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Original article

PETROCHEMICAL CHARACTERISTICS OF LATE PALEOZOIC MAGMATIC ROCKS OF THE MANDAKH AREA, SOUTHEAST MONGOLIA

Undarmaa Batsaikhan[1,2]*, Tsuchiya Noriyoshi[2], Chimedtseren Anaad[1], Batkhishig Bayaraa[1]

[1]*Department of Geology and Hydrogeology, School of Geology and Mining Engineering, Mongolian University of Science and Technology, Ulaanbaatar* 14191 *, Mongolia.*
[2]*Geomaterial and Energy Science Laboratory, Graduate School of Environmental Studies, Tohoku University, Aoba 6-6-20, Aramaki Aoba-ku, Sendai 980-8579, Japan*

**Corresponding author. Email: undarmaa@must.edu.mn*

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ABSTRACT

The late Paleozoic magmatic rocks are widely distributed in the Mandakh area which is located in the Gurvansaikhan and Manlai terrains, where porphyry Cu deposits occur. In this paper we discuss petrochemical features and mineral assemblages of magmatic rocks in the Mandakh area. Furthermore, we compared petrochemical characteristics of magmatic rocks in the Mandakh area with host magmatic rocks of the Tampakan deposit (Philippines), Cerro Colorado deposit (Chili) and negative criteria of Cu deposits (Japan) due to try to characterize potential of the porphyry copper deposit related to magmatic rocks in Mandakh area. Geochemical features of magmatic rocks in Mandakh area are calc-alkaline, magnetite-series, I-type and similar to adakite type. The Devonian intrusive rocks comprised of syenite and syenogranite, while the Carboniferous intrusive rocks consist of granodiorite, monzodiorite, quartz-monzonite and hornblende granite. Devonian magmatic rocks are more alkaline in composition. Although, Devonian and Carboniferous magmatic rocks are slightly different from each other. Comparing with bonanza copper deposits in the world, they are possible to host porphyry mineralization.

Keywords: pyrite, subduction, porphyry mineralization, I-type adakite

INTRODUCTION

Mongolia lies within the Central Asian Orogenic Belt (CAOB) which is enormous and composed of a multiplicity of terranes including ancient island and continental arcs, ophiolites, passive continental margins, Precambrian continental blocks and high-T/low-P metamorphic zones. Its largest continental crust development stage occurred during the Phanerozoic (Badarch et al., 2002; Windley et al., 2007; Yarmolyuk et al., 2008; Mihalasky et al., 2015). South Mongolia has become a major survey area for unraveling the Paleozoic tectonic evolution (Fig. 1). Badarch et al. (2002) describes the Gurvansaikhan island arc terrane (Fig. 2a) which lies in the central part of the southern domain in Mongolia. This island arc terrane is predominantly composed of Devonian to Carboniferous island arc volcanic rocks, but also includes sporadic Ordovician and Silurian volcanics, as well as Ordovician to Carboniferous sedimentary rocks, and are extensively intruded by voluminous Permian-

Carboniferous granitoids in the south (Badarch et al., 2002).
Geological setting, magmatism and mineralization of the South Mongolia arerelatively well studied, but there is considerable debate regarding thePaleozoic-Mesozoic tectonic evolution, especially in the Mandakh area (Yakubchuk, 2002; Blight et al., 2010a,b). Previous researchers (Blight et al., 2010a) have not agreed about the age of some intrusive bodies, and the tectonic setting. For instance, the Budar pluton and the Nariin Khudag monzonite bodies (Blight et al., 2010a) mapped as the same intrusive bodies but have been assigned different geological age (Fig. 2b).
On the other hand, important mineral deposits have been discovered in the South Mongolia during the last decade and consequently, the Southeast Gobi is a major mineral exploration province (Yakubchuk, 2002; Seltmann and Porter, 2005; Porter, 2016). The Kharmagtai-Khongoot-Oyut and the Tsagaan Suvarga Cu-Mo porphyry deposits were dated as Middle Carboniferous to Early Permian, and Late-Devonian to Early Carboniferous respectively (Rodionov et al., 2003).

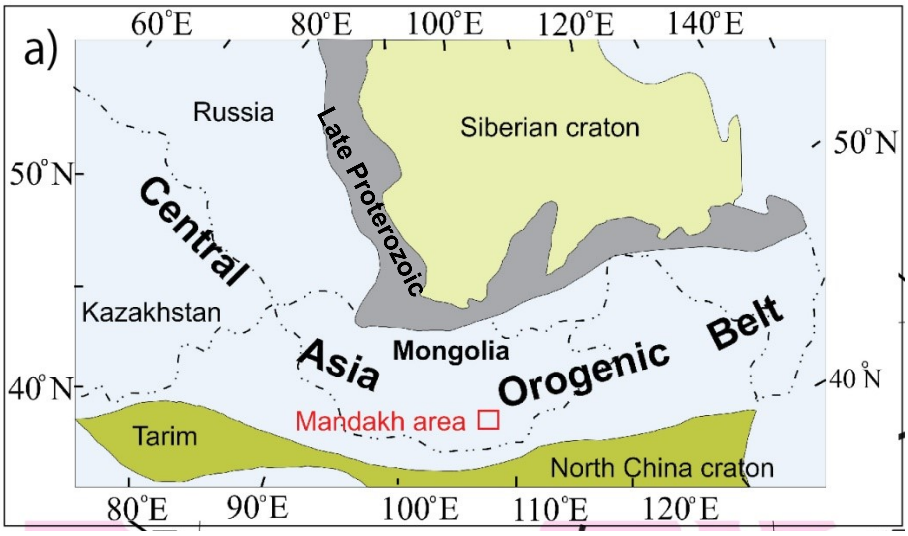

Figure 1. Simplified sketch map of the CAOB showing the main tectonic sub-divisions and location of the Mandakh area (modified after Jahn, 2004).

Devonian to Carboniferous volcanic and volcanogenic sedimentary rocks of Unduruud (D_{1-2}uu), Alagbayan (D_{2-3}ab), Ikhshankh ($C_1$is), Gunbayan (C_1gb), Tsokhiot (C_1ch), Dushiinovoo (C_2do) and Sainshandkhudag (C_2ss) Formations widespread in the Mandakh area, which are all differ in lithological characteristics. Also, Devonian to Carboniferous granitic plutons such as Tsagaan Suvarga (D_1c), Bronze Fox (C_2), Mandakh (C_2m), Mogoit (C_2mo) and Shuteen (C_2) are classified in the area. Detailed research works have been done for the Nariin Khudag, Bronze Fox, Mandakh plutons (Blight et al., 2010a, Enkhjargal et al., 2016) and Shuteen complex (Batkhishig and Iizumi, 2001; Batkhishig et al., 2010), besides other granitic plutons and Formations are not studied well.
Our study is focusing on petrochemistry of Devonian and Carboniferous magmatic rocks which are widely distributed in the Mandakh area._Moreover, we try to characterize potential of the porphyry copper mineralization in the study area, comparing geochemical characteristics of magmatic rocks to the Tampakan deposit (Philippines) and Cerro Colorado deposit (Chili) areas. They are gigantic representative porphyry deposits in the world.

GEOLOGICAL SETTINGS

Volcanogenic Formations: The Lower Devonian Unduruud Formation (D_{1-2}uu) mainly consists of basalt, porphyritic andesite and their tuffs. Age of this Formation is not studied well; the relative age was given by based on stratigraphical unconformity overlaid by Upper

Carboniferous Sainshandkhudag Formation.
Devonian Alagbayan Formation is mainly composed of basalt, basaltic andesite, dacite and their tuff, trachydacite, ignimbrite, terrigenic tuff-sandstone and tuff-aleurolite. The Alagbayan Formation contacted with Tsagaansuvarga and Sainshandkhudag Formations by tectonic fault. Absolute age of the augite basalt shows 362 Ma and while dacitic ash tuff shows 362.7±5 Ma (Dolgopolova et al., 2013).
Several different Formations of Lower Carboniferous age have been classified in the Mandakh area based on prior geological mapping works. These Carboniferous Formations mainly consist of mafic-intermediate-felsic volcanic and volcanoclastics rocks such as basalt, basaltic andesite, andesite, dacite, rhyolite, and some of them have sedimentary sequences like course to fine-grained tuff sandstone, tuff aleurolite and limestone with brachiopod fauna. The Carboniferous Formations are overlaid by Cretaceous Formations.

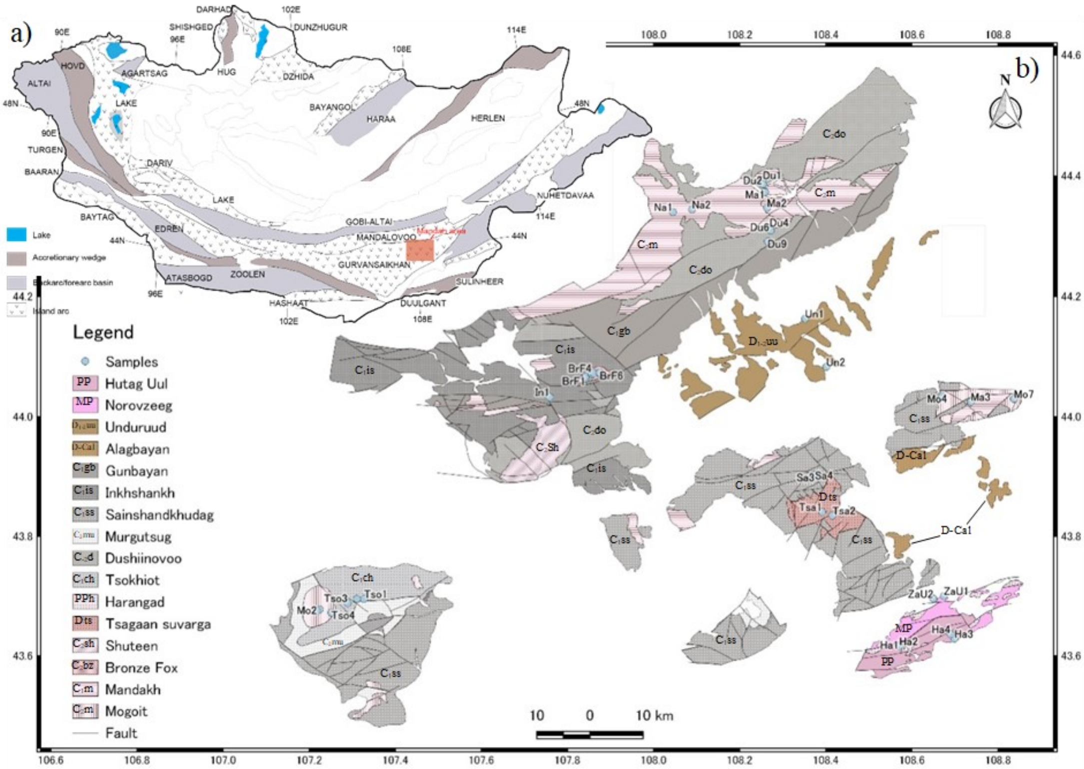

Figure 2. a. Modified terrane map of island arcs, related basins and accretionary wedge in Mongolia (Badarch, 2005), **b.** Distribution of magmatic rocks in Mandakh area

Lower Carboniferous Ikhshankh Formation ($C_1$is) consists of marine deposited tuff, conglomerate, sandstone, siltstone, and limestone,with a total thickness of about 2100–2700 m. The Formation can be divided into upper and lower members, and fossils of fauna and flora are locally observed. Hovan et al. (1984) reported a Lower Carboniferous (Tournasian–Visean) age for the Ikhshankh Formation, based on brachiopod fossils.
The Tsokhiot (C_1ch) Formation occurred in west southern part in Mandakh area (Fig. 2). This Formation consist of andesite, basaltic andesite and basalt.
The Dushiinovoo Formation (C_2do) outcrop stretches from the northeast to southeast, and intruded by the Mandakh, Shuteen, Budar and Nariin Khudag intrusions (Fig.2). It consists of mostly andesite, andesite porphyry and associated pyroclastics with a total thickness of about 3000 m. In some places, dacite and basalt are also occurred. Pennsylvanian age

was confirmed by fossils, and Rb-Sr whole rock and mineral ages yielded 336±24 Ma, 315.85±0.02 Ma and 319±0.03 Ma (Batkhishig et al., 2010, 2016).

The Sainshandkhudag Formation (C_1ss) occurs in the southeastern part of the Mandakh area (Fig. 2). Volcanic rocks of the Formation comprise of basalt to dacite in composition and are associated with pyroclastic rocks. It has contacted to Devonian Tsagaan Suvarga intrusive and Carboniferous Tsagaansuvarga Formation by north-east trending faults.

Intrusions: Devonian Tsagaan Suvarga pluton occurs in the southeastern part of the Mandakh area. The pluton is relatively well studied by previous researchers, because of hosting Cu-Mo porphyry deposit. The Tsagaan Suvarga pluton is covered by Carboniferous Tsagaansuvarga and Sainshandkhudag Formations in northwestern and south-eastern parts. Pluton is composed of monzonite to granodiorite, metaluminous with ASI values ranging from 0.97 to 1.14, I-type and the Rb-Sr and Sm-Nd isochron indicates a 338±14 Ma and 364 Ma ages respectively (Tungalag et al., 2014).

The Carboniferous magmatism is represented by Mandakh complex which includes several plutons such as the NariinKhudag, Bronze Fox and Shuteen.

The Shuteen pluton, which yields a Rb-Sr whole -rock age of 321.5±9 Ma (Iizumi and Batkhishig, 2000), and is comprised of monzonite, monzodiorite, diorite, hornblende-biotite granodiorite, granite, hornblende granite, granodiorite, and syenite, and porphyritic stocks and dikes (Batkhishig et al., 2010).

The Bronze Fox pluton consists of gabbrodiorite to granite series intruded into the Ikhshankh Formation. Blight et al., (2010b) identified U-Pb age of 333.2±0.6 Ma for the biotite-hornblende granodiorite.

The Mogoit pluton is occurred as an isometric body in southeast part of the study area and intruded into the Sainshandkhudag Formation. The Mogoit pluton consists of biotite granite, granodiorite, monzonite and diorite.

METHODS

In order to determine petrochemical characteristic, we have collected 185 rock samples including volcanogenic formations and intrusive bodies from the Mandakh area.

Thin-section preparation and petrographical studies were carried out at the Graduate School of Environmental Studies in Tohoku University, Japan.

Sample preparation for XRF analysis has been done by following method. Fusion beads and pellets were prepared as analytical media to determine the abundance of 10 major compounds (SiO_2, TiO_2, Al_2O_3, tFeO, MnO, MgO, CaO, Na_2O, K_2O and P_2O_5) and 22 trace elements (V, Cr, Co, Ni, Cu, Zn, As, Rb, Sr, Y, Zr, Nb, Sn, Sb, Cs, Ba, La, Ce, Pr, Nd, Pb, Th), respectively (Table 3, 4). The pellets have several stages of preparation. First, rocks were cut by different size saws.Second, rock pieces were crushed by hand in the mortar tungsten carbide. Third,the crushed sample was crushed again, until homogeneous powder by vibrated crush technique of the vibrating sample mill TI-100.Fourth,the powder from the rocks filled a PVC ring on the dies, which was pressed by apiston cylinder 3124-00. In addition, we used ethanol and MilliQ for cleaning between each sample and following stages of preparation for X-ray fluorescence. We have analyzed with calibrated using standard samples provided by Geological Survey of Japan (JA-3). Thirty-six igneous rock and thirty volcanic rock samples were analyzed using standard XRF techniques at Graduate School of Environmental Studies in Tohoku University, Japan (Yamasaki, et al., 2002).

RESULTS

Petrography of volcanogenic Formations in the Mandakh area

Total 56 representative samples from the Unduruud (3), Ikhshankh (3), Tsokhiot (4), Dushiinovoo (16) and Sainshandkhudag (28) are studied for petrography and the results are summarized in Table 1.

Porphyritic texture is common in all volcanogenic rocks, and phenocrysts are largely replaced by chlorite, sericite and clay minerals. Samples of the Unduruud and Dushiinovoo Formations contain more opaque minerals than the samples of other formations.

Table 1. Petrographical features of volcanogenic rocks of the Mandakh area

Formation	Alagbayan	Unduruud	Sainshandkh udag	Ikhshankh	Dushiinovoo	Tsokhiot
Primary minerals	Pl<Cpx	Pl>Amp	Cpx, Amp, Pl, Kfs, Q	Pl>Amp	Cpx, Amp, Pl, Kfs, Q	Cpx, Amp, Pl
Secondary minerals	Ore & clay minerals	Ore & clay minerals, calcite	Sericite, chlorite	Sericite, zoisite, clay mineral	Sericite, chlorite	Sericite, chlorite
Rock type	Basalt Trachy-dacite	Andesite	Dacite, Andesite, basalt tuff	Andesite, andesite tuff	Andesite, dacite, rhyolite,tuff of these	Andesite, basaltic andesite, basalt

Petrography of intrusions in the Mandakh area

Samples of the Tsagaan Suvarga (2), Mandakh (6), Bronze Fox (12), Mogoit (8) and Budar (3) plutons are studied; the results are summarized in Table 2. All of the plutons are predominantly comprised of granodiorite and granite with porphyritic medium to course-grained texture. These rocks consist mostly of euhedral plagioclase (Pl) and K-feldspars (Kfs) which altered to sericite and clay minerals. The rocks of the Mandakh, Mogoit and the Bronze Fox plutons are similar to each other in terms of petrography. Those have porphyritic texture, mineral composition (abundant plagioclase, K-feldspar, quartz (Q), hornblende, biotite (Bt), rare clinopyroxene (Cpx)), and fine to medium grained quartz in the groundmass. However, the Mandakh pluton rocks have more alkalic mineral composition than rocks of the Mogoit and the Bronze Fox plutons. The Tsagaan Suvarga pluton comprises of mainly K-feldspar, which largely altered to sericite and clay minerals, and a few calcite minerals. All rocks of the Bronze Fox, the Mogoit, the Mandakh and the Tsagaan Suvarga plutons contain ore minerals, and the pyroxene is replaced by hornblende and biotite.

Table 2. Petrographical features of the intrusions in Mandakh area.

Intrusive plutons	Tsagaan Suvarga	Bronze Fox	Mogoit	Mandakh
Primary minerals	Kfs> Pl>Q>Bt,Aeg	Cpx, Amp, Pl, Kfs, Q	Kfs>Q>Pl>Amp>Bt	Kfs>Pl>Q> Amp>Cpx,
Secondary minerals	Sericite, clay mineral, epidote, calcite	Hornblende, sericite, chlorite	Sericite, clay mineral, epidote zoisite	Sericite, clay mineral, epidote
Rock type	Syenite	Gabbro-diorite-granite	Granodiorite, Granite	Granite, Granodiorite

Geochemistry

Major and trace element composition of volcanic and plutonic rocks are shown in Table 3 and 4, respectively.

All samples of volcanic and plutonic rocks are plotted in AFM diagram and are related to calc-alkaline series (Fig 3). Magmatic rocks of the Mandakh area show a wide range of compositions for both silica and alkalis. Rock composition is ranging from diorite to granodiorite and granite. Whereas rocks of the Devonian Tsagaan Suvarga pluton show more alkaline characteristics than Carboniferous rocks, they are plotted in quartz monzonite field (Fig. 4A).

Volcanic rock show less evolved trend. Devonian Unduruud Formation rocks are more mafic (basalts), whereas Carboniferous

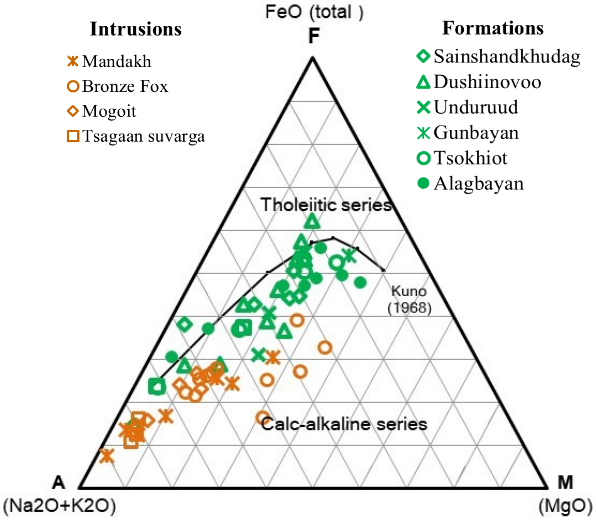

Figure 3. AFM diagram for magmatic rocks in the Mandakh area. The boundary between the calc-alkaline field and the tholeiitic field after Kuno, 1968.

Formations are ranging from mafic to felsic in composition (basalt-andesite-rhyolite). Permian Argalant Formation rocks are more alkaline, and plotted in trachyandesite and trachyte fields in terms of TAS diagram (Fig. 4B). All plutonic rocks from the Mandakh area are plotted in I-type granite field in SiO_2 vs Al/K+Na+Ca diagram (Fig. 5). Furthermore, the geochemical features of the Mandakh area are compared with plentiful of igneous rocks in giant porphyry copper deposits (Tampakan, Cerro Colorado) in order to characterize potential of porphyry copper mineralization in the Mandakh area (Fig. 5, 8, 9).

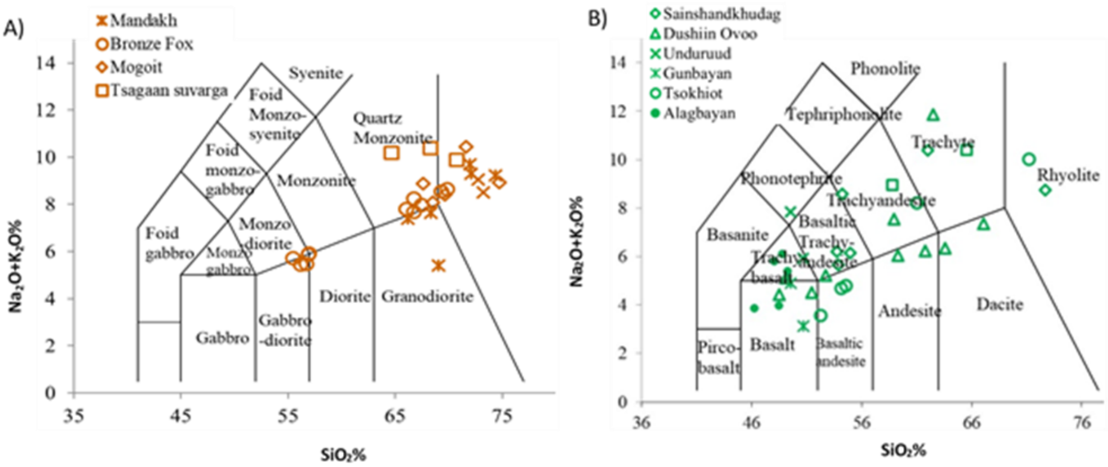

Figure 4. The total-alkalis vs. silica diagram for magmatic rocks from the Mandakh area (Le Maitre et al., 1989). a. plutonic rocks; b. volcanic rocks.

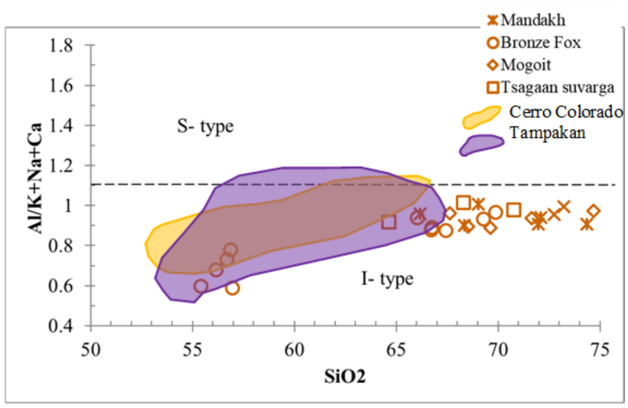

Figure 5. Al/(K+Na+Ca) vs SiO_2 diagram granitoid of the Mandakh area compared with Tampakan and Cerro Colorado granitoids (after Chappell and White, 1974) I-type igneous derived, S-type sediment derived.

Table 3. Major and trace element composition of the volcanic rocks of the Mandakh

Formation	Unduruud		Sainshandkhudag						Ikhshankh		Dushiinovoo			
Samples	Un1	Un2	Sa1	Sa2	Sa3	Sa4	Sa5	Sa6	In1	In2	Du1	Du2	Du3	Du4
N	44.163	44.083	44.357	44.362	43.903	43.901	43.901	43.901	44.033	44.033	44.393	44.392	44.386	44.315
E	108.35	108.4	107.27	107.29	108.37	108.37	108.37	108.37	107.76	107.76	108.25	108.25	108.25	108.27
Major element (%)														
SiO_2	63.64	60.76	62.01	72.69	53.9	54.96	53.75	54.26	49.55	50.68	52.72	48.5	51.46	49.1
TiO_2	0.6	0.72	1.23	0.27	1.42	0.95	0.82	1.09	0.81	0.86	0.95	1.02	0.91	0.85
Al_2O_3	15.98	17.55	15.74	14.18	14.85	17.66	17.66	14.68	18.45	18.49	16.87	16.72	17.44	19.36
Fe_2O_3	5.26	6.22	6.77	1.59	9.93	8.25	9.1	8.9	11	11.14	10.54	14.41	10.93	10.82
MnO	0.09	0.09	0.03	0.03	0.15	0.13	0.15	0.13	0.25	0.19	0.25	0.36	0.26	0.25
MgO	3.88	3.09	0.63	0.48	4.08	4.26	5.03	3.38	4.2	6.29	3.93	4.34	3.58	4.41
CaO	3.28	5.03	2.94	1.38	5.81	6.89	5.33	5.49	7.66	6.94	9.35	10.7	10.52	10.28
Na_2O	5.67	4.27	5.06	4.51	3.53	4.07	5.48	3.49	4.06	2.56	5.04	3.99	4.25	3.58
K_2O	2.18	1.65	5.33	4.24	2.12	2.07	0.72	5.09	0.84	0.58	0.2	0.43	0.27	1.54
P_2O_5	0.2	0.24	0.81	0.14	0.59	0.34	0.24	0.48	0.18	0.15	0.23	0.14	0.14	0.24
Total	100.58	99.38	99.74	99.37	98.79	99.24	98.04	98.51	98.82	98.73	99.85	100.4	99.62	100.19
Ttrace element (ppm)														
V	112	155	98	37	220	221	191	225	234	253	250	368	305	308
Cr	52	70	nd	1	3	36	14	1	1	6	28	36	91	50
Co	15	17	17	3	31	25	30	21	34	36	33	47	34	33
Ni	33	32	12	9	10	26	19	6	8	12	16	19	23	20
Cu	53	16	13	13	153	110	51	21	149	78	88	131	125	55
Zn	59	78	79	62	98	76	80	71	73	64	116	155	118	141
As	11	3	55	4	3	1	2	1	1	2	15	6	8	8
Rb	40	29	158	180	40	44	11	88	17	10	3	5	2	41
Sr	553	915	503	203	704	830	607	510	832	630	547	821	375	640
Y	11	8	22	7	29	19	17	25	17	18	27	17	18	16
Zr	150	140	330	269	163	123	77	125	56	54	85	51	57	49
Nb	5	4	44	18	5	4	3	4	3	3	3	2	3	3
Sn	1	nd	2	2	1	1	nd	1	nd	nd	1	nd	nd	nd
Sb	3	1	nd	nd	nd	nd	nd	1	nd	nd	5	5	6	5
Cs	1	3	4	5	3	1	nd	3	nd	1	nd	nd	nd	2
Ba	478	710	1165	739	987	620	370	1260	301	244	280	173	111	381
La	12	17	57	42	18	14	12	16	6	8	8	12	9	7
Ce	28	35	107	74	45	31	28	38	17	17	22	26	20	17
Pr	1	2	7	2	4	2	3	2	3	3	3	5	5	3
Nd	15	19	46	23	32	21	16	29	12	11	16	18	14	13
Pb	16	6	16	25	10	6	6	6	3	3	7	10	5	10
Th	4	3	17	19	1	1	1	3	1	1	1	1	1	1

Table 3. Continued

Formation	Dushiinovoo						Tsokhiot				
Samples	Du5	Du6	Du7	Du8	Du9	Du10	Tso1	Tso2	Tso3	Tso4	Tso5
N	44.31	44.31	44.31	44.31	44.29	44.29	43.7	43.7	43.69	43.67	43.67
E	108.3	108.3	108.3	108.3	108.3	108.3	107.3	107.3	107.3	107.3	107.3
Major element (%)											
SiO_2	62.56	62.5	58.96	59.29	67.06	60.76	54.14	60.96	52.27	71.2	54.56
TiO_2	0.69	0.65	0.91	0.86	0.39	0.58	1.16	0.59	0.85	0.48	1.18
Al_2O_3	15.84	15.2	18.11	16.33	13.99	16.34	17.78	17.3	17.75	14.81	16.81
Fe_2O_3	6.07	5.41	7.46	8.11	3.85	6.06	8.87	6.4	9.95	3.3	10.1
MnO	0.1	0.06	0.12	0.13	0.08	0.11	0.14	0.09	0.16	0.1	0.15
MgO	3.27	1.56	2.41	3.38	2.1	4.24	4.09	2.76	5.47	0.73	4.02
CaO	5.78	1.55	4.92	4.58	3.56	6.32	8.61	4.49	8.52	1.08	8.14
Na_2O	3.53	3.88	3.45	3.78	4.43	3.46	3.13	5.29	2.61	5.87	3.69
K_2O	2.81	7.97	4.11	2.26	2.94	2.78	1.57	2.93	0.97	4.16	1.12
P_2O_5	0.21	0.3	0.34	0.25	0.08	0.28	0.39	0.2	0.27	0.24	0.39
Total	100.7	98.7	100.5	98.7	98.4	100.7	99.4	100.8	98.5	101.	99.7
Trace element(ppm)											
V	154	134	171	106	85	170	268	130	247	43	237
Cr	102	44	37	26	38	114	88	15	48	4	54
Co	17	13	20	23	10	17	27	18	31	8	31
Ni	51	32	50	13	25	31	36	16	28	9	27
Cu	156	19	160	17	30	144	169	53	108	10	153
Zn	67	52	75	115	59	65	81	69	82	53	90
As	2	2	2	15	5	5	0	2	0	2	0
Rb	47	128	88	48	59	50	17	55	15	65	14
Sr	781	354	790	377	613	737	878	728	688	272	611
Y	12	15	16	24	9	15	20	10	14	16	26
Zr	113	137	154	149	138	124	125	105	78	165	135
Nb	4	4	5	6	5	4	4	3	3	6	4
Sn	1	1	1	1	1	1	0	1	1	2	0
Sb	1	0	0	2	2	0	0	0	0	0	0
Cs	3	3	7	1	2	2	1	3	0	3	1
Ba	693	1061	1282	524	665	720	641	895	342	1046	495
La	15	14	17	15	23	12	20	10	8	16	14
Ce	29	33	40	31	43	29	41	24	20	36	33
Pr	1	1	2	3	1	2	4	1	3	1	3
Nd	17	21	28	19	19	18	24	17	14	20	22
Pb	9	18	16	7	15	11	7	5	4	8	6
Th	4	6	8	5	2	3	1	5	1	8	4

Table 4. Elemental abundances for representative samples from intrusions of the Mandakh area

Intrusive	TsagaanSuvarga			Mandakh						Bronze Fox			
Sample	Tsa1	Tsa2	Tsa3	Ma1	Ma2	Ma3	Ma4	Ma5	Ma6	BrF1	BrF2	BrF3	BrF4
N	43.841	43.841	43.835	44.34	44.344	44.344	44.373	44.347	44.025	44.064	44.067	44.07	44.072
E	108.39	108.39	108.42	108.04	108.09	108.09	108.26	108.26	108.74	107.84	107.84	107.86	107.86
Major element (%)													
SiO_2	69.75	68.29	64.61	76.32	66.16	68.34	74.34	70.09	71.96	66.42	66.7	66.03	68.86
TiO_2	0.21	0.21	0.19	0.17	0.44	0.46	0.26	0.35	0.31	0.48	0.45	0.43	0.38
Al_2O_3	16.57	17.45	18.38	12.89	14.79	15.22	13.43	14.99	14.11	15.13	14.84	14.37	15.01
Fe_2O_3	1.56	1.94	2.57	0.91	4.05	4.19	1.75	2.62	1.98	4.54	4.2	4.24	3.55
MnO	0.05	0.08	0.07	0.02	0.07	0.07	0.05	0.05	0.09	0.05	0.05	0.04	0.04
MgO	0.7	0.81	0.62	0.22	2.75	2.2	0.73	1.3	0.37	2.08	1.78	1.89	1.91
CaO	1.6	1.43	3.1	0.69	2.62	3.49	1.28	1.71	1.29	3.39	3.03	2.55	2.05
Na_2O	5.86	5.94	5.87	3.93	4.73	4.1	4.4	4.89	4.87	4.42	4.32	3.89	4.29
K_2O	4.04	4.46	4.31	4.87	2.66	3.53	4.82	4.41	4.84	3.55	3.94	3.92	4.36
P_2O_5	0.14	0.12	0.17	0.19	0.2	0.23	0.12	0.21	0.2	0.14	0.17	0.19	0.21
Total	100.4	100.7	99.8	100.2	98.4	101.8	101.1	100.6	100.0	100.2	99.4	97.5	100.6
Trace element (ppm)													
V	56	62	75	23	72	102	50	72	37	101	101	98	90
Cr	1	2	1	0	41	33	2	4	3	50	54	40	32
Co	3	4	5	1	10	11	4	6	4	12	9	10	8
Ni	9	8	9	9	29	23	14	14	9	22	20	18	20
Cu	25	19	18	10	40	56	19	20	26	47	631	23	13
Zn	37	39	42	25	65	62	45	43	51	33	32	28	26
As	3	2	4	4	1	1	2	2	5	5	3	2	2
Rb	83	87	104	117	42	64	101	88	90	78	92	91	93
Sr	505	529	973	100	842	571	205	445	202	633	597	606	522
Y	7	9	9	13	8	11	14	11	32	15	14	12	13
Zr	71	94	194	129	142	180	134	179	316	185	170	167	179
Nb	6	5	6	12	4	6	8	7	8	5	5	5	5
Sn	0	0	0	1	1	1	1	1	2	1	1	1	1
Sb	0	0	0	0	1	0	0	0	0	0	0	0	0
Cs	2	4	3	1	1	3	2	5	2	1	2	2	1
Ba	825	953	737	345	649	922	755	951	934	767	741	720	693
La	12	9	11	33	20	26	25	22	27	16	13	9	22
Ce	23	23	20	57	37	51	48	45	60	37	30	22	41
Pr	1	1	1	5	2	2	2	2	5	1	1	1	1
Nd	12	11	10	15	16	25	18	21	29	20	16	14	17
Pb	7	9	9	22	8	11	17	14	17	7	8	7	7
Th	4	5	7	17	5	9	15	9	10	8	10	10	13

Table 4. Continued.

Intrusive	Bronze Fox						Mogoit				
Sample	BrF5	BrF6	BrF7	BrF8	BrF9	BrF10	Mo1	Mo2	Mo3	Mo6	Mo7
N	44.073	44.073	44.073	44.073	44.071	44.077	43.678	43.675	44.034	44.034	44.03
E	107.87	107.87	107.87	107.87	107.87	107.87	107.22	107.22	108.67	108.67	108.84
Major element (%)											
SiO_2	56.15	56.95	56.85	56.67	66.75	69.27	68.63	68.52	67.63	71.7	70.64
TiO_2	0.98	0.77	0.79	0.96	0.52	0.36	0.44	0.51	0.51	0.34	0.42
Al_2O_3	18.46	18.43	15.06	16.93	14.88	14.27	14.95	15.21	15.26	14.87	15.69
Fe_2O_3	4.64	2.28	7.62	7.74	4.64	3.57	3.78	4.36	4.04	2.24	2.35
MnO	0.1	0.07	0.11	0.2	0.06	0.03	0.06	0.07	0.06	0.04	0.09
MgO	4.7	3.51	6.91	4.38	2.13	1.53	1.21	1.55	2.06	0.79	0.65
CaO	10.04	11.92	6.1	7.88	3.44	2.09	2.97	3.31	2.1	1.65	1.11
Na_2O	5.24	5.69	3.32	5.11	3.74	3.96	4.14	3.96	4.35	4.63	6.09
K_2O	0.21	0.24	2.55	0.36	3.95	4.59	4.28	4.12	4.51	4.31	4.35
P_2O_5	0.43	0.46	0.26	0.42	0.23	0.15	0.19	0.13	0.27	0.17	0.19
Total	100.9	100.3	99.5	100.6	100.3	99.8	100.6	101.7	100.7	100.7	100.5
Trace element (ppm)											
V	323	239	162	262	128	86	69	80	95	58	43
Cr	106	66	332	58	60	31	22	31	14	1	2
Co	11	4	22	22	9	8	9	11	8	5	5
Ni	51	15	140	28	19	15	13	14	18	9	8
Cu	57	8	80	47	1687	174	39	15	164	33	11
Zn	36	30	66	64	46	23	83	54	49	41	54
As	0	1	1	0	5	4	12	8	2	2	6
Rb	6	7	60	11	93	105	126	130	126	95	73
Sr	1387	1274	1147	1400	672	518	356	352	355	221	188
Y	18	27	11	13	14	12	21	21	14	15	26
Zr	63	169	104	122	164	184	197	223	190	222	268
Nb	5	4	4	5	5	5	5	5	5	6	7
Sn	1	1	0	0	0	0	2	3	1	1	1
Sb	0	0	0	0	0	0	0	0	0	0	0
Cs	0	0	2	0	2	2	5	6	2	3	3
Ba	218	151	667	211	711	706	855	824	718	794	1091
La	14	20	14	18	16	14	16	17	19	7	28
Ce	34	60	31	38	37	35	36	37	40	17	62
Pr	5	10	2	5	2	1	1	1	2	1	2
Nd	20	39	19	21	20	15	21	20	19	10	30
Pb	5	6	5	7	7	7	15	13	10	14	12
Th	3	5	1	1	8	16	10	10	11	11	9

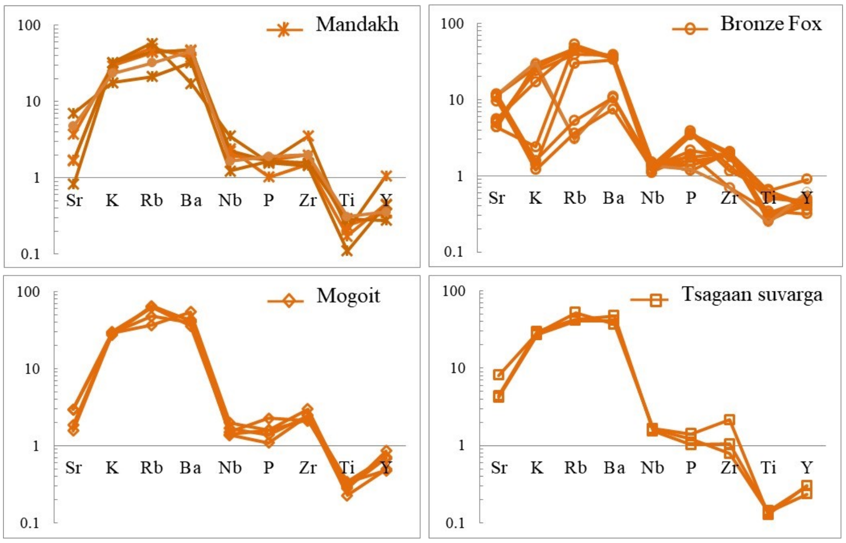

Figure 6. Spider diagram for the samples of plutonic rocks from the Mandakh area. Trace element values are normalized to MORB (Pearce and Cann, 1973)

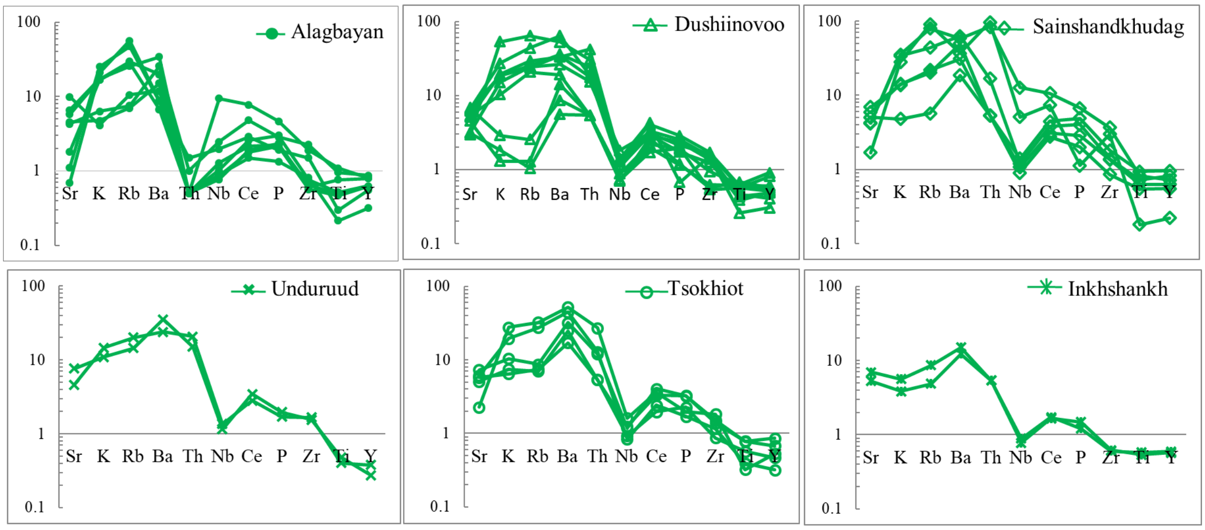

Figure 7. Spider diagram for the volcanic rocks from the Mandakh area. Trace element values are normalized to MORB (Pearce and Cann, 1973).

Samples of plutonic rocks in the Mandakh area show enriched values of LILE and depleted values of HFSE (Fig. 6). Positive anomalies of K, Rb, Ba, and negative anomalies of Nb, P, Ti and Y; which indicate subduction environment. Samples from Bronze Fox pluton show two different patterns in LILE, some are enriched in K, Rb and Ba, the others are depleted in K and Rb (Fig. 6). Andesitic rocks of the Dushiinovoo Formation are enriched in LILE, whereas dacite and rhyolites give some depletion on LILE, for instance K, Rb and Ba. The rocks of Shuteen pluton and Dushiinovoo Formations, as well as other magmatic rocks in the Mandakh area are distinguished as adakite-like rocks, by the previous researchers (Batkhishig et al., 2010; Blight, 2010a). Therefore, we also try to show how our new data plot in the Y vs Sr/Y diagram, comparing with data from the Cerro Colorado and Tampakan area. Samples show differentiation trend from ADR to adakitic rocks (Fig. 8). Plutonic rocks are all characterized as Volcanic Arc Granite in terms of tectonic discrimination diagram (Fig. 9).

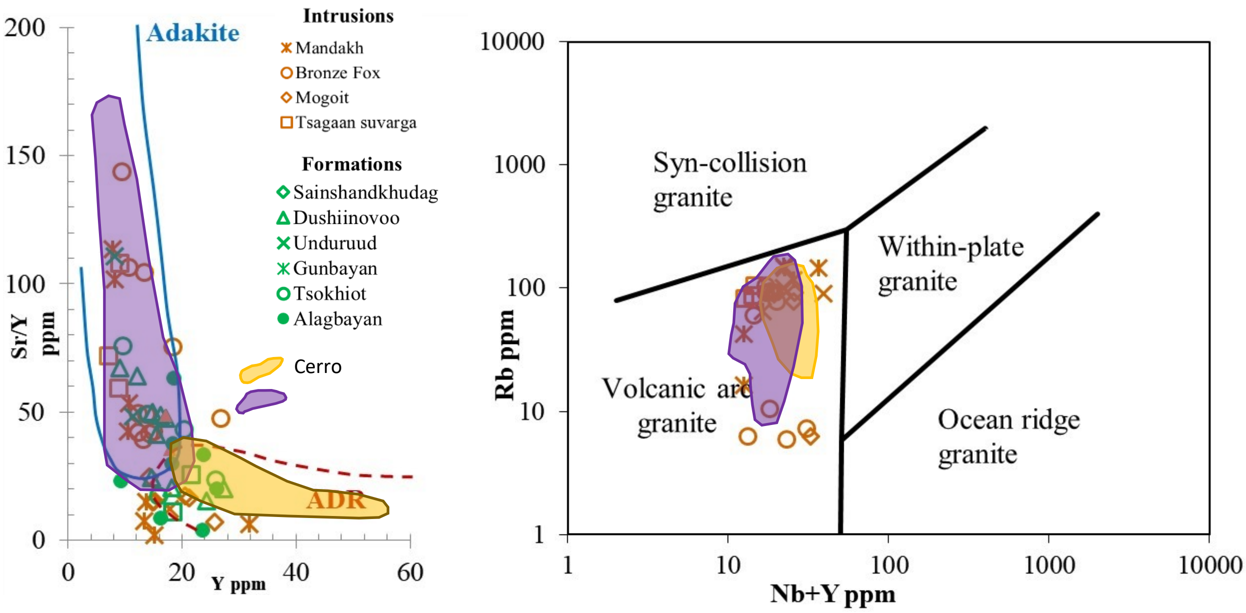

Figure 8. Sr/Y-Y plot for rocks of the Mandakh area TTD: trondhjemite-tonalite-dacite, ADR: andesite-dacite-rhyolite.

DISCUSSION

Petrochemical differences of Devonian and Carboniferous rocks in the Mandakh area

Geochemical features of Devonian Tsagaan Suvarga pluton are slightly different than Carboniferous rocks. The Tsagaan Suvarga pluton rocks are calc-alkaline, I-type and alkali series ($Na_2O+K_2O>9.8\%$), Sr 505-973 ppm, Y 7-9 ppm, Nb>5 ppm, Rb>87 ppm. Porphyry systems related to Devonian magmatic rocks in South Mongolia mostly host economic deposits such as Tsagaan Suvarga and OyuTolgoi.

Carboniferous magmatic rocks distributed in the Mandakh area are characterized by calc-alkaline series, I-type, silica saturated SiO_2 ≥50 %, high Al_2O_3 ³12.9%, $Na_2O+K_2O>5$ %, contain Sr 300-800 ppm, Y ≤ 25 ppm, Nb≤12 ppm, Rb≤150 ppm which are indicating adakitic features and are formed within volcanic arc tectonic setting (Table 5). Carboniferous plutonic and volcanic rocks show co-magmatic features, formed during the Carboniferous subduction zone developed in South Mongolia. Carboniferous plutonic rocks are commonly host copper porphyry systems (Shuteen, Oyut-Ulaan and Kharmagtai), but economic deposits are not yet discovered.

Porphyry copper mineralization potential in Mandakh area related to Devonian and Carboniferous magmatic rocks

The Devonian and Carboniferous magmatic rocks have porphyritic texture and contain plagioclase, K-feldspar, quartz, hornblende, biotite, rare clinopyroxene phenocrysts. All rocks of the Bronze Fox, the Mogoit, the Mandakh (Carboniferous) and the Tsagaan Suvarga (Devonian) plutons contain ore minerals, and the pyroxene replaced to hornblende and biotite. Richards (2011) considered the presence of hydrous phenocryst phases and arc magmatic suites with high Sr/Y ratios are indeed prospective for porphyry Cu+/-Mo+/-Au deposits. The biotite within magmatic rock in this study area is greenish brown, implying the magnetite-series (Ishihara, 1998). These magmatic rocks were affected by hydrothermal alteration. However, samples of Tsagaan Suvarga pluton contain calcite, carbonate minerals and show pinkish red color, implying Devonian rocks are more alkalic than Carboniferous plutonic rocks.

Furthermore, the porphyry copper deposits are closely related to subduction system. However, there are two types of subduction system depending on porphyry copper deposit in the world. One is rich in porphyry copper deposits

Table 5. Carboniferous magmatic rocks of the Mandakh area compared to adakitic

Adakite characteristics	**Intrusive rock**	**Volcanic rock**
Trondhjemite-tonalite-dacite	Gabbrodiorite-granite-syenite	Basalt-rhyolite, andesite and dacite tuff
SiO_2> 56%wt	*56 – 76.3 %	*48.5- 72.7%
High Al_2O_3>15% wt.	*12.9-18.46%	*14- 19.36%
Low Y<18ppm	*7– 32 ppm	Mostly<16 ppm; Rarely~ 25ppm
Sr rich>400 ppm	max: 1387 ppm min: 100 ppm mostly 300-600ppm	max: 915 ppm min: 203 ppm mostly 500-800ppm
Usually < 3%MgO (rare above 6%)	Lower than 3% MgO	Almost around 1-4% MgO
Plagioclase is ubiquitous	Plagioclase is common all the rocks and hornblende.	
Amphibolite is common; a common assemblage is Pl&Amp	Pyroxenes are to Hornblende.	Plagioclase is common all of the rocks and also hornblende.
Tectonic setting What is tectonic setting?	I-type Volcanic arc granite Adakite like	Adakite like

such as Chili, Indonesia and Philippines. Another is poor in porphyry copper deposits, which is Japan. Sillitoe (2018) mentioned some reasons why Japan has lack of porphyry copper deposits and further impossible geological factors for large and high-grade porphyry copper deposits. As he classified that lack porphyry copper deposits have formed in association with convergent plate margin settings by slab rollback and consequent crustal extension, volcano-plutonic complexes generated during caldera flare-ups, arc processing chemically reduced crustal profiles, ilmenite-series intrusion, arc having few and locally high Sr/Y igneous suites, fractionated intrusions of rhyolitic (granitic) composition, metallogenic belts or provinces dominated by rhyolite-associated VMS deposits or low-sulfidation epithermal Au deposits and steep subduction (Sillitoe, 2018).

Based on comparison in Table 9, the geochemical features of the late Devonian and Carboniferous magmatism in Mandakh area, are considered much different from these negative criteria of the location of porphyry Cu deposits. In addition, the Devonina Tsagaansuvarga deposit (Cu-Mo) and the Carboniferous Shuteen mineralized area (Cu-Au) are indication possibility of porphyry copper deposits formation in the study area (Table 7).

Geochemical data of Devonian and Carboniferous igneous rocks of the Mandakh area compared with igneous rocks of giant porphyry copper deposit Tampakan and Cerro Colorado (Fig. 5, 8 and 9). The Tampakan deposit is a large copper and gold ore body located in the south of the Philippine which is classic example of the island arc (adakite) tectonic setting (Rohrlach, 2002; Cooke et al, 2005), the Cerro Colorado (Cu 0.81%, Mo 0.005%) occurs in the Chili that is good example of the continental margin setting (Tsang et al, 2018; Cooke et al, 2005). Geochemical features of Devonian to Carboniferous igneous rocks in the Mandakh area are close to rocks in the Tampakan deposit but differ from rocks in Cerro Colorado deposit (Fig.5, 8 and 9; Table 7). It means that Devonian to Carboniferous magmatic rocks in the Mandakh area somehow related to porphyry copper system and I-type adakite which has chemical characteristics of high Sr/Y ratios. Defant and Drummond (1990) identified a suite of rocks called “adakites” that are inferred to be the product of melting of the subducted slab, which generated by melting of eclogitic basaltic crust.

Tungalag et al (2014) identified that whole-rock geochemical characteristics of quartz monzodiorite and quartz monzonite of the

Table 7. Regional factors to indicate porphyry Cu potential in the Mandakh area compared with other

Regional factors influencing porphyry Cu potential	Japan	Philippine	Chili	Mandakh area	
		Tampakan Porphyry deposit	Cerro Colorado Porphyry deposit	Late Devonian	Carboniferous
Erosion level	Erosion level not suitable (too deeply eroded, at less more 4 km)	Erosion level suitable (Tampakan)	Erosion level suitable (Cerro Colorado)	Erosion level suitable (Tsagaansuvarg a)	Erosion level suitable (Shuteen)
Plate tectonic setting	Subduction, slab rollback, consequent crustal extension	Subduction and Adakite, I- type	Subduction and Continental arc system, A-type	Subduction and Island arc system, Adakite type	Subduction and Island arc system, Adakite type
	-steep subduction (>30°)	Low angle subduction (<30°)	Low angle subduction (<30°)	unclear	unclear
	-back-arc basin opening	back-arc basin	No back-arc basin	back-arc basin opening*	back-arc basin*
Volcanic-plutonic style	Not determined	Magnetite-(±Ilmenite) series Stratovolcanoes	Magnetite-series, Stratovolcanoes	Magnetite-series Stratovolcanoes	Magnetite-series Stratovolcanoes
Magma type	Not determined	Oxidized	Oxidized	Oxidized	Oxidized
		High Sr/Y	High Sr/Y	High Sr/Y	High Sr/Y
		fractionated	fractionated	fractionated	fractionated

*- Seltmann and Porter, 2005; Badarch et al., 2002; Watanabe and Stein, 2000

Tsagaan Suvarga pluton are similar to oxidized fertile porphyry magma during Upper Devonian island arc.

Carboniferous magmatic rocks (Bronze Fox, Mandakh, Mogoit, Shuteen) are composed of monzodiorite, quartz monzodiorite, granodiorite and granite, which whole rock geochemical characteristics show I-type, magnetite-series, adakitic nature, island arc tectonic setting and similar to rocks in giant porphyry copper deposits.

Porphyry Cu-Mo, Cu-Au deposits and occurrences are associated with typical calc-alkaline metaluminous, oxidized with a fO_2 above the FMQ+2 (fayalite-magnetite-quartz buffer), I-type, magnetite series granitoids (Sillitoe, 2018; Hattori, 2018), which is dominated granitoid type in Mongolia. The petrochemical features of magmatic rocks of the Mandakh area are similar to above characteristics of magmatic rocks which contain potential porphyry mineralization.

CONCLUSION

The late Paleozoic magmatic rocks are broadly distributed in the Mandakh area located in the Gurvansaikhan and Manlai terrains with porphyry Cu deposits. We have investigated petrochemical features and mineral assemblages of Devonian and Carboniferous magmatic rocks in the Mandakh area and compared with magmatic rocks in giant porphyry copper deposits in the world.

We summarized the following remarks:

-Intrusive rocks in the Mandakh area are composed of syenite, granite, quartz monzonite and granodiorite, while volcanogenic rocks consist of dominant basalt, andesite, dacite and their tuffs. Carboniferous magmatic rocks from the Mandakh area are silica saturated (SiO_2 =50-73 %), have high Al_2O_3 12.9-19.4%, Na_2O+K_2O 4-12%, Sr 300-800 ppm, Y£25 ppm, Nb 3-6 ppm, and Rb≤150 ppm, and are hydrothermally altered.

-Igneous rocks are calc-alkaline, magnetite-series, I-type and are close to adakite type. All magmatic rocks in the Mandakh area are widely distributed, but petrochemical characteristics of Devonian and Carboniferous magmatic rocks are slightly different from each other, which may indicate that they are formed in separate subduction systems. Devonian magmatic rocks have more alkalic composition.

-Carboniferous plutonic and volcanic rocks show co-magmatic features, formed during the Carboniferous subduction zone developed in Southeast Mongolia.

-Similarity of petrographical and geochemical characteristics of magmatic rocks in the Mandakh area to those magmatic rocks in giant porphyry deposit area in the world could indicate a good possibility for new discovery of giant porphyry copper deposit, like Tampakan which related to adakite type magmatism. It implies that magmatic rocks source in Mandakh area may be melting subduction slab.

REFERENCES

Badarch, G., Cunningham W.D., Windley B.F.2002. A new terrane subduction for Mongolia: implications for the Phanerozoic crustal growth of Central Asia, Journal for Asian Earth Sciences, no.21, p.87-110.

Badarch, G. 2005. Tectonic overview of Mongolia: Mongolian Geoscientist, no.27, p.1-7.

Batkhishig B and Iizumi, S. 2001.Petrographical, petrochemical and geochronological study of the Carboniferous Shuteen Complex in South Mongolia. Geology (Journal of School of Geology, Mongolian University of Science and Technology) v.2, p.135-145.

Batkhishig, B., Tsuchiya Noriyoshi, Bignall Greg. 2010. Magmatism of the Shuteen Complex and Carboniferous subduction of the Gurvansaikhanterrane, South Mongolia, Journal of Asian Earth Sciences v. 37, p.399-411.

Batkhishig, B., Christian, K and Wencke, W. 2016. Rb-Sr geochronology of the DushiinOvoo formation, South Mongolia, Goldschmidt Conference Abstracts, p.173.

Blight, J.H.S., Crowley, Q.G., Petterson, M.G and Gunningham, D. 2010a. Granites of the Southern Mongolia Carboniferous Arc: New geochronological and geochemical constraints: Lithos, v. 116, p.35-52.

Blight, J.H.S., Petterson, M.G., Crowley, Q.G and Gunningham, D. 2010b. The OyutUlaan Volcanic Group: Stratigraphy, magmatic evolution and timing of Carboniferous arc development in SE Mongolia: Journal of the Geological Society, v. 167, p.491-509.

Chappell, B. W. and White, A. J. R. 1974. Two contrasting granite types. Pacific Geology 8, p.173–174.

Cooke, D.R., Hollings P.,Walshe J.L. 2005. Giant Porphyry Deposits:Characteristics, Distribution, and Tectonic Controls. v.100. Economic geology. p.801-819

Defant M.J and Drummond M.S, 1990.Derivation of some modern arc magmas by melting of young subducted lithosphere. Nature 347, p.662-665.

Dolgopolova, A., Seltman, R., Armstrong, R., Belousova, E., Pankhurst, R.J., Kavalieris, I.2013.Sr-Nd-Pb-Hf isotope systematics of the Hugo Dummett Cu-Au porphyry deposit (OyuTolgoi, Mongolia). Lithos, v.164, p.47-64.

Enkhjargal, B., Jargalan, S., Turmagnai, D., Osanai, Ya., Kimano., Altankhuyag, D., Oyungerel, S and Bolorchimeg, N., 2016. Geochemical and geochronological characterization prospects and deposit of porphyry related granitoid of the Gurvansaikhan island arc terrane, South Mongolia: Khaiguulchin, No. 55, p.100-116.

Hattori, K. 2018. Porphyry copper potential in Japan based on magmatic oxidation state, Resource geology, v. 68,p.126-137.

Hovan, M., Gregush, Ya., Moravek, R., Delgertsogt, B. and Hovanova, M. 1984. Result ofgeological prospecting work on the volcano-plutonic structure Shuteen, Ikh-Shankhai and Kharmagtai area in South Gobi district. Geological Report, 49, Geo-

Information Center, Ulaanbaatar, Mongolia, 131p (in Russian).

Iizumi, S and Batkhishig B. 2000. Petrology of Carboniferous Shuteen Pluton in the South Gobi Fold Belt, South Mongolia. Abstracts, The 107th Annual Meeting of the Geological Society of Japan, p.319.

Ishihara, S. 1998. granitoid series and Mineralization in the Circum-Pacific Phanerozoic Granitic Belts, v.48, no.4, p.219 -224.

Jahn, B.M. 2004. The Central Asian Orogenic Belt and growth of the continental crust in thePhanerozoic: London, Geological Society, Special Publication 226, p.73.

Kuno, H. 1968. Differentiation of Basalt Magmas. In: Hess, H.H. and Poldervaart, A., Eds., Basalts: The Poldervaart Treatise on Rocks of Basaltic Composition, Interscience Publishers, New York, p.623-688.

Le Maitre R.W. 1989.A classification of igneous rock and glossary of terms.Blackwell Scientific Publications, pp. 193.

Mihalasky, M.J., Ludington, S., Hammarstrom, J.M., Alexeiev, D.V., Frost, T.P., Light, T.D., Robinson, G.R., Briggs, D. A., Wallis, J and Miller, R.J. 2015.Porphyry Copper Assessment of the Central Asian Orogenic Belt and Eastern Tethysides—China, Mongolia, Russia, Pakistan, Kazakhstan, Tajikistan, and India: Scientific Investigations Report 2010–5090–X, USA, p.18, 23, 48-53.

Pearce, J.A and Cann, J.R. 1973.Tectonic setting of basic volcanic rocks determined using trace element analysis. Earth and Planetary science letters, v.19, p.290-300

Pearce, J.A., Harris, N.B., Tindle, A.G. 1984. Trace element discrimination diagrams for the interpretation of granitic rocks. Journal of Petrology, v.25, p.956-983.

Porter, T.M., 2016, The geology, structure and mineralization of the OyuTolgoi porphyry copper-gold-molybdenum deposits, Mongolia: A review, Geoscience Frontiers, p.375-407.

Richards, J.P., 2011, High Sr/Y arc magmas and porphyry Cu±Mo±Au deposits: Just add water: Economic Geology, v. 106, No.7, 1075-1080.

Rodionov, S.M., Obolenskiy, A.A.,Distanov, E.G., Badarch, G., Dejidmaa, G., Hwang D.H., Khanchuk,A.I., Ogasawara, M., Nokleberg, J.W., Parfenov, L.M., Prokopiev, A.V., Seminskiy, Z.V., Smelov, A.P., Yab, H., Birul'kin, G.V., Davydov, Y.V.V., Fridovskiy, V.Yu., Gamyanin, G.N., Gerel, O., Kostin,A.V., Letiunov, S.A., Li, X., Nikitin, V.M., Sudo, S., Sotnikov, V.I., Spiridonov, A.V., Stepanov, V.A., Sun, F., Sun, J., Sun, W., Supletsov, V.M., Timofeev, V.F., Tyan, O.A., Vetluzhskikh, V.G., Wakita, K., Yakovlev, Y.V and Zorina, L.M. 2003. Preliminary Metallogenic Belt and Mineral Deposit Maps for Northeast Asia, Open-File Report 03-204, p.22, 26.

Rohrlach, B.D. 2002. Tectonic evolution, Petrochemistry, Geochronology and Palaeohydrology of the Tampakan Porphyry and High sulphidation Epithermal Cu-Au deposit Mindanao, Philippines. Published doctoral thesis. Australian National University, p.174-189.

Seltmann, R and Porter, T.M. 2005. The Porphyry Cu-Au/Mo Deposits of Central Eurasia 1. Tectonic, Geologic and Metallogenic Setting, and Significant Deposits: in Porter T.M (Ed), Super Porphyry Copper & Gold Deposits: A Global Perspective, PGC Publishing, Adelaide, v.2, p.467-512.

Sillitoe, R. H.2018. Why no porphyry copper deposits in Japan and south Korea: Resource geology, p.1-19.

Tsang, D.P.W and Wallis, S.R., Yamamoto, K., Takeuchi, M., Hidaka, H., Horie, K and Tattitch, B.C.2018. Zircon U-Pb geochronology and geochemistry of the Cerro Colorado porphyry copper deposit, northern Chile, Ore Geology Reviews, v.93, p.114-140.

Tungalag, N., Jargalan, S and Orolmaa, D., 2014. Geochemical characteristics of the

Tsagaansuvarga porphyry Cu-Mo deposit, South Mongolia: Korea, the fifth conference of MUSTAK, p.1-4

Yamasaki, Sh., Matsunami, H., Tsuchiya, N. 2011. Simultaneous Determination of Trace Elements in Soils and Sediments by Polarizing Energy Dispersive X-ray Fluorescence Spectrometry. Bunsekikagaku v.60(4), p.315-323.

Yakubchuk, A. 2002. The Baikalide-Altaid, Transbaikal-Mongolian and North Pacific Orogenic Collages" Similarity and Diversity of Structural Patterns and Metallogenic Zoning. In: Geological Society, v. 204. Special Publications, London, p.273-298.

Yarmolyuk, V.V., Kovalenko, V.I., Sal'nikova, E.B., Kovach, V.P., Kolovsky, A.M., Kotov, A.B and Lebedev, V.I. 2008. Geochronology of igneous rocks and formation of the late Paleozoic south Mongolian active margin of the Siberian continent. Stratigraphy and Geological Correlation v. 16, p.162-181.

Watanabe, Y and Stein,J. H. 2000. Re-Os ages for the Erdenet and Tsagaansuvarga porphyry Cu-Mo deposits, Mongolia, and tectonic implications, Economic Geology, v.95, p.1537-1542.

Windley, B.F., Alexeiev, D., Xiao, W., Kroner, A and Badarch, G., 2007. Tectonic for accretion of the cenral Asian Orogenic Belt. Journal of the Geological Society, London, v.164, p.31-47.