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
Carboniferous granitoids in the south (Badarch et al., 2002). Geological setting, magmatism and mineralization of the South Mongolia are relatively well studied, but there is considerable debate regarding the Paleozoic-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).

**GEOLOGICAL SETTINGS**

**Volcanogenic Formations:** The Lower Devonian Undurud Formation (D1,2ulu) 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 overlayd by Upper Devonian to Carboniferous volcanic and volcanogenic sedimentary rocks of Undurud (D1,2ulu), Alagbayan (D2,3ab), Ikhshankh (C1,1s), Gunbayan (C1,gb), Tsokhiot (C1,Ch), Dushinovoo (C2,do) and Sainshandkhudag (C2,ss) Formations widespread in the Mandakh area, which are all differ in lithological characteristics. Also, Devonian to Carboniferous granite plutons such as Tsagaan Suvarga (D1,c), Bronze Fox (C2), Mandakh (C2,m), Mogoit (C2,mo) and Shuteen (C2) 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.

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

Lower Carboniferous Ikhshankh Formation (C1is) 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 (C1ch) Formation occurred in west southern part in Mandakh area (Fig. 2). This Formation consist of andesite, basaltic andesite and basalt. The Dushiinovoo Formation (C2do) outcrop stretches from the northeast to southeast, and intruded by the Mandakh, Shuteen, Budar and Narii 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

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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
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 (C1ss) 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 NarinKhudag, 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 Ikshankh 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$_2$O$_3$, tFeO, MnO, MgO, CaO, Na$_2$O, K$_2$O and P$_2$O$_5$) 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), Ikshankh (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 | Sainshandkhudag | Ikshankh | Dushinovoo | Tsokhiot |
|---------------|-----------|----------|----------------|----------|------------|----------|
| **Primary minerals** | Pl>Cpx | Pl>Amp | Cpx, Amp, Pl, Kfs, Q | Pl>Amp | Cpx, Amp, Pl, Kfs, Q | Cpx, Amp, Pl, Kfs, Q |
| **Secondary minerals** | Ore & clay minerals | Ore & clay minerals | Sericite, chlorite, zoisite, clay mineral | Sericite, chlorite | Sericite, chlorite | Sericite, chlorite |
| **Rock type** | Basalt, Trachydacite | Dacite, Andesite, basaltic tuff | Andesite, dacite, rhyolite, tuff of these | Andesite, dacite, rhyolite, tuff of these | Andesite, dacite, rhyolite, tuff of these | Andesite, dacite, rhyolite, tuff of these |

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 comprises 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>Am>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
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 SiO₂ 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).
### Table 3. Major and trace element composition of the volcanic rocks of the Mandakh

| Samples | Unduruud | Sainshandkhudag | Ikshankh | Dushinovoo |
|---------|----------|----------------|----------|------------|
|         | 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 (%)**

|          | SiO₂   | Al₂O₃  | FeO    | Na₂O   | CaO   | MnO   | MgO   | K₂O   | P₂O₅  | Total |
|----------|--------|--------|--------|--------|-------|-------|-------|-------|-------|-------|
| Unduruud | 63.64  | 15.98  | 8.25   | 5.67   | 3.28  | 0.09  | 3.88  | 2.18  | 0.2  | 100.58 |
| Sainshandkhudag | 60.76  | 17.55  | 11.03  | 4.27   | 5.03  | 0.09  | 4.09  | 1.65  | 0.24 | 99.38  |
| Ikshankh | 62.01  | 17.48  | 10.93  | 5.06   | 2.94  | 0.03  | 0.63  | 5.33  | 0.2 | 99.74  |
| Dushinovoo | 53.9  | 14.85  | 14.68  | 3.53   | 1.38  | 0.03  | 0.48  | 2.42  | 0.14 | 98.79  |

**Trace element (ppm)**

|          | V      | Cr     | Co     | Ni     | Cu     | Zn     | As     | Rb     | Sr     | Y      | Zr     | Nb     | Sm     | Eu     | Tb     | Th     |
|----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Unduruud | 112    | 52     | 15     | 33     | 53     | 59     | 11     | 40     | 553    | 11     | 150    | 5     | 1      | 478    | 12     |
| Sainshandkhudag | 155   | 70     | 17     | 32     | 16     | 78     | 3      | 29     | 503    | 8      | 140    | 4     | 2      | 710    | 17     |
| Ikshankh | 98     | 3      | 12     | 12     | 16     | 79     | 3      | 22     | 303    | 7      | 150    | 5     | 1      | 478    | 12     |
| Dushinovoo | 37    | 3      | 9      | 10     | 13     | 62     | 4      | 7      | 269    | 19     | 150    | 5     | 3      | 710    | 17     |
### 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 (%)**

| SiO₂      | 62.56 | 62.5 | 58.96 | 59.29 | 67.06 | 60.76 | 54.14 | 60.96 | 52.27 | 71.2 | 54.56 |
| TiO₂      | 0.69  | 0.65 | 0.91  | 0.86  | 0.39  | 0.58  | 1.16  | 0.59  | 0.85  | 0.48 | 1.18  |
| Al₂O₃     | 15.84 | 15.2 | 18.11 | 16.33 | 13.99 | 16.34 | 17.78 | 17.3  | 17.75 | 14.81| 16.81 |
| Fe₂O₃     | 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  |
| Na₂O      | 3.53  | 3.88 | 3.45  | 3.78  | 4.43  | 3.46  | 3.13  | 5.29  | 2.61  | 5.87 | 3.69  |
| K₂O       | 2.81  | 7.97 | 4.11  | 2.26  | 2.94  | 2.78  | 1.57  | 2.93  | 0.97  | 4.16 | 1.12  |
| P₂O₅      | 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   | 5   | 5  | 0   | 0   | 2   | 0   | 0  | 2   |
| 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    | N | E | N | E | N | E | N | E | N | E | N | E | N | E | N | E |
| Ts1       | 43.84 | 43.84 | 43.84 | 43.84 | 44.34 | 44.34 | 44.34 | 44.34 | 44.34 | 44.34 | 44.34 | 44.34 | 44.06 | 44.06 | 44.06 | 44.06 |
| Ts2       | 43.84 | 43.84 | 43.84 | 43.84 | 44.34 | 44.34 | 44.34 | 44.34 | 44.34 | 44.34 | 44.34 | 44.34 | 44.06 | 44.06 | 44.06 | 44.06 |
| Ts3       | 43.84 | 43.84 | 43.84 | 43.84 | 44.34 | 44.34 | 44.34 | 44.34 | 44.34 | 44.34 | 44.34 | 44.34 | 44.06 | 44.06 | 44.06 | 44.06 |

**Major element (%)**

|  | SiO₂ | TiO₂ | Al₂O₃ | Fe₂O₃ | MgO | CaO | Na₂O | K₂O | P₂O₅ | Total |
|---|------|------|-------|-------|-----|-----|------|-----|------|-------|
| N | 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 |
| 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 |

**Trace element (ppm)**

|  | V   | Cr  | Co | Ní | Cu | Zn | As | Rb | Sr | Y  | Zr  | Nb | Sn | Sb | Cs | Ba | La | Ce | Pr | Nd | Pb | Th |
|---|-----|-----|----|----|----|----|----|----|----|----|-----|----|----|----|----|----|----|----|----|----|----|----|
|  | 56  | 62  | 75 | 23 | 72 | 102 | 50 | 72 | 37 | 101 | 101 | 98 | 90 | 50 | 54 | 40 | 32 | 12 | 9 | 8 |
|  | 1   | 2   | 1  | 0  | 41 | 33  | 2  | 4  | 3  | 50  | 54  | 40  | 32  | 22 | 30  | 12 | 9  | 8  | 7  | 6  |
|  | 1   | 2   | 1  | 0  | 10 | 11  | 4  | 6  | 4  | 12  | 9   | 10  | 8   | 10 | 11  | 12 | 9  | 8  | 7  | 6  |
|  | 9   | 8   | 9  | 9  | 29 | 23  | 14 | 14 | 9  | 22  | 20  | 18  | 20  | 47 | 63  | 21 | 13 | 12 | 11 | 10 |
|  | 25  | 19  | 18 | 10 | 40 | 56  | 19 | 20 | 26 | 47  | 63  | 23  | 13  | 33 | 32  | 28 | 26 | 25 | 23 | 20 |
|  | 37  | 39  | 42 | 25 | 65 | 62  | 45 | 43 | 51 | 33  | 32  | 28  | 26  | 15 | 14  | 13 | 12 | 11 | 10 | 9  |
|  | 83  | 87  | 104 | 117 | 42 | 64  | 101 | 88 | 90 | 78  | 92  | 91  | 93  | 63 | 597 | 606 | 522 | 13 | 12 | 11 |
|  | 505 | 529 | 973 | 100 | 842 | 571 | 205 | 445 | 202 | 633 | 597 | 606 | 522 | 185 | 170 | 167 | 179 | 15 | 14 | 13 |
|  | 7   | 9   | 9  | 13 | 8  | 11  | 14 | 11 | 32 | 15  | 14  | 13  | 13  | 185 | 170 | 167 | 179 | 15 | 14 | 13 |
|  | 71  | 94  | 194 | 129 | 142 | 180 | 134 | 179 | 316 | 185 | 170 | 167 | 179 | 185 | 170 | 167 | 179 | 15 | 14 | 13 |
|  | 6   | 5   | 6  | 12 | 4  | 6   | 8  | 7  | 8  | 5   | 5   | 5   | 5   | 5   | 5   | 5   | 5   | 5   | 5   | 5   |
|  | 6   | 5   | 6  | 12 | 4  | 6   | 8  | 7  | 8  | 5   | 5   | 5   | 5   | 5   | 5   | 5   | 5   | 5   | 5   | 5   |
|  | 0   | 0   | 0  | 1  | 1  | 1    | 1  | 1  | 2  | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   |
|  | 0   | 0   | 0  | 0  | 0  | 0    | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
|  | 0   | 0   | 0  | 1  | 1  | 3    | 2  | 5  | 2  | 1   | 2   | 2   | 1   | 2   | 2   | 1   | 2   | 2   | 1   | 2   |
|  | 2   | 4   | 3  | 1  | 1  | 3    | 2  | 5  | 2  | 1   | 2   | 2   | 1   | 2   | 2   | 1   | 2   | 2   | 1   | 2   |
|  | 825 | 953 | 737 | 345 | 649 | 922 | 755 | 951 | 934 | 767 | 741 | 720 | 693 | 16 | 13  | 9  | 22 | 16 | 13 | 9  |
|  | 12  | 9  | 11 | 33 | 20 | 26  | 25 | 22 | 27 | 16  | 13  | 9   | 22  | 16 | 13  | 9  | 22 | 16 | 13 | 9  |
|  | 23  | 23 | 20 | 57 | 37 | 51  | 48 | 45 | 60 | 37  | 30  | 22  | 41  | 37 | 30  | 22 | 41 | 37 | 30 | 22 |
|  | 1  | 1  | 1  | 5  | 2  | 2    | 2  | 2  | 5  | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   |
|  | 12  | 11 | 10 | 15 | 16 | 25   | 18 | 21 | 29 | 20  | 16  | 14  | 17  | 20 | 16  | 14 | 17 | 20 | 16 | 14 |
|  | 7  | 9  | 9  | 22 | 8  | 11   | 17 | 14 | 17 | 7   | 8   | 7   | 7   | 7   | 8   | 7   | 7   | 7   | 7   | 7   |
|  | 4  | 5  | 7  | 17 | 5  | 9    | 15 | 9  | 10 | 8   | 10  | 10  | 13  | 8   | 10  | 10 | 13 | 8   | 10 | 10 | 13 | 13 |
Table 4. Continued.

| Intrusive Sample | Bronze Fox | Moogoit |
|------------------|------------|---------|
| N                | BrF5       | BrF6    | BrF7 | BrF8 | BrF9 | BrF10 | Mo1  | Mo2  | Mo3  | Mo6  | Mo7  |
| BrF5             | 44.073     | 44.073  | 44.073 | 44.073 | 44.077 | 43.678 | 43.675 | 44.034 | 44.034 | 44.03 |
| BrF6             | 107.87     | 107.87  | 107.87 | 107.87 | 107.87 | 107.22 | 107.22 | 108.67 | 108.67 | 108.84 |
| | SiO2       | 56.15     | 56.95   | 56.85  | 56.67  | 66.75  | 69.27  | 68.63 | 68.52 | 67.63 | 71.7  | 70.64 |
| | TiO2       | 0.98      | 0.77    | 0.79   | 0.96   | 0.52   | 0.36   | 0.44  | 0.51  | 0.51  | 0.34  | 0.42  |
| | Al2O3      | 18.46     | 18.43   | 15.06  | 16.93  | 14.88  | 14.27  | 14.95 | 15.21 | 15.26 | 14.87 | 15.69 |
| | Fe2O3      | 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  |
| | Na2O       | 5.24      | 5.69    | 3.32   | 5.11   | 3.74   | 3.96   | 4.14  | 3.96  | 4.35  | 4.63  | 6.09  |
| | K2O        | 0.21      | 0.24    | 2.55   | 0.36   | 3.95   | 4.59   | 4.28  | 4.12  | 4.51  | 4.31  | 4.35  |
| | P2O5       | 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     |
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).
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$_2$O+K$_2$O>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$_2$O$_3$ ≥12.9%, Na$_2$O+K$_2$O>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 phenocrysts and are 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$_2$O$_3$ >15% wt.** | *12.9-18.46%* | *14- 19.36%* |
| **Low Y<18ppm** | *7– 32 ppm* | Mostly<16 ppm; Rarely~ 25ppm |
| **Sr rich>400 ppm** (rare above 6%) | max: 1387 ppm min: 100 ppm mostly 300-600ppm | max: 915 ppm min: 203 ppm mostly 500-800ppm |
| **Plagioclase is ubiquitous** | Plagioclase is common all the rocks and hornblende. | Plagioclase is common all of the rocks and also hornblende. |
| **Amphibolite is common; a common assemblage is Pl&Amp** | Pyroxenes are to Hornblende. | |
| **Tectonic setting What is tectonic setting?** | I-type Volcanic arc granite 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 |
|---------------------------------------------------|-------|------------|-------|--------------|
| 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 (Tsagaansuvarga) |
| 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 |
| Volcanic-plutonic style                           | Not determined | Magnetite-series, Stratovolcanoes | Magnetite-series, Stratovolcanoes | Magnetite-series Stratovolcanoes |
| Magma type                                        | Not determined | Oxidized | Oxidized | Oxidized |

|                      | Tampakan Porphyry deposit | Cerro Colorado Porphyry deposit | Late Devonian | Carboniferous |
|----------------------|---------------------------|-------------------------------|---------------|--------------|

* - 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 \( f_\text{O}_2 \) 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\(_2\)O\(_3\) 12.9-19.4%, Na\(_2\)O+K\(_2\)O 4-12%, Sr 300-800 ppm, Y\(\leq\)25 ppm, Nb 3-6 ppm, and Rb\(\leq\)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 Gurvansaikhan terrane, 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 OyuUlaan 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, L. 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 of geological prospecting work on the volcano-plutonic structure Shuteen, Ikh-Shankhai and Kharmagai area in South Gobi district. Geological Report, 49, Geo-
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., Distano, 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., Fridovskyi, 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., Vetlushskikh, 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, Geochemistry 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 central Asian Orogenic Belt. Journal of the Geological Society, London, v.164, p.31-47.