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原著論文

Two types of volcanic rocks in the Bombookhoi Formation, South Gobi Province, Mongolia—A preliminarily report

Davgadorj KHISHIGBADAM[1)]*, Kazuhiro TSUKADA[2)],
Jamsuren ERDENEBAYAR[3)], and Nuramkhaan MANCHUK[4)]

1）Graduate School of Environmental Studies, Nagoya University, Nagoya 464-8601, Japan
2）Nagoya University Museum, Nagoya 464-8601, Japan
3）Department of Geology and Hydrogeology, School of Geology and Mining Engineering, Mongolian University of Science and Technology, Ulaanbaatar, 14191, Mongolia
4）Empasoft Institute of Technology, Ider University, Ulaanbaatar, Mongolia
*Corresponding author (E-mail address: b.khishigbadam@gmail.com)

Abstract

The Central Asian Orogenic Belt (CAOB) is the core geologic unit to understand the tectonic history of Eurasian continent. Although the Mesozoic volcanic rocks in the South Mongolia are the key factor in revealing the later stage of the CAOB formation, very few attempt on its geochemistry have been made. This study gives the basic geochemical information of the volcanic rocks of the Bombookhoi Formation, which has been assigned to the "Upper Cretaceous," of the South Mongolia, and discusses its tectonic setting.

The volcanic rocks of the study area are divided into the tholeiitic basalt (SiO_2: 46–49 wt%, FeO*/MgO: 6.0–9.0, Mg#: 17–23) and calc-alkaline andesite (SiO_2: 54–57 wt%, FeO*/MgO: 1.6–2.6, Mg#: 40–52). Although the both has a signature of volcanic arc environment such as distinctive Nb negative anomaly in the MORB-normalized multi-element concentration diagram, these has probably been derived from the different sources of magma each other judging from FeO*/MgO ratio, Mg#, and others.

It is considered that, by the Jurassic, the South Mongolia block and Siberian craton/North China block had already been amalgamated each other to complete the core part of the "East Asia," and neither oceanic plate subduction nor arc volcanism is assumed to have occurred in the South Mongolia at the Late Cretaceous. Therefore, age-confirmation of this formation, such as by isotopic dating and others, should be required further. Then, if the volcanic rocks of the Bombookhoi Formation are truly Upper Cretaceous, re-consideration for the basic tectonic scheme around the South Mongolia block at Late Cretaceous will be needed.

Keywords: tholeiitic basalt, calc-alkaline andesite, volcanic arc, Late Mesozoic, Bombookhoi Formation

Introduction

The Central Asian orogenic belt (CAOB), which lies among Siberian craton, North China block, Tarim block, and East European craton (Sengör *et al*., 1993) is a crucial geologic unit in understanding the development process of the Eurasian continent (Kovalenko *et al*., 2004) (Fig. 1a). It is generally accepted that the CAOB has been formed due to several processes such as subduction-accretion of the oceanic plate, volcanic arc magmatism, and collisions of continental fragments during the amalgamation of these cratons and blocks.

In the southern CAOB, an area lying the Siberian craton, South Mongolia block, and North China block from north to south, the geological setting of Mongolia is a significant factor in clarifying the Paleozoic–Mesozoic tectonics of the CAOB. It is considered that the core part of the "East Asia" was formed basically by the collision

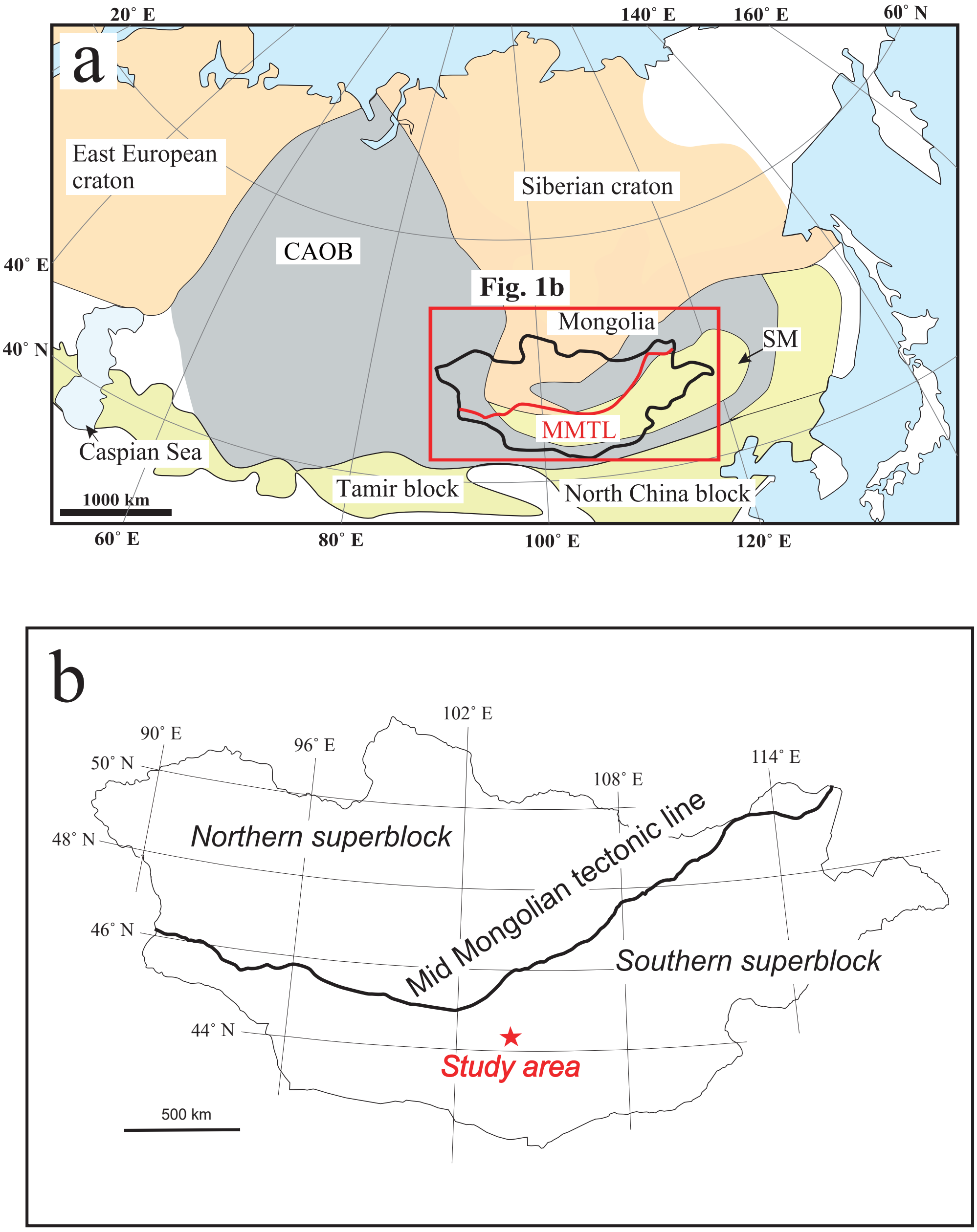

Fig. 1 (a) Simplified Tectonic map of Northeast Asia showing the Central Asian Orogenic Belt based on Tsukada (2013). (b) Tectonic division of Mongolia is after Tomurtogoo (2003). CAOB: Central Asian orogenic belt, SM: South Mongolia block, MMTL: Mid Mongolian tectonic line, Red star: Study area.

and amalgamation of the Siberian craton, South Mongolia block, and North China block at Late Mesozoic. And, volcanic activities have been recognized at South Mongolia in the Late Jurassic–Early Cretaceous (Mineral Resource Authority of Mongolia and Mongolian Academy of Sciences, 1998; Tomurtogoo, 2003; Badarch *et al*., 2002; Kurihara *et al*., 2008; Onon and Tsukada, 2017). Lebadeva (1933) firstly defined the "Mesozoic and Cenozoic basalts" in the South Mongolia, and Togtokh *et al*. (1986) redefined the basalts as a part of the Upper Cretaceous Bombookhoi Formation. Despite the Late Mesozoic igneous activity is essential part to know the tectonic setting of the South Mongolia at the Late Mesozoic, little is known on the detail petrography and geochemistry of the "Mesozoic basalts." This study describes petrography and geochemical composition of the volcanic rocks of the "Upper Cretaceous" Bombookhoi Formation at the Ulaannuur area, Mandal-Ovoo Village, Umnugovi Prefecture, Mongolia, and discusses its tectonic setting.

Geological setting at the study area

Mongolia is geologically divided into the Northern and Southern superblocks by the Mid Mongolia tectonic line, and the study area is in the Southern superblock (Fig. 1b). The basement rocks of the study area are divided into the Silurian Mandal-Ovoo, Kharaatshand, Khanankhyar, and Mushgai formations, and the Jurassic Ulgii Formation (Togtokh *et al.*,1986). The Mandal-Ovoo Formation consists mainly of shale, sandstone, and minor limestone. The Kharatshand Formation conformably overlies the Mandal-Ovoo Formation. This formation yields Upper Silurian rugose corals from limestone layers. The clastic and volcanic rocks of the Khanankhyar Formation, which consists of siltstone, limestone, sandstone, gravel, and andesite, unconformably cover the Kharatshand Formation (Togtokh *et al.*, 1986). The Mushgai Formation, which thrusts over the Mandal-Ovoo Formation, consists of sandstone with thick limestone layers in 20–30 m having abundant coral fossils (Togtokh *et al.*,1986). The Permian Khoolt Formation, consists mainly of gabbro, gabbro diorite, and granitic rocks, is overlain by the Lower Cretaceous Manlai Formation. The Upper Jurassic Ulgii Formation is generally composed of dacite, andesite/basalt, rhyolite, and calcareous and clayey rocks. The Ulgii Formation unconformably overlies the Mandal-Ovoo Formation, then is unconformably overlain by the Cretaceous rocks (Fig. 2).

The Cretaceous rocks, overlying the basements, are divided into the the following three formations with conformable relationship in ascending order, Manlai, Khukhshiyr, and Bombookhoi formations. And, the Bombookhoi Formation is overlain by the Baruungoyot Formation which yeilds Upper Cretaceous fossils of dinosaurs, crocodilians, and other land-lived mammals. According to the stratigraphic relationship, the Bombookhoi Formation has been assumed to be the Upper Cretaceous (Togtokh *et al.*, 1986). The Bombookhoi Formation is composed of coarse clastic rocks in its lower part and overlying volcanic rocks (Fig. 3a). The study

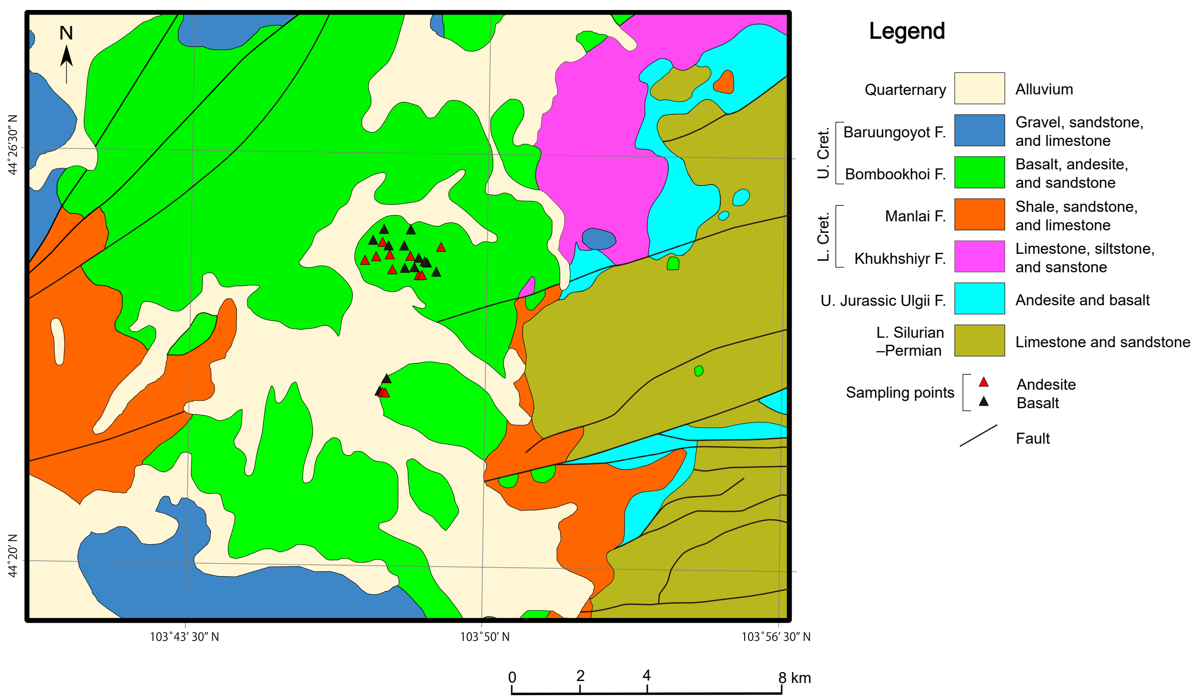

Fig. 2 Simplified geological map of the study area (modified from Togtokh *et al.*,1986). Sampling localities are also shown. L. Silurian: Lower Silurian, U. Jurassic: Upper Jurassic, U. Cret: Upper Cretaceous, L. Cret: Lower Cretaceous, F.: Formation.

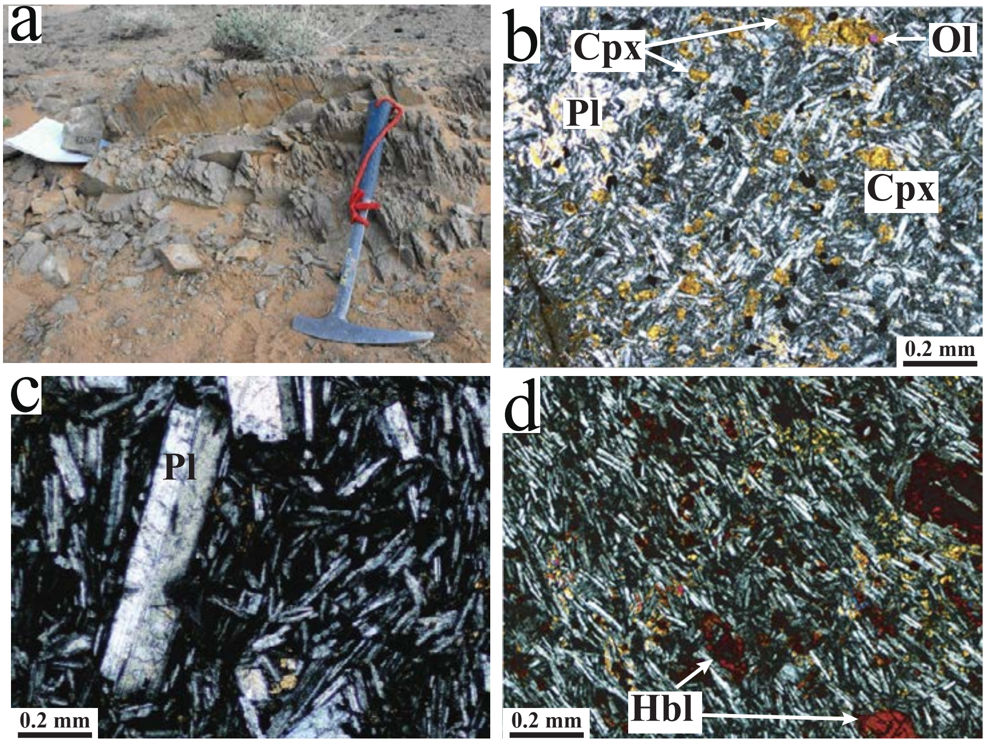

Fig. 3 (a) Field occurrence and photomicrographs of the volcanic rocks of the Bombookhoi Formation. (b) Photomicrograph of the sample No. GU302 showing an intersertal texture with plagioclase and clinopyroxene, olivine in basalt. (c) Photomicrograph of the sample No. GU201. Plagioclase phenocrysts are embedded in a matrix. (d) Photomicrograph of the sample No. GU306 showing a flow texture of small plagioclase laths. Cpx: clinopyroxene; Hbl: hornblende; Pl: plagioclase; Ol: Olivine.

area exposes the volcanic rocks of the Bombookhoi Formation.

Petrographic examination for 30 lava samples from the Bombookhoi Formation shows that the lava with intersertal/trachytoid texture has euhedral/subhedral plagioclase up to 5 cm in major axis, clinopyroxene (Cpx), olivine, and hornblende lie in a groundmass composed of smaller plagioclase and interstitial chloritic material (Fig. 3b–d). Samples containing olivine are free of hornblende, and those including hornblende are barren of olivine. The main constituent is plagioclase, and next in abundance is Cpx, then olivine/hornblende. Minor amounts of opaque minerals are included. In some samples, plagioclase and hornblende crystals arrange sub-parallel to show a flow structure texture (Fig. 3d).

Chemical composition of the volcanic rocks of the Bombookhoi Formation

Twenty-five samples of the volcanic rocks of the Bombookhoi Formation were analyzed for the major 10 elements and trace elements (Cr, Co, Ni, Cu, Zn, Ga, Rb, Sr, Y, Nb, Mo, Ba, Pb, and Th) using X-ray Fluorescence Spectrometer installed at the Field Research Center of the Mongolian University of Science and Technology (XRF; Rigaku Primus II ZSX equipped with Rh X-ray tube, 50 kV, 60 mA). In the XRF analysis, glass beads were prepared by fusing mixtures of 1.5 g of powdered sample with 6.0 g of lithium tetraborate. Calibration was carried out using the standard rock samples issued by the Geological Survey of Japan (GSJ) and the composite standards prepared by Yamamoto and Morishita (1997). Analytical precision of major elements was estimated to be < 1% for Si and about 3% for other elements, except for TiO_2 and MnO, whose analytical precision is > 3% when the measured level is < 0.1% (Takebe and Yamamoto, 2003) and that for trace elements (Co, Zn, and Ga) was estimated to be less than 10% (Yamamoto and Morishita, 1997). The analytical results are shown in Table 1.

Table 1 Whole rock chemical composition of the volcanic rocks of the Bombookhoi Formation. Major elements are displayed to 3 significant digits. No.: number, Fe_2O_3*: total iron as Fe_2O_3, FeO*: total iron as FeO, b.d.l.: below detection limit, -: not analyzed.

	Basalt													Andesite											
Sample No.	GU317	GU302	GU201	GU410	GU411	GU303	GU305-2	GU409	GU203	BZ8	BZ7	GU607	GU604	GU206	GU314	GU211	GU212	GU215	GU306	GU210	GU414	GU209	GU605	GU608	MS802
Major elements (wt%)																									
SiO_2	47.1	46.5	48.2	48.8	46.8	48.4	46.2	48.9	48.7	47.5	49.3	47.9	48.5	55.6	56.6	55.6	55.9	54.7	55.1	55.8	55.6	56.5	56.1	57.1	53.8
TiO_2	1.82	1.73	1.78	1.64	1.80	1.68	1.57	1.83	1.84	1.91	1.76	1.39	1.39	1.09	1.10	1.10	1.09	1.10	1.12	1.14	1.08	1.12	0.886	0.946	1.09
Al_2O_3	11.7	11.7	13.9	12.0	11.5	12.2	11.4	14.0	14.0	13.4	14.1	12.3	12.4	17.3	17.6	17.3	17.4	17.3	17.3	17.6	17.6	17.7	18.6	19.1	15.2
Fe_2O_3*	18.7	19.7	16.5	17.9	20.0	17.1	20.7	16.1	16.8	18.2	16.0	19.4	18.3	8.32	7.66	8.39	8.11	8.00	8.25	8.02	7.46	7.24	7.50	7.96	11.2
MnO	0.306	0.319	0.282	0.211	0.262	0.263	0.356	0.305	0.204	0.266	0.316	0.313	0.301	0.133	0.117	0.115	0.110	0.108	0.171	0.0750	0.109	0.0760	0.127	0.124	0.203
MgO	2.03	2.88	2.41	2.19	2.59	2.39	2.54	2.21	2.49	2.27	2.16	1.92	2.19	3.38	3.20	3.06	2.81	3.50	3.15	2.72	3.45	2.86	2.63	2.71	6.04
CaO	8.92	8.61	9.38	8.64	9.00	9.58	8.18	9.28	9.47	9.36	9.22	8.58	8.46	6.19	6.24	6.27	6.46	7.16	6.09	6.37	6.05	6.16	5.87	5.98	7.28
Na_2O	3.59	3.33	3.00	3.42	3.06	3.48	3.49	3.09	2.99	2.94	3.16	3.12	3.21	4.17	4.31	4.26	4.24	4.33	4.29	4.28	4.34	4.35	4.46	4.24	3.26
K_2O	2.88	2.59	3.06	2.81	2.12	2.46	2.64	3.12	2.44	3.17	3.06	2.51	2.55	1.88	1.82	1.65	1.78	2.19	2.16	1.91	2.15	2.27	1.92	1.91	0.684
P_2O_5	0.437	0.421	0.501	0.443	0.448	0.438	0.415	0.506	0.509	0.502	0.507	0.344	0.346	0.435	-	0.441	0.449	0.433	0.440	0.439	0.434	0.446	0.325	0.331	0.215
Total	97.5	97.8	99.0	98.1	97.6	98.0	97.5	99.3	99.4	99.5	99.6	97.8	97.6	98.5	98.6	98.2	98.4	98.8	98.0	98.4	98.2	98.7	98.4	100	98.9
FeO*	16.6	17.5	14.7	15.9	17.8	15.2	18.4	14.3	15.0	16.2	14.2	17.3	16.3	7.41	6.82	7.47	7.21	7.12	7.34	7.13	6.64	6.45	6.68	7.09	9.92
Trace elements (ppm)																									
Cr	87	120	116	110	124	100	112	118	131	124	94	21	24	109	108	116	110	117	122	117	114	110	21	25	207
Co	20	20	25	20	20	21	20	20	21	24	19	16	17	22	22	24	24	22	23	23	21	22	17	18	34
Ni	32	43	47	40	44	30	40	43	47	46	35	6	8	45	43	46	46	39	48	45	42	45	7	11	55
Cu	33	75	31	31	37	33	39	34	40	24	27	25	29	36	35	37	35	37	39	36	31	29	29	30	5
Zn	92	93	99	95	93	102	93	85	93	93	91	92	88	91	93	92	90	87	90	92	94	84	93	91	82
Ga	19	20	19	18	20	22	19	21	20	20	20	21	17	16	17	19	18	15	20	21	15	17	21	22	15
Rb	47	43	48	47	39	29	46	46	33	48	36	41	43	45	43	49	48	45	49	25	46	47	43	40	15
Sr	834	801	795	808	853	956	798	820	840	780	834	858	793	820	821	837	847	818	789	840	813	794	864	852	211
Y	17	17	18	18	17	20	17	17	18	18	17	17	17	16	19	17	19	18	17	19	17	18	17	19	31
Nb	14	13	15	14	13	14	13	14	13	14	13	7	8	15	14	15	14	14	15	15	13	14	9	9	2
Mo	10	10	11	10	11	15	10	10	11	13	11	10	b.d.l.	11	8	11	13	13	12	10	10	11	12	9	9
Ba	832	756	822	804	821	933	824	859	821	808	811	780	759	822	825	806	847	799	840	846	780	755	756	789	21
Pb	8	7	7	6	11	8	9	9	7	8	8	11	8	5	10	10	11	4	8	8	9	10	10	7	20
Th	8	4	4	7	b.d.l.	1	5	4	6	2	2	6	11	11	9	8	6	13	6	4	12	10	3	1	17

Major elements are displayed to 3 significant digits. No.: number, Fe_2O_3*: total iron as Fe2O3, FeO*: total iron as FeO, b.d.l.: below detection limit, -: not analyzed.

As a results, the examined samples are clearly divided into the following two groups, (1) basaltic rocks of about 46–49 wt% in SiO_2 concentration (call basalt hereinafter) and (2) andesitic rocks of about 54–57 wt% in SiO_2 concentration (call andesite hereinafter) (Table 1). The basalt is, TiO_2: 1.4–1.9 wt%, Al_2O_3: 11–14 wt%, FeO*: 14–18 wt%, MnO: 0.20–0.36 wt%, MgO: 1.9–2.9 wt%, CaO: 8.2–9.6 wt%, Na_2O: 2.9–3.6 wt%, K_2O: 2.1–3.2 wt%, P_2O_5: 0.34–0.51 wt%. And, the andesite is, TiO_2: 0.9–1.1 wt%, Al_2O_3: 15–19 wt%, FeO*: 6.5–10 wt%, MnO: 0.080–0.20 wt%, MgO: 2.6–6.0 wt%, CaO: 5.9–7.3 wt%, Na_2O: 3.3–4.5 wt%, K_2O: 0.68–2.3 wt%, P_2O_5: 0.22–0.45 wt%. The basalt is higher in TiO_2, FeO*, MnO, CaO, and K_2O concentrations, and lower in Al_2O_3 and Na_2O concentrations than those of the andesite (Fig. 4). MgO and P_2O_5 concentrations of both types seem to be nearly the same. With increasing SiO_2 concentration, the basalt shows obvious decreasing trends of FeO* and MnO, and increasing trend of Al_2O_3. In the andesite, Al_2O_3 concentration increases with increasing SiO_2. The decreasing of the MnO, MgO, and CaO concentrations with increasing SiO_2 concentration might be recognized (Fig. 4).

Tectonic setting of the volcanic rocks of the Bombookhoi Formation

Volcanic rocks are largely formed at a mid-oceanic ridge, a volcanic arc, and an intra-oceanic/-continental plate (i.e., within-plate). The mid-oceanic ridge basalt (MORB) generally shows tholeiitic nature, and rocks erupted at the within-plate typically have alkaline/tholeiitic characteristics. And, at the volcanic arc, calc-alkaline/tholeiitic rocks are commonly formed (e.g., Miyashiro and Kushiro, 1975; Pearce, 1982). The important geochemical indicator of the rocks formed at the volcanic arc are an enrichment of large ion lithophile elements (LILE) and a depletion of Nb and Ta compared to LILE at MORB-normalized multi-element concentration diagram (spidergram hereinafter), a feature that is not observed in MORB and rocks at the within-plate (e.g., Gill, 1981; Pearce *et al.*, 2005). The spidergram of the volcanic rocks examined here likely that the both basalt and andesite of the

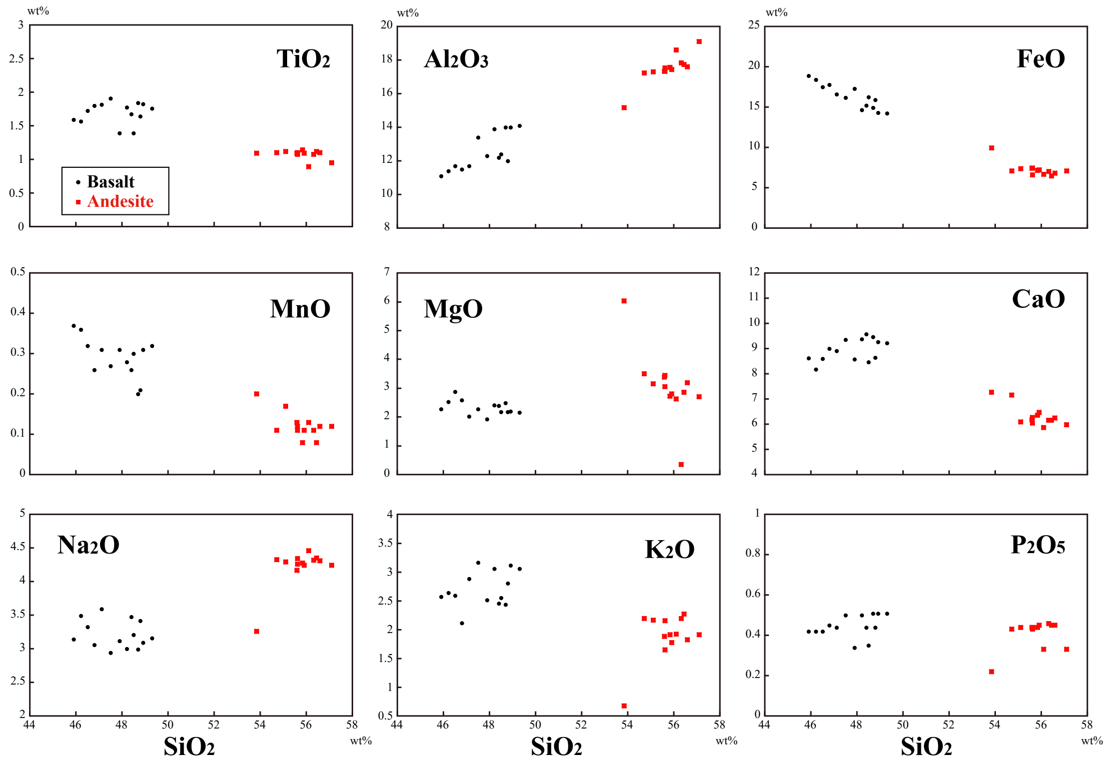

Fig. 4 Variation diagrams for major elements of the samples. FeO*: total iron as FeO.

Bombookhoi Formation were formed at an arc environment where had a subduction of some oceanic plate beneath a continent (Fig. 5).

The next question is whether the magma of the andesite had evolved, as a result of crystallization differentiation, from the basalt magma. If so, increasing of FeO* and Na_2O and decreasing of MgO and CaO are expected with increasing SiO_2 concentration, from basalt to andesite, along with the crystallization of olivine, pyroxene, plagioclase, and others in a magma. However, in the reality, FeO* concentration of the basalt is definitely higher

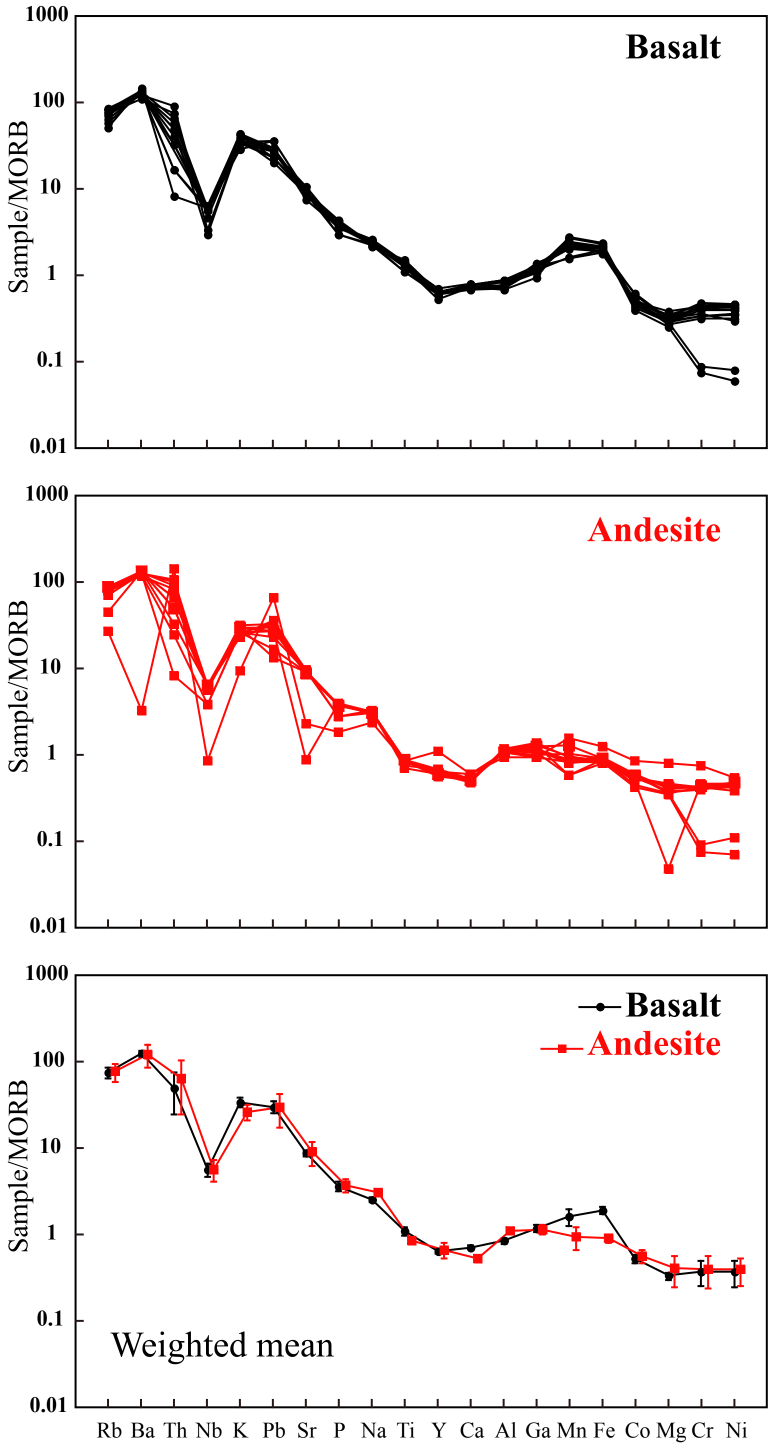

Fig. 5 MORB-normalized multi-element concentration diagram.

than the andesite, and MgO of the basalt is slightly lower than the andesite (Fig. 4). Besides, if the both basalt and andesite were derived from a single magma, K_2O concentration of the andesite is assumed to be higher than that of the basalt, however the andesite is clearly lower in K_2O concentration than the basalt (Fig. 4). This fact also suggests that the magma of the andesite was not the product evolved from the basalt magma through crystallization differentiation process. Furthermore, according to Mg# (100 × Mg / (Mg + Fe) calculated on a molar basis using total Fe^{2+} content) vs. SiO_2 diagram, the basalt is clearly lower in Mg# than the andesite. Incidentally, it is generally known that the plots of samples form a liner trend in the diagrams when these are the resulted from crystallization differentiation in a magma. The data of Mg# of the basalt samples are almost the same regardless SiO_2 concentration, while those of the andesite samples decreases with increasing SiO_2, and the basalt and andesite may not form a trend together. Taking these lines of evidence together, the deduction is that a magma of the andesite was not formed through a simple crystallization differentiation process from that of the basalt.

In the FeO*/MgO vs. SiO_2 diagram, the basalt and andesite are assigned to tholeiitic and calc-alkaline rocks, respectively, and this is also confirmed by the plots in the (Na_2O + K_2O)- FeO*-MgO diagram (Irvine and Baragar, 1971; Miyashiro, 1974) (Fig. 6b, c). Therefore, the basalt and andesite of the Bombookhoi Formation might be derived from the tholeiitic and calc-alkaline magmas each other.

Future issues to be required

This study revealed that a part of the volcanic rocks of the Bombookhoi Formation were formed at a volcanic arc where some oceanic plate should have been subducted beneath a continent. The Bombookhoi Formation has been assigned to the Upper Cretaceous (Togtokh *et al*., 1986). On the contrary, it is generally accepted that, by the Jurassic, the oceans existed between the South Mongolia block and Siberian craton/North China block had already been extinct, and these craton and blocks had amalgamated each other to complete the core part of the "East Asia" (Van der Voo *et al*., 2015). In other words, neither oceanic plate subduction nor arc volcanism is assumed to have occurred in the South Mongolia at the Late Cretaceous. Then, the question on the certainty of the age, "Late Cretaceous," of this formation arises. Very few attempts have been made on the exact age of the Bombookhoi Formation so far, and the necessary step next seems to be the confirmation of the age of this formation by isotopic dating and others. Then, if the volcanic rocks of the Bombookhoi Formation are truly Upper Cretaceous, re-consideration for the basic tectonic scheme around the South Mongolia block at the Late Cretaceous time will be required.

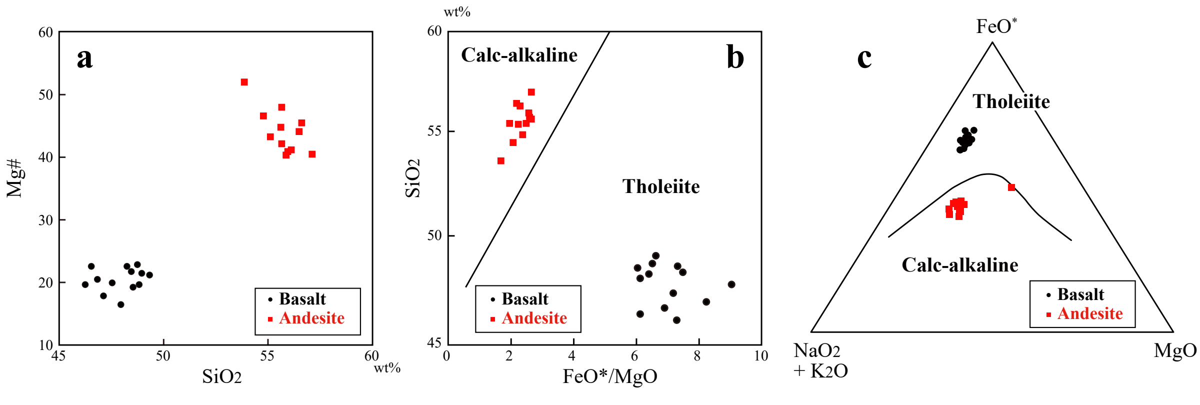

Fig. 6 (a) Mg# vs. SiO_2 diagram. (b) FeO*/MgO vs. SiO_2 diagram. (c) (Na_2O + K_2O) - FeO* - MgO diagram. Mg#: 100 × Mg / (Mg + Fe) calculated on a molar basis using total Fe^{2+} content. FeO*: total iron as FeO.

Distinct two volcanic rocks, high-Fe/Mg basalt and low-Fe/Mg andesite, were detected in this study. Other great deals of issue, e.g. the stratigraphy of the tholeiitic basalt and calc-alkaline andesite, and the reason of the bimodal volcanism had occurred, are remained. Besides, it may perhaps be difficult to infer that these basalt and andesite, which were obtained from a single caldera, have different sources, and the possibility that they were differentiated by some processes such as assimilation, contamination, or transition is not eliminated. Although it is presently difficult to discuss more due to the lacking of detail stratigraphical and geochemical information for the volcanic rocks, this would be confirmed when further data on stratigraphy and geochemistry of the Bombookhoi Formation become available.

Conclusion

The geochemistry of the volcanic rocks of the Bombookhoi Formation is a key for understanding the Mesozoic tectonic setting of the South Mongolia block. This study revealed that a part of the volcanic rocks of the Bombookhoi Formation are classified into the basalt and andesite which of them were formed at a volcanic arc. The basalt shows clearly lower Mg#, FeO*/MgO ratio, and higher K_2O concentration than the andesite. Although the Bombookhoi Formation has been assigned to Upper Cretaceous, it is generally considered that there was no oceanic plate subduction which caused the arc-magmatism at the margin of the South Mongolia block at that time. Therefore, age confirmation of this formation should be needed further.

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