantle wedge.

The rocks collected from the Quaternary volcanic units from Kabanjahe Region range in composition from basic to acid (basal to rhyolite) and belong to an arc magma of moderate to high K-calc-alkaline, low abundance of TiO_2, P_2O_5, and MgO with high-Nb and low Sr. They show a high concentration in incompatible elements and some geochemical characters which are typical arc calc-alkaline volcanics, they also occur in a continental margin arc such as low Ni, V/Ni >10, high Al_2O_3 (15.97 - 19.50 wt. %), and REE pattern with fractionated light REE and almost flat heavy REE pattern. On the other hand, high Nb, K, and La are characteristic features of intraplate signature rocks continental intraplate alkali basalt and OIB-type mantle component but distinct from MORB. These characters suggest that the Quaternary volcanic rocks from Kabanjahe Region have been formed by a similar genetic process as arc calc-alkaline rocks. The general characteristic features of the rocks are their enrichment in LILE that can be derived from subducted fluid at the subduction zone (Bailey, 1983).

According to Wilson (1989), in some rift basalt and more evolved lavas it can be clearly related by a process of fractional crystallization. However, there is the involvement of crustal rock in their petrogenesis, contamination, and AFC (Assimilation Fractional crystallization and Contamination) process. As mentioned in the previous section, Ba and Sr concentrations in the Quaternary andesite are significantly higher and lower respectively than those in the average island arc (Jakes and White, 1972) and also from calc-alkaline island arc rocks of West Sumatra (Harahap and Abidin, 2006; Harahap, 2006). The characteristically great enrichment of arc lavas in Ba and Ba/La ratios (14 - 35) like those from Java had been argued as the involvement of sediments in the magma source as subducting materials (Hartono, 1994).

Comparison of the spider diagram pattern for island arc basalts (calc-alkaline and tholeiite) with those of MORB and oceanic island alkali basalts, reveals that both group show the same range in overall slope of the REE pattern (La, Ce, Sm) from light-REE depleted to light-REE enriched. Thompson *et al*. (1984) considered that this was because the convecting mantle wedges above subducted slabs contained variable proportions of MORB-source and OIB-source components, to which fluids derived from the subducted slab were added. Thus, they regard low-K oceanic island-arc tholeiites as the hydrous subduction-related equivalents of MORB, whereas calc-alkali basalts and alkali (shoshonites) are generated from subduction modified OIB source components. So, for the generation of calk-alkaline and shoshonitic magmas, the subduction-zone fluid has a strong negative anomaly which, when superimposed upon Nb-enriched OIB source component, would produce arc basalts with a negative Nb anomaly. The Nb peak on the spider diagram on Figure 16 is similar to alkalic oceanic-island basalt (OIB) (Wilson, 1989) which suggests that the source of the Kabanjahe volcanic rocks may also be enriched in incompatible elements.

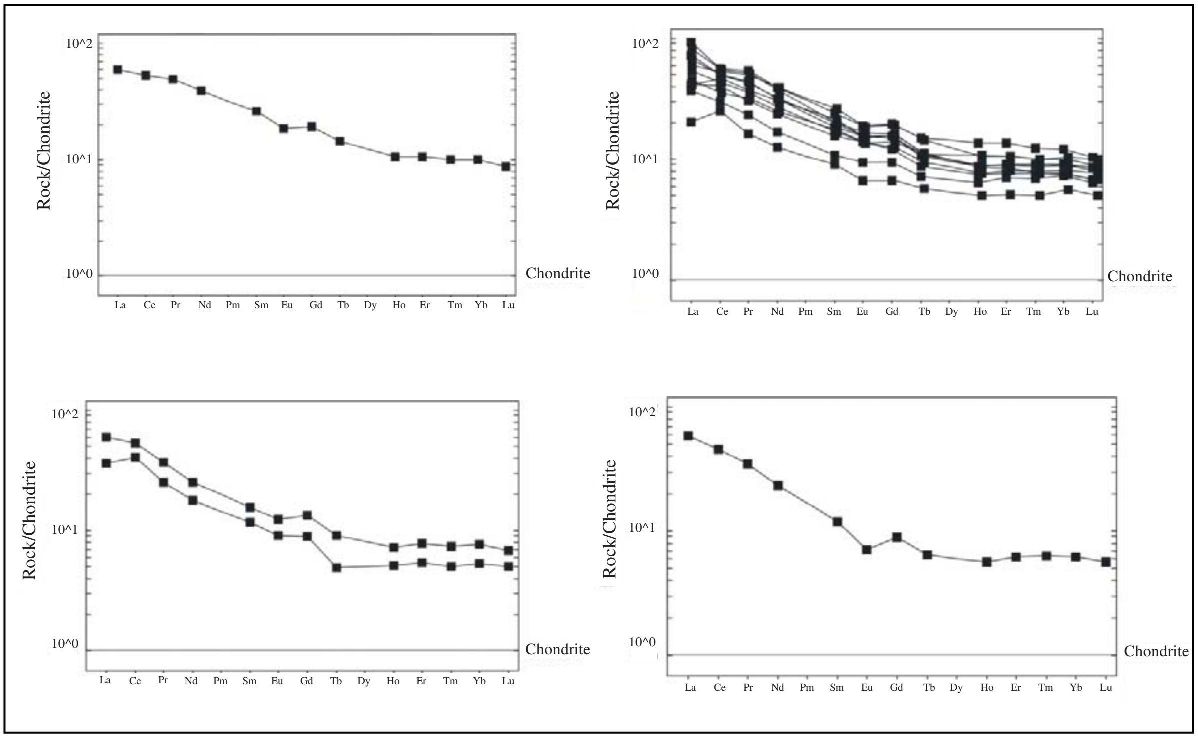

Figure 18. Diagram of basalt (a), basaltic and andesite (b), dacite (c), and rhyolite (d) of the rocks from Kabanjahe Region normalized into chondritic value (Wood *et al*., 1979).

The negative Sr anomaly is most probably a consequence of the low-pressure fractional crystallization of plagioclase. Crustal contamination may also be important in the generation of the negative Sr, P, and Ti spikes, but the effects can not be isolated easily from those of subduction-modified mantle source.

The presence of normative corundum is one of evidences indicating their magma was formed by partial melting of continental crust. The low K/Rb (280 - 1059) ratio is consistent with this interpretation. The partial melting may have been a result of heating of the crust by the input of basic magma since the Miocene. They are on a fault in an active continental margin. The high K-calc-alkaline and high Nb contents are thought to be influenced by the deep seated fault reaching the lower mantle (or probably "deep mantle plume"). Therefore, the present of Investigator fault zone should be fully accounted.

Once primary magmas have been generated by partial melting of the subduction-modified mantle wedge, they must subsequently rise through a thick section of continental crustal rocks, up to approximately 30 km in the case of Kabanjahe Region (Hamilton, 1979). Crustal contamination seems inevitable and subsequent geochemical evolution of the magmas must be dominated by assimilation - fractional crystallization processes (AFC) (DePaolo, 1981). The increase of K_2O with differentiation is not followed by Na_2O and ASI (Alumina Saturation Index) (see Figures 13 a, h, j), which means that these volcanics are not differentiated from metalluminous to peraluminous.

In general, the active continental margin magmas appear to show greater enrichment of a whole range of incompatible trace elements compared to oceanic island-arc basalts, which may reflect the combined effects of derivation from an enriched mantle source and crustal contamination.

Phenocrysts of biotite, hornblende, clinopyroxene and also ratio of K_2O/Na_2O = 0.61 - 1.1 are typical of calc-alkaline of continental margin. A combination of low and extremely high Al_2O_3 is typical for high-K rocks. The evidence of geochemistry shows that the rocks are moderate to high-K calc-alkaline, high Al_2O_3, low TiO_2 and low Mg values.

The trace element similarities of Kabanjahe rocks to OIBs and MORB generally suggest the presence of an OIB and MORB source. Thus, it seems inescapable that residual TNT phases (Ti-Nb-Ta, e.g. rutile, ilmenite, and perovskite; Arculus and Powell, 1986) are involved in the genesis at Kabanjahe. Arculus and Powel (1986) suggest that residual TNT phases (Ti-Nb-Ta, e.g. rutile, ilmenite, and perovskite) elevate the partition coefficients of HFS and sometimes LRE elements during melting of more enriched OIB source mantle (Saunders *et al*., 1980), thereby depleting these elements with respect to LIL elements.

Conclusions

The volcanic rocks from Kabanjahe region in northern Sumatra are ranging in composition from basalt to rhyolite. They are highly porphyritic in texture with phenocryst of plagioclase, clinopyroxene, hornblende, and biotite set in groundmass of glass suggesting rapid cooling. The principal major element characteristic of Kabanjahe volcanic rocks is their high Al_2O_3 content. A fluctuation of Al_2O_3 is typical for high-K rocks. Rock with low SiO_2 contents (<50%) do not occur, but 50.80 - 58.00 wt.% are common. Mg value is generally very low (24.00 - 42.00) and much of the compositional variation, particularly the range of SiO_2 contents, may be attributable to the combined effects of low-pressure fractional crystallization and crustal contamination. The volcanic products which are located 50 km east of the SFS are dominated by basaltic andesite with a high Nb, low Sr and P of medium to high K-calc-alkaline character.

A continuous range in Harker diagram indicates they are cognate. The petrogenetic model is controlled by crystal fractionation. Geochemical characteristics suggest they resemble the typical of arc volcanic rocks with enrichment in large ion lithophile elements and light rare earth elements relative to high field strength elements and heavy rare earth element. However, the high Nb-contents and low Sr of these volcanic rocks are not typical a common calc-alkaline and tholeiite series in island arc and continental margin arc related to a subduction environment like Java and West Sumatra and Kalimantan respectively. It can be seen that immobile elements such as P_2O_5, Zr, Ti, Y, Yb, Ni, and Cr define a negative anomaly and flat pattern. The high Nb-contents and the corundum normative suggest an alkaline magmatic source. The spider-diagram patterns normalized to chondrite show an Nb through compared to the light element that resemble the arc type magma commonly found in rift continental margin.

The volcanic rocks from continental margin of Kabanjahe region have also high elements concentrations of Rb, Th, and Ce concentration. The characteristically great enrichment of arc lavas in K, Th, Rb, and Nb was argued to be an indication of involvement OIB source magma. It is interpreted that the volcanic rocks are probably related to the Investigator Ridge as a conduit magma from the lower mantle rich alkali magma of an OIB character. A positive Nb anomaly is interpreted associated with the presence in the mantle of a phase which is stable under the P, T, and H_2O conditions generated by the geodynamic context. The negative spikes of Sr, P, and Ti of the volcanic rocks from Kabanjahe region were also thought to be related to the crustal contaminations.

Regarding the pattern of the rock samples in REE pattern-diagram (Figures 18a - d), the rock pattern represents relatively flat pattern of HREE (Lu-Yb-Tm-Er-Ho-Tb). The HREE concentration is similar for the basalt to rhyolite. Their coherence suggests that the rocks may have a similar magma source. The differences depend on the degree of the primitive magma and the crystallization processes.

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