Journal of Geological Issues 446 (14); (2016) 64-71

GIMAR 2016
Geological Issues of Mongolia and Adjacent Regions

Petrogenesis and geochronology of granitoids from the Tseel terrane, SW Mongolia

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ABSTRACT

In this study, geochemistry and geochronology of granitoids in the Tseel area of the Tseel terrane, SW Mongolia, are examined to constrain the tectonic setting for the igneous activity and its relation to metamorphism. The massive of granitoid in the central part of the Tseel area was dated to be 281.3 ± 1.1 Ma. Comparison with the previous geochronological studies on metapelites suggests that these granitoid intrusions occurred after the main metamorphic events. In the Tseel area, granitoids yield various ages including the Devonian and Permian ages. These granitoids show geochemical signatures for subduction-related magmatism, including the concave and negative anomalies of Eu in the REE pattern and enriched LILEs. The similarity in the geochemical signature between the Tseel terrane and the Chinese Altai implies that these regions are the same arc related system, which extended from SW Mongolia to Chinese Altai.

Keywords: granitoids, geochemical characteristics, Tseel terrane, SW Mongolia

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1. Introduction

The Central Asian Orogenic Belt (CAOB) is one of the largest orogenic belts, that extends from the Urals in the west through Kazakhstan, Mongolia, southern Siberia, northern China and the Okhotsk Sea in the east (Fig.1a). The CAOB contains several high-temperature metamorphic zones associated with intrusion of granitoids (Kozakov et al., 2002; Windley et al., 2007; Wei et al., 2007, Burenjargal et al., 2014, Broussolle et al., 2015). The geochemical characteristics of these granitoids are of special importance for constraining the tectonic setting for the granitoid intrusions and their relations to the high-*T*/low-*P* metamorphism during the evolution of the CAOB.

Mongolia is located in the central part of the CAOB (Fig. 1a) and subdivided into the northern and southern domains separated by Main Mongolian Lineament (MML; Fig. 1b). The northern domain contains many granitic rocks with various ages and various chemical compositions, and these granitoids occur associated with metamorphic rocks of Precambrian and Lower Paleozoic ages (Badarch et al., 2002). The southern domain is composed of middle to late Paleozoic arc-related assemblages (Badarch et al., 2002) and fragments of ophiolites and serpentinite mélanges (Rippington et al., 2008).

The Tseel terrane is located in the SW Mongolia along the south boundary of the Main Mongolian Lineament (MML, Fig. 1b) and extension of this terrane is more than 600 km from east to west. The Tseel terrane is a high-T and low-P crustal segment of an early Paleozoic arc system within the CAOB (Kozakov et al., 2002; Jiang et al., 2012; Burenjargal et al., 2012; 2014 & 2016; Fig. 1). Previous studies have proposed that two metamorphic events occurred in the Tseel terrane (Burenjargal et al., 2014); the early stage of high-P/low-T metamorphism during the Silurian (450-400 Ma), and the low-P and high-T metamorphism during the Devonian (377 ± 30 Ma), respectively. The low-P and high-T metamorphism continued for c. 100 Ma, suggesting the elevation of geotherm during the Devonian caused by continuous intrusion of several granitoid bodies and/or by radioactive heat production subsequent to the granitoid intrusions (Burenjargal et al., 2014). In spite of several petrological and geochronological studies, geochemical studies on the granitoids within the Tseel area are lacking.

In this study, we investigated geochemical compositions of granitoids in the Tseel area for understand their petrogenesis and tectonic setting of the Tseel terrane. The granitoid samples analyzed in this study are taken from the different mineral zones. In addition, we obtained new U-Pb zircon ages of the granitoids in the Tseel area. This paper presents the geochemical characteristics and timing of granitoid intrusions and finally concluded that relationship between metamorphic evolution and intrusions of granitoid in the Tseel area, Tseel terrane, SW Mongolia.

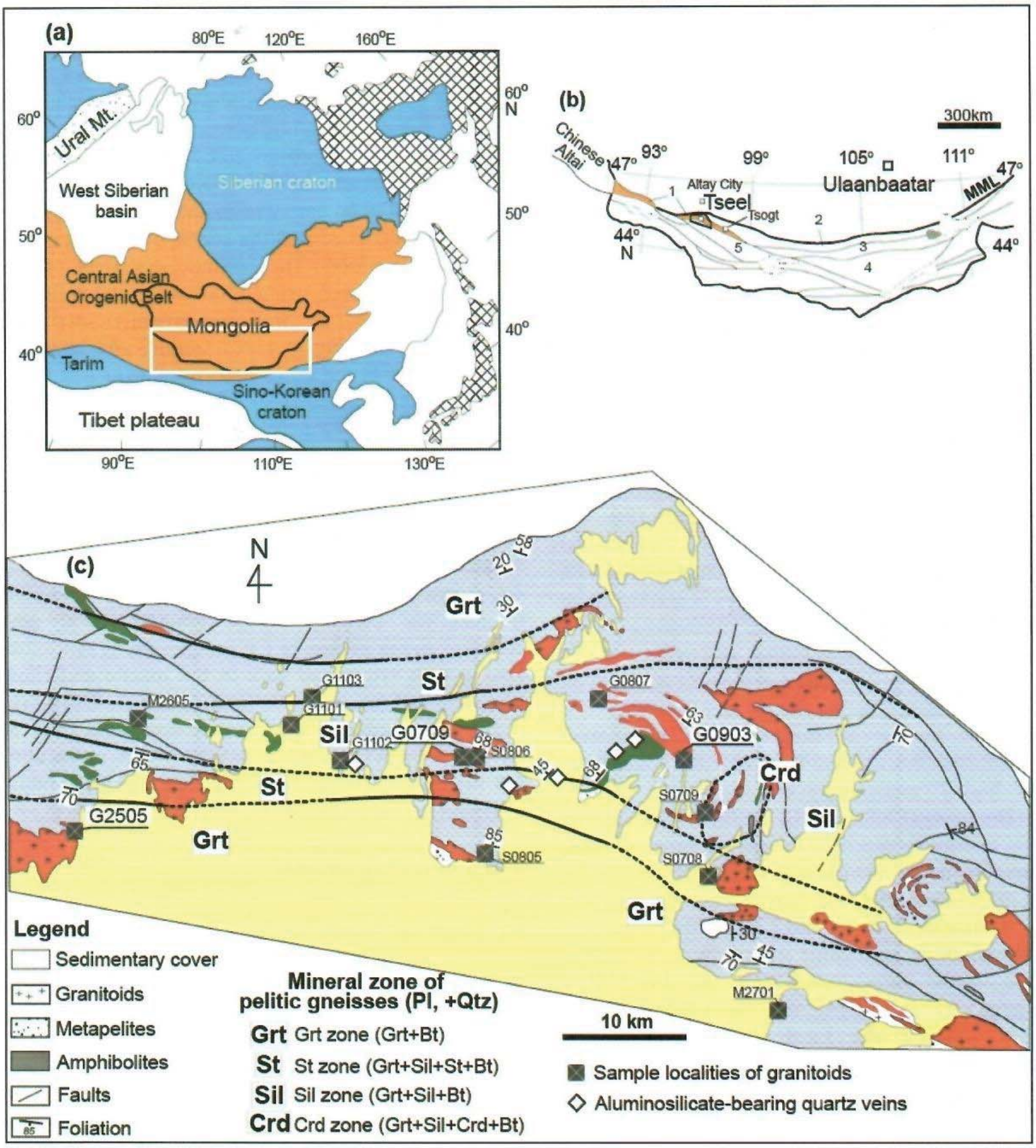

Fig. 1. (a) Major tectonic components of the Central Asian Orogenic Belt (CAOB). Blue areas indicate Archean to Mesoproterozoic cratons (modified after Jahn et al., 2000). (b) Tectonostratigraphic terrane map of southern Mongolia: 1. Tseel terrane, 2. Gobi-Altai terrane, 3. Mandalovoo terrane, 4. Gurvansaikhan terrane, 5 Edren terrane (Badarch et al., 2002). MML, Main Mongolian Lineament. (c) Geological map of the Tseel area showing the four mineral zones: garnet (Grt), staurolite (St), sillimanite (Sil) and cordierite (Crd) (Burenjargal et al., 2014).

2.Geological setting

The CAOB extends from the Urals to the Pacific and from the Siberian and East European (Baltica) cratons to the North China (Sino-Korean) and Tarim cratons (Jahn et al., 2000; Windley et al., 2007). The collision of these cratons led to the formation of the CAOB through the accretion of island arcs, ophiolites, oceanic islands, seamounts, accretionary wedges and microcontinents at a convergent margin (e.g. Khain et al., 2002; Windley et al., 2007). The Tseel terrane in SW Mongolia is one of the metamorphic terranes in the CAOB, which is characterized by high-T metamorphism and granitoid intrusions (Kozakov et al., 2002; Burenjargal et al., 2012; 2014 & 2016).

The Tseel area, which belongs to the eastern block of the Tseel terrane (Fig. 1b), is composed mainly of pelitic gneisses and amphibolites intruded by numerous granitoids (Fig. 1c). This area predominantly shows the E-W striking foliation, although its orientation is locally curved by granitoid emplacement (Fig. 1c). The granitoids occur as large kilometer-scale massive bodies or as layers up to several meters thick.

The Tseel area is divided into four mineral zones, on the basis of the index minerals in the metapelites; garnet, staurolite, sillimanite and cordierite (Fig. 1c; Burenjargal et al., 2014). The distribution of mineral zones is symmetrical about an E-W trending axis, with the high-grade sillimanite assemblages occurring along a central strip, and the grade decreasing to a sillimanite-absent biotite ± garnet assemblage to the north and south (Fig. 1c). The petrological analyses on the pelitic gneisses in the Tseel area revealed two metamorphic events: an earlier high-*P* and low-*T* metamorphism (kyanite stability field) and a later low-*P* and high-*T* metamorphism (sillimanite stability field) (Burenjargal et al., 2012 & 2014). The former event is mainly recorded in the garnet zone, whereas the latter in the sillimanite and cordierite zones. The garnet in the staurolite zone records both metamorphic stages (Burenjargal et al., 2012 & 2014). Granitoids are common in the sillimanite and cordierite zones, but are rare in the garnet zones (Fig. 1c; Fig. 14 of Burenjargal et al., 2014). In the sillimanite and staurolite zones of the Tseel area, aluminosilicate-bearing quartz veins occur (Burenjargal et al., 2012 & 2014). These veins contain all three aluminosilicate polymorphs, which formed in the order of Ky → Sil → And (Burenjargal et al., 2012 & 2014).

3.Zircon U-Pb dating granitiod

3.1. Sample and analytical method

A granitoid sample (samples G0709) for the SHRIMP U-Pb zircon age dating was taken from the sillimanite zone in the Tseel area. The locality and its coordinate are shown in Fig. 1c. The sample is part of the large granitoid and occurs as an interlayer with pelitic gneisses. The sample is coarse grained granitoid and composed of quartz + plagioclase + K-feldspar + biotite ± garnet + magnetite + zircon + apatite.

Zircon grains for the SHRIMP analyses were separated from rock samples through standard crushing, grinding, sieving, magnetic and heavy-liquid separation techniques, followed by hand picking under a binocular microscope. The grains from the sample were mounted in an epoxy resin and polished until the surface was flattened and the center of the embedded grains was exposed. The internal structures of the zircon were assessed using transmitted and reflected light microscopy, as well as cathodluminescence image (CLI) imaging to reveal zoning and to select optimum sites in the cores and rims for in situ U-Pb dating.

3.2. Results

Representative cathodoluminescence (CL) images of zircons for selected sample (G0709). Tera-Wasserburg diagram and comparison of all age data are shown in Fig. 2a and 2b, respectively. Granitoid samples are contains coarse grained (>100 μm) euhedral zircon grains. In CL images, the grains show zoning with bright and dark in the mantle and rims. The weighted means for the granite sample G0709 (N = 20) and combined age data show a main peak at 281.3 ± 1.1 Ma (95% conf.; MSDW = 1.3, probability = 0.14; Fig. 2b) (error: 1σ of Fig. 2b). The Th/U ratios of zircon in sample G0709 range from 0.30 to 0.58.

4. Whole rock geochemistry

4.1. Major and Trace elements

Thirteen granitoid samples were selected for major and trace element analyses and are mainly composed of quartz + plagioclase + K-feldspar + biotite ± garnet + magnetite + zircon + apatite and some gneissose granitoids are composed of quartz + plagioclase + amphibole ± biotite + muscovite + zircon. Granitoids represent, ranging from 69.82 to 76.42 wt. % SiO_2. Harker diagrams display negative linear correlations of SiO_2 with Al_2O_3, Fe_2O_3, MgO, CaO, MnO, TiO_2 and K_2O.

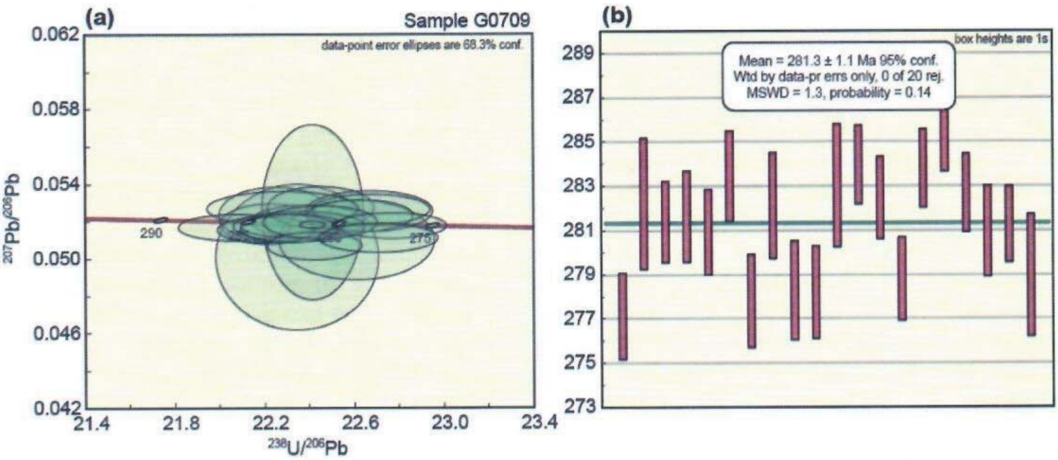

Fig. 2. (a) Tera-Wasserburg diagram of U-Pb zircon ages from granitiod, sample G0709. (b) Comparison of all age data N = 20 for sample G0709. The data-point error ellipses in these concordia plots are 1σ.

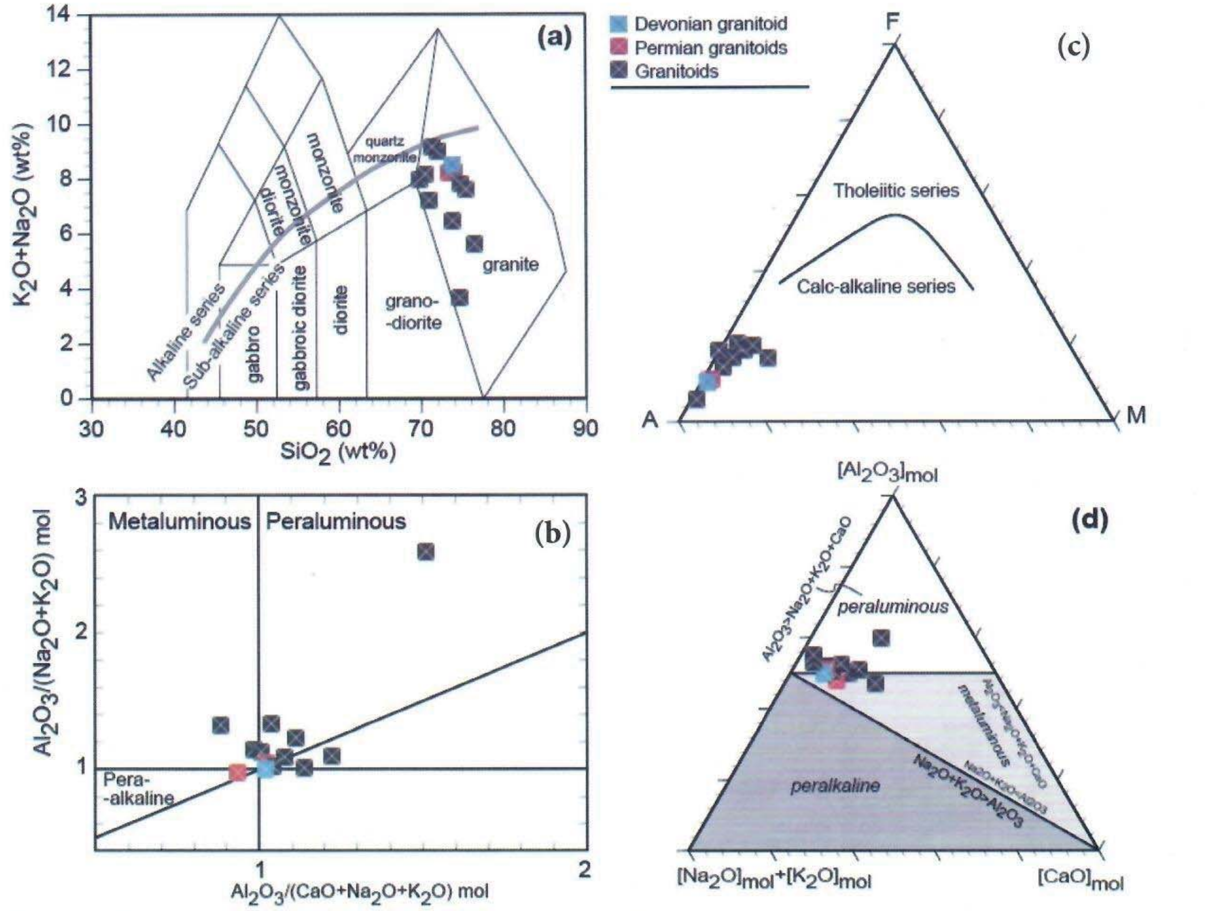

Fig. 3. (a) Total alkali-silica diagram, TAS, modified after Middlmost, 1994. (b) A/CNK vs. A/NK (Manier & Piccoli 1989). (c) AFM diagram of the granitoids with the tholeiitic/calc-alkalic dividing line from Irvine and Barager (1971). (d) Peraluminous, metaluminous and peralkaline fields shown in a ternary plot of whole rock Al_2O_3, $Na_2O + K_2O$ and CaO contents (in molar proportions).

Sodium prevails over potassium in granitoids show ratio ranges from 0.16 to 3.4.The Mg numbers [*molar 100* MgO/(MgO + FeOt)*] are mostly ranges from 23.23 to 58.96 and the sample S0708 show 2.99. The granitoids are composed of sub-alkaline rocks and plotted in the granite field, as demonstrated by the Total alkali-silica (TAS) diagram (Fig. 3a) (Middlemost 1994). Shand's index A/CNK [*molar* $Al_2O_3/(CaO + Na_2O + K_2O)$], most granitoid samples are represents the peraluminous (A/CNK = 0.88-1.51) and samples S0708, G1103 are plotted in metaluminous and G0807 shows the perakaline granitoids (A/CNK = 0.88-0.98) (Fig. 3b, c). The granitoids are calc-alkaline series and alkaline rich rocks in the AFM diagram (Irvine and Baragar 1971) (Fig. 3d).

The rare earth elements (REE) and other trace elements of the studied samples are presented in Figure 4 and normalized to chondrite and primitive mantle (Boynton 1984; Sun and McDonough 1989). Devonian granitoid (M2505) shows concave REE pattern (Fig. 4a) and negative anomalies for Nb (Fig. 4b) that indicating the subduction related trace element characteristics (Jiang et al. 2012; Helo et al. 2006). Permian (Fig. 4c) and other granitoids (Fig. 4e) of REE patterns represents the relatively flat HREE distribution and negative Eu anomalies, consistent with melting of plagioclase-bearing crustal sources (Fig. 4c, e) and lack anomalies for Nb, Sr, Zr and very weak Eu (Fig. 4d, f) suggesting subduction-related trace element features (Jiang et al. 2012; Helo et al. 2006). In the tectonic discriminant diagrams proposed by Pearce et al. (1984), most granitoids plotted in the volcanic arc granite field (Fig. 5a, b). The sample S0709, G1103 and S0708 are plotted in the within plate granite field (Fig. 5).

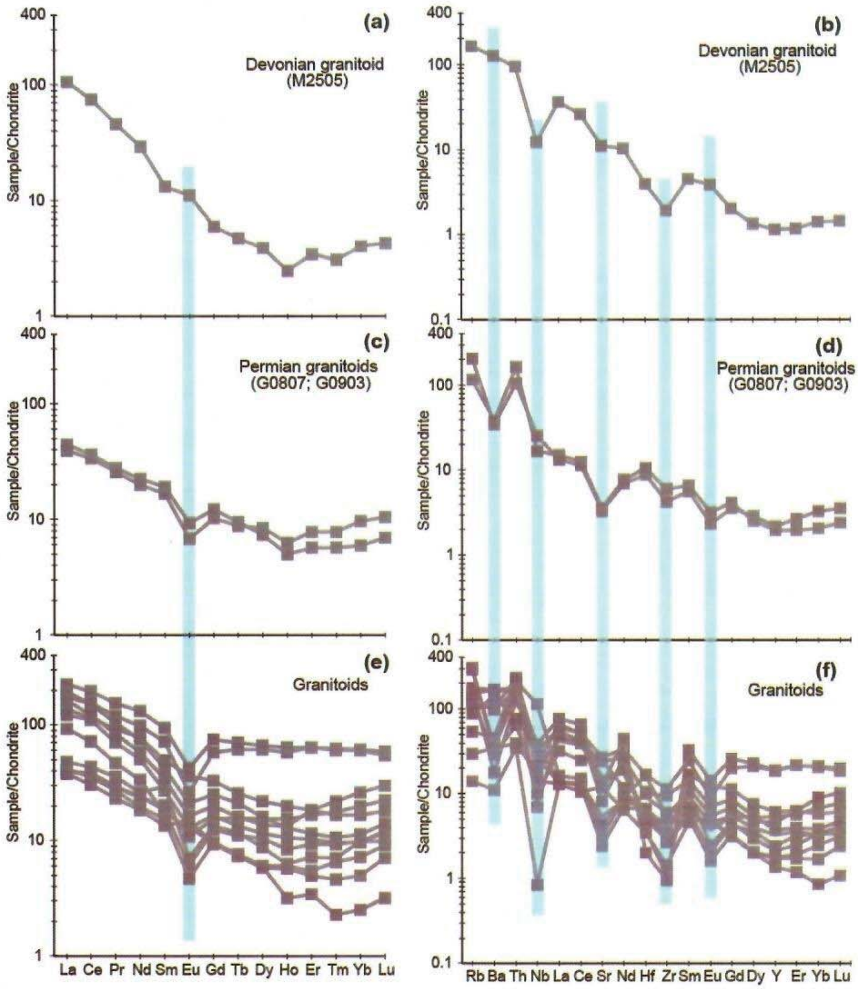

Fig. 4. (a-c) Rare Earth Elements pattern normalized to chondrite (Boynton 1984). (d-f) Spider plots normalized to primitive mantle (Sun and McDonough 1989). The ages of samples G0903 and M2505 are detail in Burenjargal et al., 2014.

5. Discussion

5.1. Several stages of granitoid intrusions of Tseel area

The ages of granitoids reported in the Tseel terrane range from 580 to 270 Ma (Bibikova et al., 1992; Kozakov et al., 2002; Kröner et al., 2007; Demoux et al., 2009a; Jiang et al., 2012; Burenjargal et al., 2014), but most yield Middle Devonian ages (400-380 Ma; e.g. Bibikova et al., 1992; Kozakov et al., 2002; Demoux et al., 2009a). In the Tseel area, two stages of granitoid intrusions have been reported in the previous studies; the Devonian (385 ± 7 Ma; Grt zone, G2505, Burenjargal et al., 2014, 385 ± 5 Ma for the deformed granitoid, Bibikova et al., 1992) and Permian ages (297 ± 11 Ma; Sil zone, G0903). Demoux et al., (2009a) showed theearly Permian (c. 280) age of the feldspar porphyry granitoids, which intruded the Early Devonian low-grade volcano-sedimentary rocks. The U-Pb ages of this study (281 ± 1.1 Ma, G0709; 279 ± 0.8 Ma, G0903 and 278 ± 1.6 Ma, G0807) for the granitoid in the central part of the Tseel area corresponds to the later phase of granitoids intrusion reported in Demoux et al., (2009a) and Burenjargal et al. (2014), although the value is slightly younger than the later phase of granitoids intrusion identified by Burenjargal et al. (2014). This difference in age between this study and that in by Burenjargal et al. (2014) is greater than 10 My (out of the error), indicating that the timing of intrusion are various for among different bodies, or the several intrusions could occur even in the same body during the Permian.

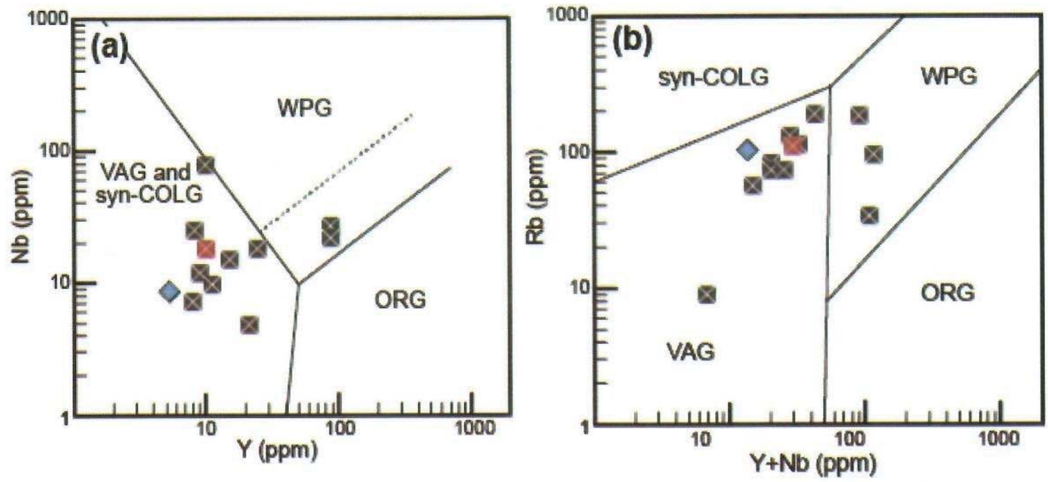

Fig. 5. Tectonic discriminant diagrams Y vs. Nb and Y + Nb vs. Rb of Pearce et al. (1984). Syn-COLG = Syn-Collisional Granite, WPG = Within-Plate Granite, ORG = Ocean Ridge Granite, VAG = Volcanic Arc Granite.

5.2. Timing of granitoid intrusion and its relation to the metamorphic events of Tseel area

Based on the petrological analyses on the garnet-bearing pelitic gneises, the *P-T* conditions in the Tseel area were estimated to be 520-680 °C and 3-7 kbar (Fig. 13 of Burenjargal et al., 2014), and the *P-T* conditions are roughly divided into two groups: high-*P* and low-*T* condition (Grt and St zones), and low-*P* and high-*T* (St, Sil and Crd zones) condition respectively (Burenjargal et al., 2014). The high-*P* and low-*T* conditions are 520-570 °C and 4.5-7 kbar in the kyanite stability field. The low-*P* and high-*T* conditions are 570-680 °C and 3-6 kbar in the sillimanite stability field (Burenjargal et al., 2014). These multiple metamorphic events occurred in response to temperature increases >50 °C (Crd zone) and the pressure is similar to both events (Burenjargal et al., 2014). The textural relationship among the aluminosilicate polymorphs in the aluminosilicate (Ky-Sil-And)-bearing quartz veins reveal that the aluminosilicates in the veins formed in the order of Ky → Sil → And (Burenjargal et al., 2012 & 2014), which suggests a transition from the high-*P* and low-*T* to low-*P* and high-*T* conditions (Burenjargal et al., 2014).

Burenjargal et al. (2014) showed the results of zircon age dating for the metamorphic events from the metapelites as follows; high-*P* and low-*T* metamorphism is pre-dated at 450-400 Ma in samples M2507 and M3001 in St zone and the low-*P* and high-*T* metamorphism occurred at 377 ± 30 Ma in sample M0901 in Crd zone in the Tseel area. Based on the special correlation between granitoids and peak temperatures, Burenjargal et al. (2014) suggest that Devonian granitoids (385 ± 7 Ma) were the heat source of a regional contact metamorphism at middle to upper crustal levels during the Middle Devonian (377 ± 30 Ma; Fig. 12c of Burenjargal et al., 2014) at middle crustal depths. In contrast, the second-stage Permian granitoids including the body analyzed in this study (Fig. 4) would have been emplaced after the main metamorphic events.

5.3. Tectonic implications

Jiang et al (2012) proposed that Tseel terrane and Chinese Altai is the same crustal segment of an early Paleozoic arc system. This crustal segment of terrigeneous sedimentary rocks was accreted at an active continental margin during the Cambrian (Long et al., 2007; Sun et al., 2008). The geochemical data of the granitoids of the Tseel area (Figs. 6-8) indicates the volcanic arc setting both in the low- and high-grade, which is consistent with the previous studies (Helo et al., 2006), and these signatures are consistent with those of the Chinese Altai (Cai et al., 2011).

In summary, high-*P* and low-*T* metapelitic rocks of the Tseel area were intruded by Devonian arc related magmatism in the subduction zone. As the result of that Devonian arc related intrusion, the Tseel area of metamorphic rocks was changed from high-*P* and low-*T* (450-400 Ma; Burenjargal et al., 2014) to low-*P* and high-*T* (377±30 Ma; Burenjargal et al., 2014) metamorphism. This low-*P* and high-*T* metamorphism continued for *c*. 100 Ma that influenced subduction related magmatism within the crust. After the main metamorphism the arc related magmatism of the Permian granitoids were intruded and that present the massive of the granitoids in the Tseel area.

6. Conclusion

1.Zircon SHRIMP U-Pb dating on granitoids from the sillimanite zone in the Tseel area shows 281.3 ± 1.1 Ma. This age indicates that massive granitoids (sillimanite and cordierite zones) in Tseel area is formed at the Early Permian and intruded after peak metamorphism.

2.In the Tseel area, granitoids are at various ages (Devonian and Permian). In spite of the difference in ages, these granitoids possess the geochemical signature of the arc-related magmatism. Comparison with the metamorphic and magmatic ages suggests that the Devonian subduction-related magmatism would act as the heat source for the low-*P* and high-*T* metamorphism of the Tseel terrane.

3.The geochemical data of the granitoids from the Tseel terrane are similar to those of the Chinese Altai, which supports the scenario that these are arc related subduction system probably extended from SW Mongolia to Chinese Altai.

Acknowledgments

The Global COE program, Tohoku University, Japan, funded this research. Authors thank to O. Gerel, J. Lkhamsuren, B. Munkhtsengel, B. Batkhishig and A. Chimedtseren (School of Geology and Mining Engineering, Mongolian University of Science and Technology) for their help and advice during the course of this study. D. Tsendbazar in thanked for providing assistance in the field. We also grateful to S. Yamasaki, R. Yamada and T. Watanabe for help with the XRF and ICP-MS analyses.

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