名古屋大学博物館報告
Bull. Nagoya Univ. Museum
No. 37, 00–00, published online as early view
DOI: 10.18999/bulnum.037.01

Ages from the "Mogod Formation" of the Permian–Triassic igneous rocks in the Sayan–Baikal belt, northern Mongolia

TSUKADA Kazuhiro[1]*, UMEDA Kanta[2], NADMID Bayart[2], SODNOM Khishigsuren[3], and NURAMKHAAN Manchuk[4]

[1] Nagoya University Museum, Nagoya 464-8601, Japan

[2] Graduate School of Environmental Studies, Nagoya University, Nagoya 464-8601, Japan

[3] School of Geology and Mining Engineering, Mongolian University of Science and Technology, Ulaanbaatar, Mongolia

[4] Academic Affairs, Branch of Mongolian University of Science and Technology, Division of Erdenet Mining Co., Erdenet, Mongolia

*Corresponding author: Tel.: +81-52-789-5768; Fax: +81-52-789-5896
E-mail address: tsukada@num.nagoya-u.ac.jp (K. Tsukada)

Abstract

Late Paleozoic–Early Mesozoic volcano-plutonic rock unit at the southern margin of the Sayan–Baikal belt, Mongolia is a significant factor in understanding the Paleozoic–Mesozoic arc system along the Siberian continental margin. The Permian–Triassic igneous rocks have been divided into the Lower–Middle Permian Khanui Group, Late Permian–Early Triassic Selenge plutonic rock complex, Permian?–Middle Triassic Erdenet plutonic rock complex, and Upper Triassic–Lower Jurassic Mogod Formation. However, a U-Pb age pointing latest Permian was recently reported from the Khanui Group, and stratigraphy of the Permian–Triassic igneous rocks is required to be reexamined. This paper describes zircon U-Pb age of 257.6 ± 3.6 Ma (Late Permian) and hornblende K-Ar age of 292.9 ± 14.1 Ma (Early Permian) from the Mogod Formation, which has previously been assigned to Upper Triassic–Lower Jurassic, and presents a possibility that the stratigraphic division of the Permian–Triassic igneous rocks is revised.

Key words: Permian–Triassic igneous rocks, Mogod Formation, U-Pb age, K-Ar age.

Introduction

The Central Asian Orogenic belt (CAOB), which lies among the Siberian craton, North China block, Tarim block, and East European craton, is a critical geologic unit in understanding the development process of the Eurasian continent (e.g., Sengör *et al.*, 1993; Kovalenko *et al.*, 2004: Fig. 1). In general, the CAOB has been formed through various processes, such as subduction-accretion of the oceanic plate, volcanic arc magmatism, and collisions of continental fragments during the amalgamation of these cratons and blocks (e.g., Sengör *et al.*, 1993). Geological data from Mongolia, an area between the Siberian craton and North China block, is essential in revealing the Paleozoic–Mesozoic tectonics of the southern margin of the "Siberian continent" (Siberian craton and accreted geologic units) in the southern part of the CAOB. Here, the features of the Sayan–Baikal belt (Precambrian–Paleozoic continental basement and intrusive rocks) and Khangai–Daur belt (Late Paleozoic–Early Mesozoic accretionary complexes) have been established (e.g., Tomurtogoo, 1998, 2003, 2014; Badarch *et al.*, 2002; Kurihara *et al.*, 2008; Onon and Tsukada, 2017: Figs. 1 and 2).

Permian–Triassic igneous rock unit (Permian–Triassic igneous rocks, hereinafter) at the southern margin of the

Sayan–Baikal belt is a significant factor in understanding the previous arc system along the Siberian continental margin (e.g., Tomurtogoo, 1998, 2003, 2014; Badarch *et al.*, 2002; Gerel and Munkhtsengel, 2005; Munkhtsengel *et al.*, 2007a; Tsukada *et al.*, 2018: Fig. 2). The Permian–Triassic igneous rocks are classified into the volcanic-clastic rock sequences (Permian Khanui Group, and Triassic–Jurassic Mogod, Bugat, and Baruunburen formations) and plutonic rock complexes (Permian–Triassic Selenge and Permian?– Triassic Erdenet complexes)

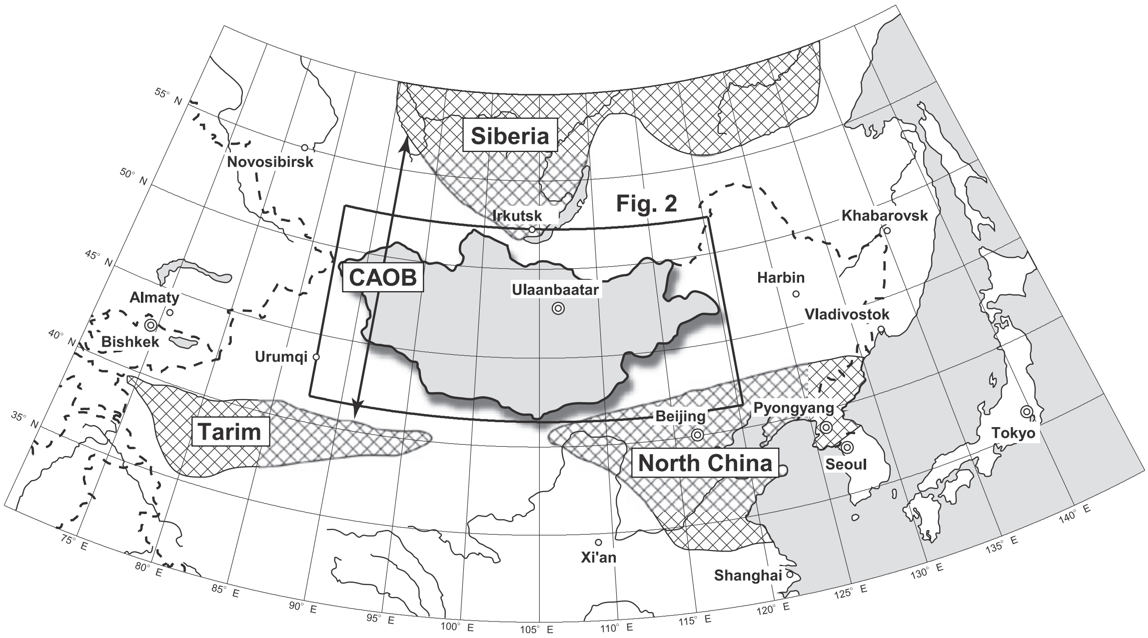

Fig. 1 Index map (modified from Kurihara *et al.*, 2008). CAOB: Central Asia Orogenic belt, Siberia: Siberian craton, North China: North China block, Tarim: Tarim block.

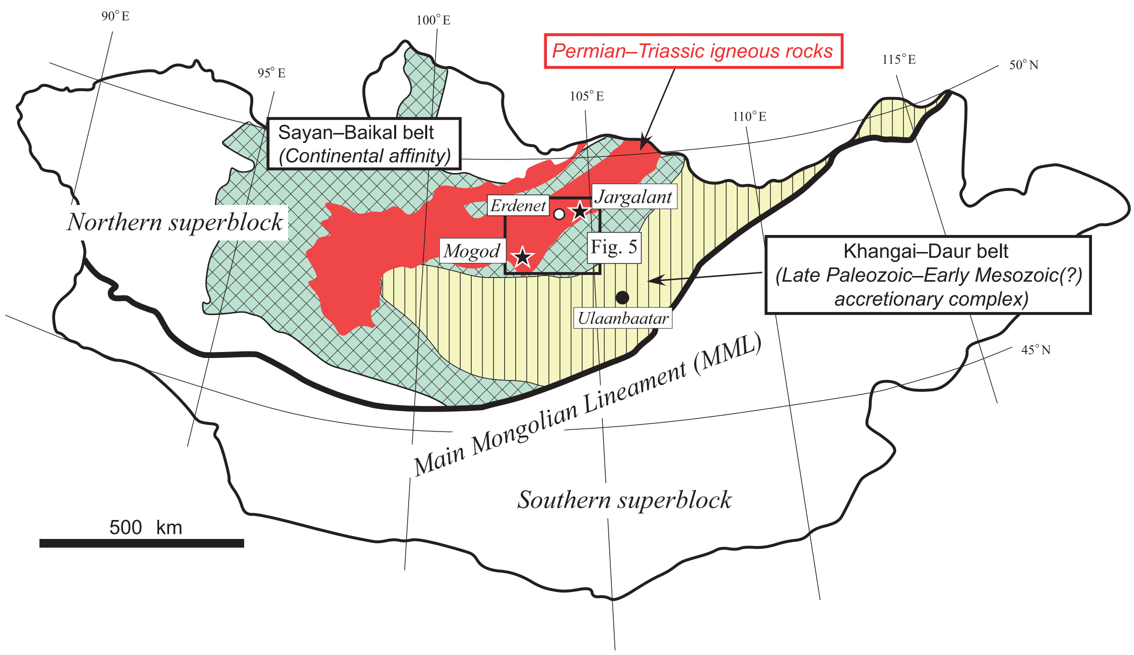

Fig. 2 Simplified tectonic division of northern Mongolia showing Jargalant and Mogod areas (modified from Badarch *et al.*, 2002; Tomurtogoo, 2003, and Tsukada *et al.*, 2018).

(e.g., Tomurtogoo, 2003; Gerel and Munkhtsengel, 2005; Munkhtsengel, 2007; Munkhtsengel *et al.*, 2007a: Figs. 3 and 4). The Khanui Group had been subdivided into four conformable successions in ascending order: mafic–intermediate volcanic rocks, felsic volcanic rocks, volcaniclastic rocks, and mafic volcanic rocks (e.g., Gabcho *et al.*, 1967; Tovuudorj *et al.*, 1971; Mossakovsky and Tomurtogoo, 1976; Gerel and Munkhtsengel, 2005: Fig. 3). A flora suggesting Cisuralian–Guadalupian was obtained from the felsic volcanic rock formation (e.g., Mossakovsky and Tomurtogoo, 1976: Figs. 3 and 4). The Mogod, Bugat, and Baruunburen formations are composed mainly of mafic–intermediate volcanic rocks (Kepezhinskas and Luchitsky, 1974: Figs. 3 and 4). The Bugat Formation produces 220–195 Ma of K-Ar ages. The Selenge and Erdenet complexes consist of granitic rocks accompanied by minor gabbro, diorite, and syenite–granosyenite, intruded by intermediate dikes (e.g., Gerel and Munkhtsengel, 2005; Munkhtsengel *et al.*, 2007a; Tsukada *et al.*, 2018). The Selenge plutonic rock complex gives ^{40}Ar-^{39}Ar ages of 247 to 258 Ma and SHRIMP ages of 243 to 250 Ma (e.g., Gerel and Munkhtsengel, 2005; Sotnikov *et al.*, 2005; Munkhtsengel, 2007; Munkhtsengel *et al.*, 2007b: Figs. 3 and 4). The Erdenet plutonic rock complex shows 253 ± 18 Ma Ma (Rb-Sr age), ca. 235 Ma (^{40}Ar-^{39}Ar age), 246 to 236 Ma (U-Pb age), and 224 to 191 Ma (K-Ar age) (Sotnikov *et al.*, 1995, 2005; Munkhtsengel, 2007; Munkhtsengel *et al.*, 2007b; Berzina *et al.*, 2009: Figs. 3 and 4).

Recently, Amgalan *et al.* (2017) classified the Khanui Group in ascending order as the Cisuralian Khustai (mafic to felsic volcanic rocks), Guadalupian Khargana (volcaniclastic rocks), and Guadalupian Tulbur (mafic volcanic

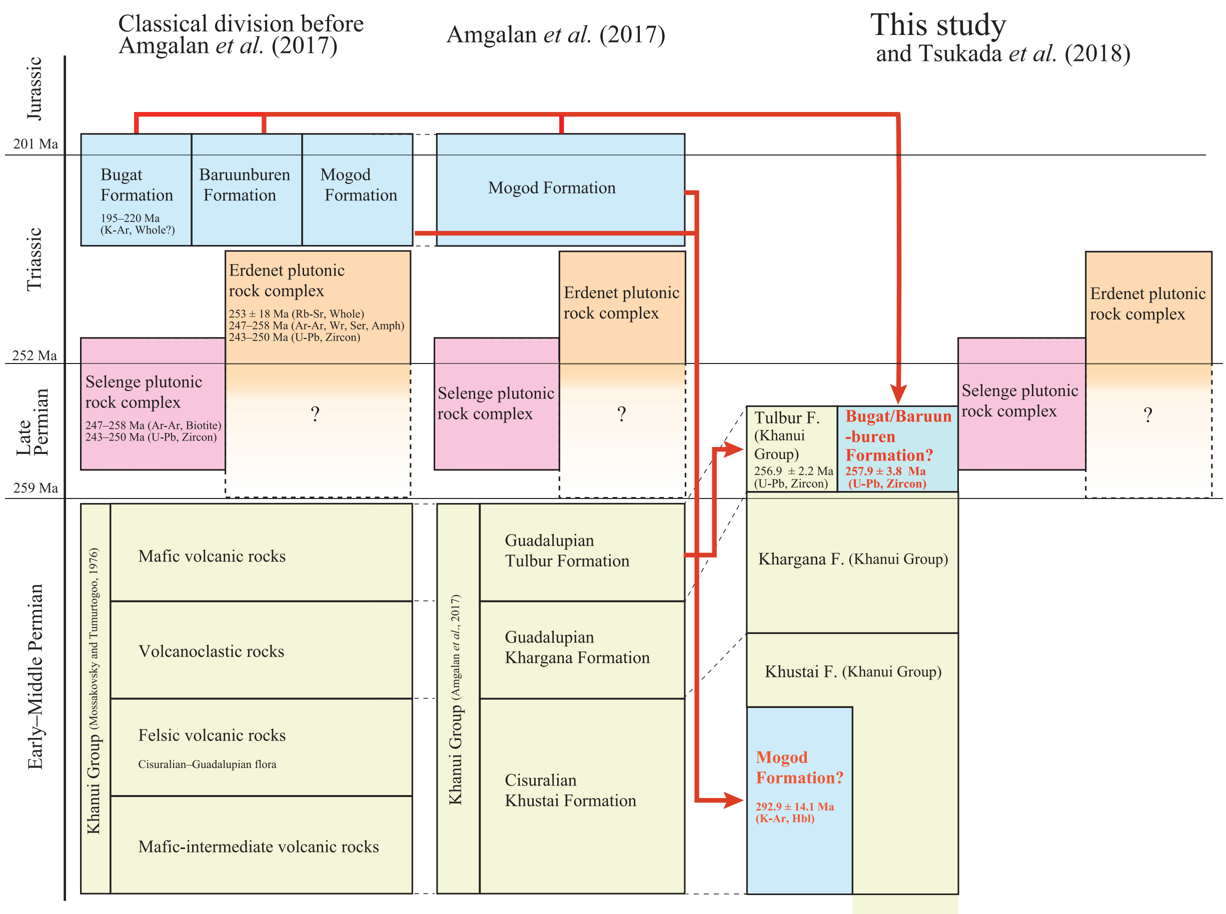

Fig. 3 Comparison of the stratigraphic divisions of the Permian–Triassic igneous rocks among previous studies and this study. Age data were from Kepezhinskas and Luchitsky (1974), Mossakovsky and Tomurtogoo (1976), Sotnikov *et al.* (1995, 2005), Izawa and Ohsawa (2004), Munkhtsengel (2007), Munkhtsengel *et al.* (2007b), Berzina *et al.* (2009), and Tsukada *et al.* (2018). Amph: amphibole, F.: Formation, Hbl: hornblende, Ser: sericite, Wr: whole rock.

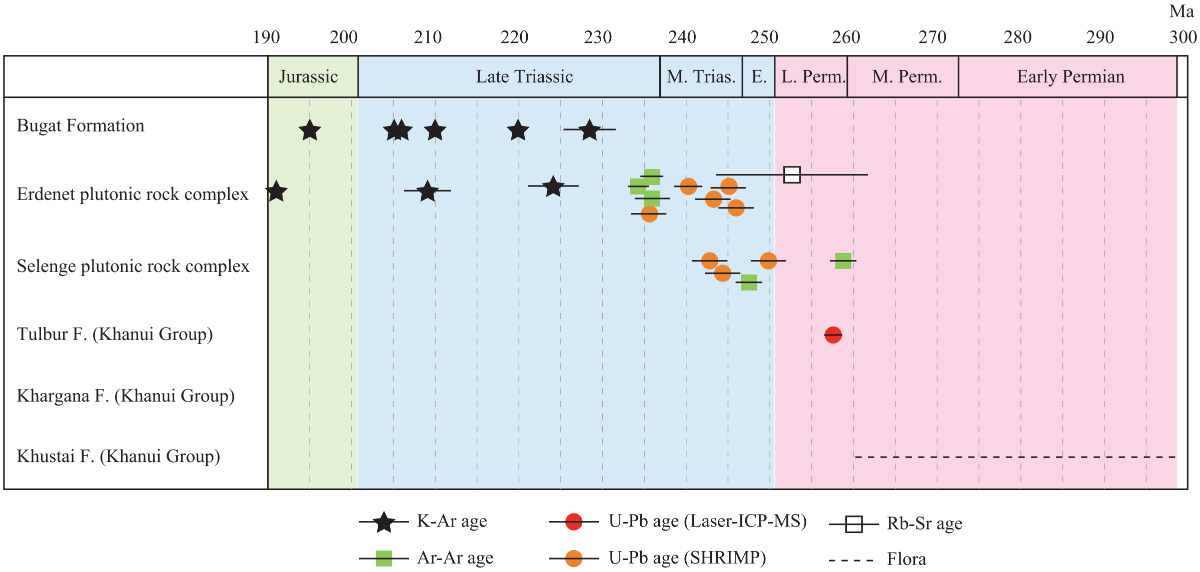

Fig. 4 Summary of the previously published absolute ages and fossil record from the Permian–Triassic igneous rocks. Data were from Kepezhinskas and Luchitsky (1974), Mossakovsky and Tomurtogoo (1976), Sotnikov *et al.* (1995, 2005), Izawa and Ohsawa (2004), Munkhtsengel (2007), Munkhtsengel *et al.* (2007b), Berzina *et al.* (2009), and Tsukada *et al.* (2018). F.: Formation.

rocks) formations. Besides, they unified the Mogod, Bugat, and Baruunburen formations as the Mogod Formation (Fig. 3). Tsukada *et al.* (2018) reported zircons dated as 256.9 ± 2.2 Ma from the Tulbur Formation. It shows that a part of the Khanui Group is contemporaneous to the Selenge plutonic rock complex, and the stratigraphy of the Permian–Triassic igneous rocks are required to be reexamined (Fig.3). This paper describes the zircon U-Pb age from the Baruunburen Formation at the Jargalant Village and the hornblende K-Ar age from the Mogod Formation at Mogod Village to reexamine the stratigraphy of the Permian–Triassic igneous rocks (Fig. 5).

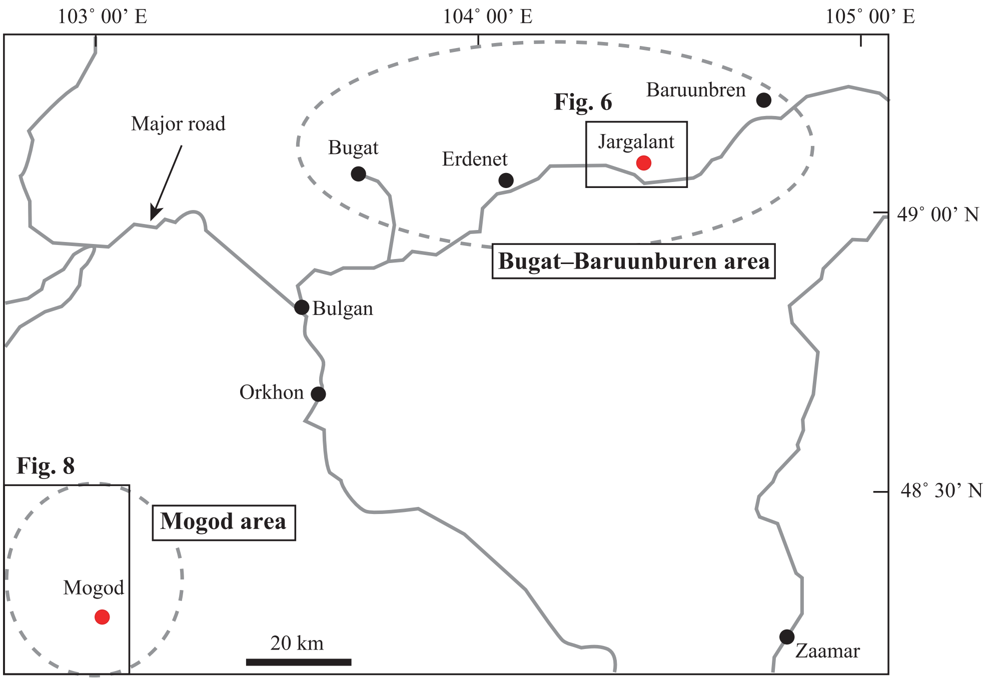

Fig. 5 Index map of the study areas. Localities of Figs. 6 and 8 are also shown.

Geological Description of the Study Areas

Lithology and structure at Jargalant Village

The Jargalant Village, located 20 km east of Erdenet City, Mongolia, exposes intermediate vesicular lava and tuff breccia of the Baruunburen formation (Amgalan *et al.*, 2017: Figs. 5 and 6). The lava has platy joints striking NW and dipping south by 20° to 40°. The vesicles are, places, filled with calcite or chlorite to form amygdule. The lava is fine to coarse and has porphyritic, aphyric, or trachytic textures, and in places, holocrystalline (Fig. 7a, b).

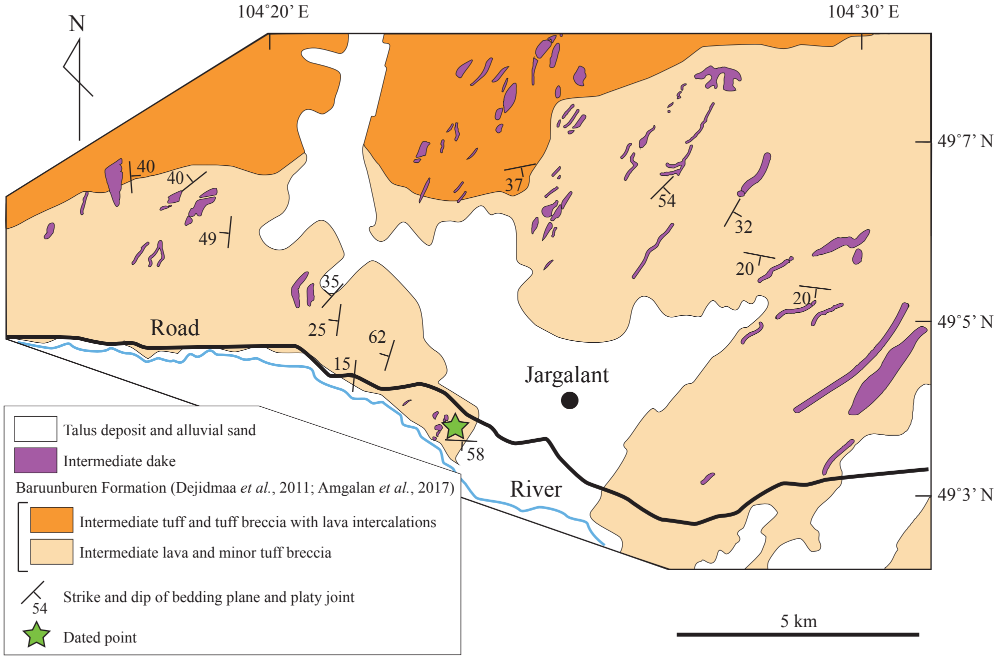

Fig. 6 Geologic map of the Jargalant area showing the dated point. Geologic division in the map follows Dejidmaa *et al.* (2011) and Amgalan *et al.* (2017).

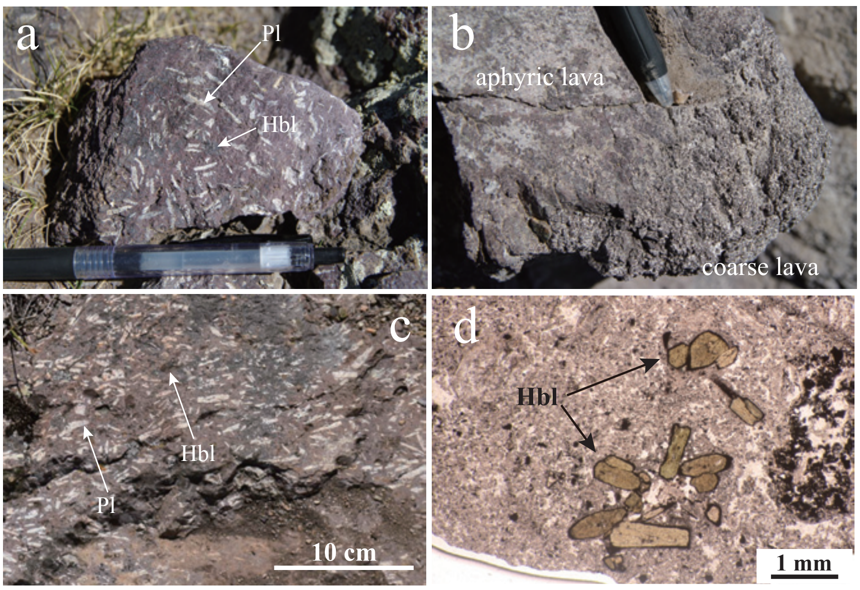

Fig. 7 (a) Intermediate lava showing trachytic texture with plagioclase and hornblende phenocrysts of the Baruunburen Formation at the Jargalant area. (b) Aphyric–coarse lava of the Baruunburen Formation at the Jargalant area. The boundary between the aphyric lava and the coarse lava is obscure. (c) Intermediate lava showing trachytic texture with plagioclase and hornblende phenocrysts of the Mogod Formation at the Mogod area. (d) A photomicrograph of the dated sample from the Mogod Formation. Pl: plagioclase, Hbl: hornblende.

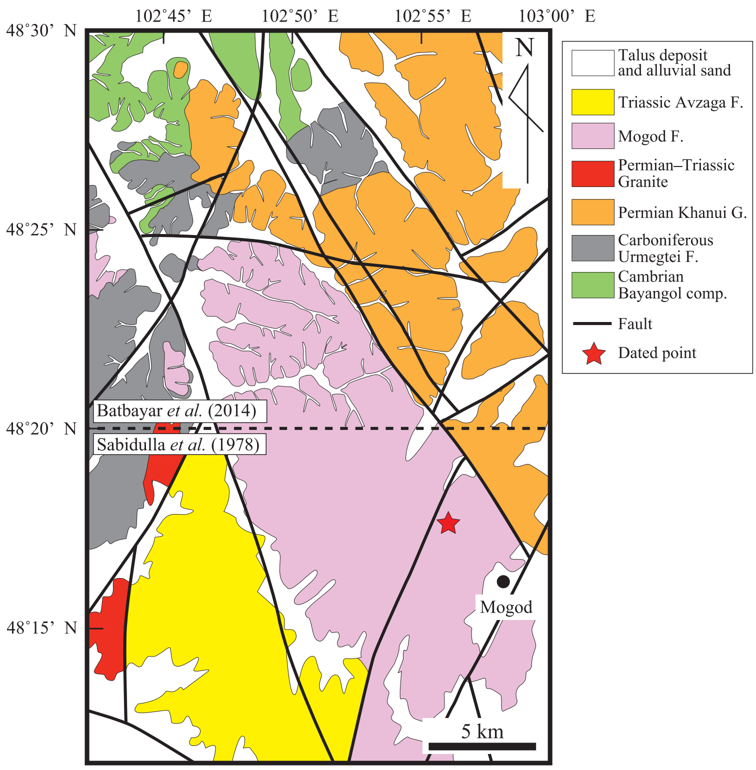

Fig. 8 Simplified geologic map of the Mogot area (Sabidulla *et al.*, 1978; Batbayar *et al.*, 2014) with dated point. F.: Formation, G.: Group.

The lava was partly altered so that some minerals could be replaced by chlorite, muscovite, and opaque minerals. In the lava with porphyritic texture, subhedral or euhedral plagioclase, clinopyroxene, and hornblende, more than 0.5 mm of the major axis lie in a groundmass. The coarse lava rarely includes subhedral/euhedral zircon. The tuff breccia shows clear bedding striking NW and dipping south by 5° to 30°.

Lithology and structure at Mogod Village

The Mogod Village, located 70 km southwest of Bulgan City, Mongolia, exposes intermediate volcanic rocks of the Khanui Group and the Mogod Formation (Sabidulla *et al.*, 1978; Batbayar *et al.*, 2014: Figs. 5 and 8). The Mogod Formation's volcanic rocks are composed of intermediate vesicular lava, tuff breccia, and conglomerate formed by a volcanic mudflow. The lava, fine- to coarse-grained, has porphyritic, aphyric, or trachytic textures with plagioclase and hornblende (Fig. 7c). The lava has platy and columnar joints and partly includes abundant fragments of intermediate lava. The vesicles of the lava, partly filled with calcite or chlorite, forms amygdule. The tuff breccia includes abundant angular clasts of intermediate volcanic rocks, up to 10 cm in diameter, in a cognate matrix. The tuff breccia has sub-horizontal bedding.

Absolute ages from the Baruunburen and Mogod Formations

Zircon U-Pb age of the Baruunburen Formation

U-Pb dating of zircons from the coarse lava of the Baruunburen Formation in the Jargalant area (49° 3' 39" N, 104° 23' 7" E) was conducted to clarify the age of the volcanism (Figs. 5 and 6). The zircons, colorless with about 200 μm in the major axis, generally show clear oscillatory zoning in the cathode luminescence image (Fig. 9a).

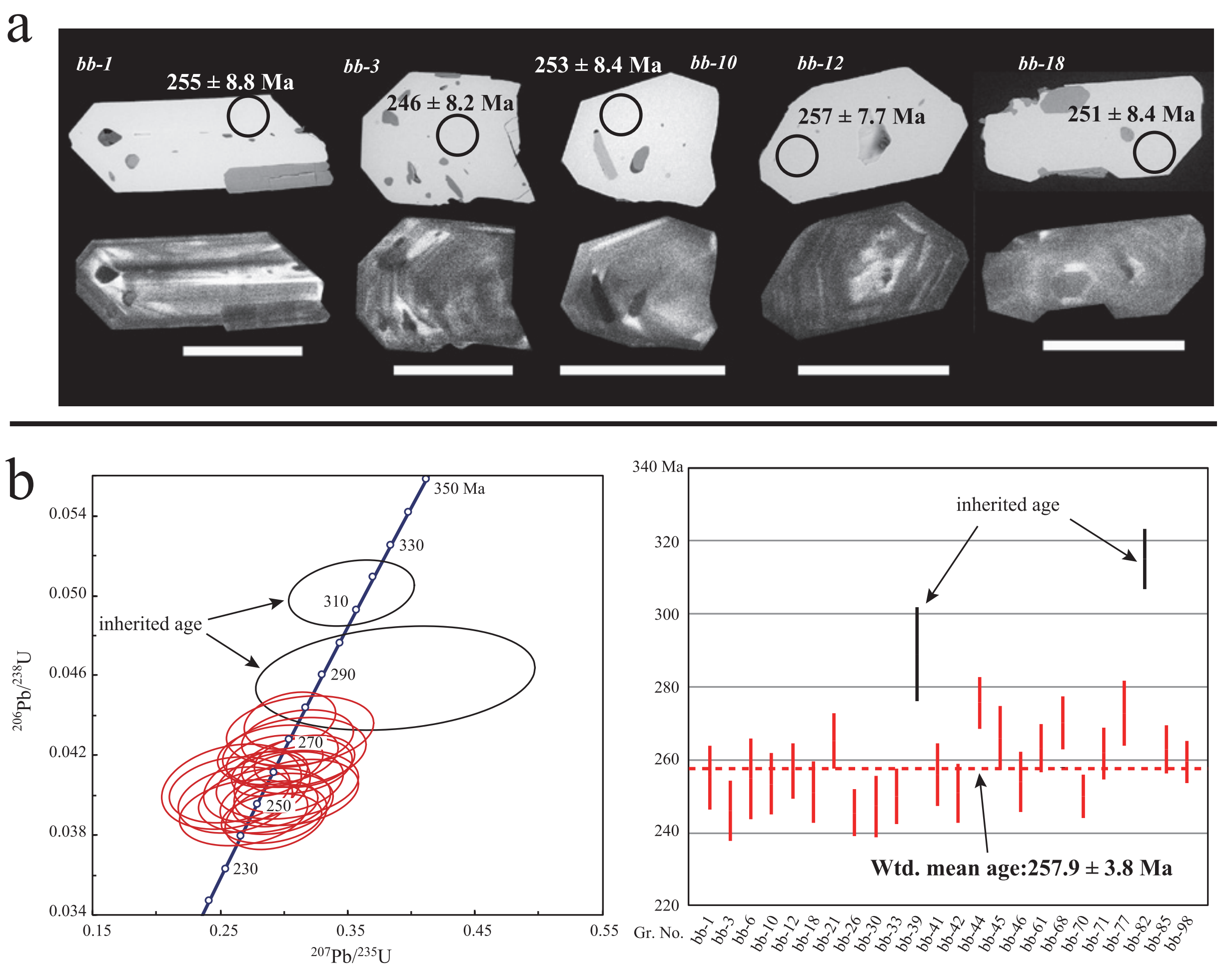

Fig. 9 (a) Backscattered electron (upper) and cathode luminescence (lower) images of selected zircons. The circles show dated spots. Scale bars denote 100 μm. (b) Concordia plots (left), and individual zircon concordia ages (right). The weighted mean age of 24 concordant data is 257.6 ± 3.6 Ma. Gr. No.: grain number, Wtd. mean: weighted mean.

The analysis was performed using Inductively Coupled Plasma Mass Spectrometry (Quadrupole type ICP-MS; Agilent 7700x) connected with the NWR-213 LA system (Electro Scientific Industries, Inc.) at Nagoya University in Japan, with a conventional procedure. Details of the analytical procedure are described in Kouchi *et al.* (2015). The data obtained from 24 grains were plotted on a concordia diagram using Isoplot 3.70 software (Ludwig, 2008). The ages, except for two data sets (315.3 ± 8.6 Ma and 289.1 ± 13.4 Ma), which are likely to be inherited ages, cluster at ca. 276–246 Ma (257.9 ± 3.8 Ma in weighted mean age) (Fig. 9b, Table 1).

Hornblende K-Ar age of the Mogod Formation

K-Ar dating of hornblende extracted from a lava sample of the Mogod Formation in the Mogod area (48° 17' 42" N, 102° 56' 5" E) was conducted (Sabidulla *et al.*, 1978: Figs. 5 and 8). The sample contains plagioclase and hornblende with a trachytic texture. The secondary minerals are chlorite, epidote, and opaque minerals. Hornblende is generally fresh (Fig. 6d). The sample was coarse crushed using a stainless steel bowl and pounder. Hornblende was then concentrated using heavy liquid (sodium polytungustate solution) and Ferrite and Neodymium magnets.

Dating was performed by the Hiruzen Institute for Geology and Chronology, Japan. Quantitative analysis for potassium was conducted using the ultra-low blank method (Itaya *et al.*, 1996). About 50 mg of hornblende,

Table 1 Results of Laser-ICP-MS analysis.

Grain No.	$^{232}Th/^{238}U$	$^{206}Pb_C$ (%)	Isotope ratios						Concordia ages (Ma)			
			$^{207}Pb/^{206}Pb$	Error	$^{207}Pb/^{235}U$	Error	$^{206}Pb/^{238}U$	Error	Conc. age	error	MSWD	Probability
bb-1	0.40	0.98	0.050	0.0059	0.28	0.034	0.040	0.0014	255	8.8	0.20	0.65
bb-3	0.51	0.90	0.055	0.0058	0.29	0.033	0.039	0.0013	246	8.2	1.6	0.21
bb-6	0.40	0	0.046	0.0078	0.26	0.045	0.040	0.0017	255	11	1.5	0.21
bb-10	0.57	0	0.056	0.0070	0.31	0.040	0.040	0.0014	254	8.4	1.8	0.18
bb-12	0.46	0	0.054	0.0060	0.30	0.035	0.041	0.0012	257	7.7	0.85	0.36
bb-18	0.38	1.5	0.048	0.0065	0.26	0.037	0.040	0.0014	251	8.4	1.2	0.27
bb-21	0.44	0	0.051	0.0065	0.30	0.039	0.042	0.0012	265	7.6	0.031	0.86
bb-26	0.54	0	0.054	0.0058	0.29	0.032	0.039	0.0010	246	6.3	1.2	0.28
bb-30	0.56	1.1	0.050	0.0074	0.27	0.041	0.039	0.0014	247	8.5	0.13	0.72
bb-33	0.47	0	0.054	0.0064	0.29	0.036	0.040	0.0012	250	7.6	0.72	0.40
bb-39	0.44	0	0.061	0.014	0.39	0.089	0.046	0.0021	289	13	1.8	0.18
bb-41	0.45	0	0.054	0.0079	0.30	0.045	0.041	0.0014	256	8.6	0.52	0.47
bb-42	0.61	0	0.052	0.0075	0.29	0.042	0.040	0.0013	251	8.2	0.050	0.82
bb-44	0.60	0	0.050	0.0047	0.30	0.029	0.044	0.0012	276	7.1	0.32	0.57
bb-45	0.53	0	0.053	0.0077	0.31	0.046	0.042	0.0014	266	8.8	0.15	0.70
bb-46	0.47	0	0.046	0.0068	0.26	0.039	0.040	0.0013	254	8.3	2.1	0.15
bb-61	0.53	1.7	0.055	0.0054	0.32	0.032	0.042	0.0011	263	6.6	1.6	0.20
bb-68	0.51	0.78	0.053	0.0058	0.31	0.036	0.043	0.0012	270	7.3	0.11	0.74
bb-70	0.80	1.6	0.054	0.0049	0.29	0.027	0.040	0.0010	250	5.9	1.1	0.30
bb-71	0.49	0.73	0.054	0.0060	0.31	0.035	0.041	0.0012	262	7.1	0.84	0.36
bb-77	0.45	0	0.052	0.0077	0.31	0.047	0.043	0.0014	273	8.9	0.035	0.85
bb-82	0.53	1.5	0.051	0.0057	0.35	0.040	0.050	0.0014	315	8.3	0.33	0.56
bb-85	0.53	0	0.051	0.0053	0.29	0.031	0.042	0.0011	263	6.6	0.039	0.84
bb-98	0.72	0	0.051	0.0042	0.29	0.025	0.041	0.00094	260	5.8	0.039	0.84

$^{206}Pb_C$: common lead, Conc. age: concordia age, MSWD: mean square weighted deviation. The data are displayed to 2 significant digits.

powdered in an agate mortar, was placed in a Teflon container and decomposed with nitric acid, hydrofluoric acid, and hydrogen peroxide in a closed system box for more than 12 hours. After decomposition, the sample solution was evaporated to dryness in a closed system, and then the fused cake was re-dissolved with hydrochloric acid for analysis. The analysis was performed using atomic absorption and flame spectrometer (Hitachi 180-30).

Argon isotope ratio was measured using a mass spectrometer (HIRU, Itaya *et al.*, 1991) with isotope dilution method (Nagao *et al.*, 1984; Nagao and Itaya, 1988; Itaya *et al.*, 1991). About 50 mg of sample was used for the analysis. The sample was evacuated at about 180 to 200°C for three days to remove the adsorbed argon. After reducing the background in the analytical system, the sample was dissolved at about 1500°C. The gas extracted from the sample was mixed with the spike (nearly 100% pure ^{38}Ar). The gas other than inert gas was removed using a Ti-Zr getter, and the purified gas was introduced into the mass spectrometer.

The results of the analysis showed that potassium concentration is 0.0931 ± 0.0047 wt%, and radioactive ^{40}Ar is 114.9 ± 1.8 (10^{-8}cc (STP)/g); then K-Ar age is calculated as 292.9 ± 14.1 Ma (Table 2). Analytical error under the same condition is less than 1% (Itaya *et al.*, 1991; Yagi *et al.*, 2015).

Table 2 Results of K-Ar dating.

Sample No.	Sample	K concentration (wt%)	Radioactive ^{40}Ar (10^{-8}cc STP/g)	K-Ar age (Ma)	Stable ^{40}Ar (%)
19062311	Hornblende	0.0931 ± 0.0047	114.9 ± 1.8	292.9 ± 14.1	20.7

STP: standard temperature and pressure.

Stratigraphy of the volcanic rocks of the Permian–Triassic igneous rocks

Mossakovsky and Tumurtogoo (1976) described the upper volcanic rocks than the Khanui Group at the Bugat – Baruunburen area as Triassic–Jurassic formation based on K-Ar ages of 220 to 195 Ma (Kepezhinskas and Luchitsky, 1974). Dejidmaa *et al.* (2011) divided the Triassic–Jurassic volcanic rocks into the Mogod Formation exposed at the Mogod area, and Bugat and Baruunburen formations at Bugat–Baruunburen area (Fig. 5). Amgalan *et al.* (2017) unified these formations as Mogod Formation on the grounds that there is no difference in lithology and age among them. The lithology of these formations is remarkably similar to each other (Fig. 7a, c). However, the Mogod Formation and the Bugat and Baruunburen formations are exposed in different areas, and the stratigraphic correlation between these areas' rocks is unclear (e.g., Batbayar *et al.,* 2014; Amgalan *et al.*, 2017: Fig. 5). Therefore, the intermediate volcanic rocks previously regarded as "Upper Triassic–Lower Jurassic" exposed in the Mogod area are called Mogod Formation, and that in the Bugat–Baruunburen area is referred to as Bugat/Baruunburen Formation, in this paper (Fig. 3).

The Bugat/Baruunburen Formation has previously been assigned to Upper Triassic–Lower Jurassic based on the K-Ar ages (220–195 Ma) (Kepezhinskas and Luchitsky, 1974). The Bugat/Baruunburen Formation rocks, close to the Erdenet Mine, are partly metasomatized and K-Ar age, which is easily modified by alteration, is not the proper approach for magmatic age constraint. It is generally accepted that zircon is comparatively less affected by weathering and hydrothermal alteration. And, clear oscillatory zoning in the cathode luminescence image evidences less alteration for the dated zircons. We could conclude that the zircon U-Pb age, 257.9 ± 3.8 Ma, from the intermediate lava of the Bugat/Baruunburen Formation points to its magmatic age. Therefore, the Bugat/Baruunburen Formation in the Jargalant area is not Triassic–Jurassic; however, the Upper Permian volcanic rock formation (Fig. 3). The Selenge plutonic rock complex producing 258 to 243 Ma is partly contemporaneous to the Tulbur and Bugat/Baruunburen formations (e.g., Gerel and Munkhtsengel, 2005; Sotnikov *et al.*, 2005; Munkhtsengel, 2007; Munkhtsengel *et al.*, 2007b; Tsukada *et al.*, 2018: Fig. 3). The geochemical similarity among the rocks of the Selenge plutonic rock complex, Tulbur Formation of the Khanui Group, and the Bugat/Baruunburen Formation was identified, and these were likely attributed to single magmatism at the end of Permian (e.g., Berzina *et al.*, 2009; Tsukada *et al.*, 2018; Umeda, 2018 MS).

A hornblende K-Ar age of 292.9 ± 14.1 Ma (Early Permian) was obtained from the intermediate lava assigned to the Mogod Formation in the geologic map by Sabidulla *et al.* (1978) (Fig. 8). Argon in a rock can be outgassed when it undergoes alteration. Thus, it is generally said that K-Ar dating of an altered rock could give a younger age than its formation (e.g., Kaneoka, 1998; Vural, 2017). The dated hornblende is fresh and hardly altered (Fig. 6d). Therefore, the K-Ar dating here is supposed to show the original (magmatic) age. Although, the Mogod Formation in the Mogod area has been regarded as equivalent to Bugat/Baruunburen Formation as an upper geologic unit of the Permian–Triassic igneous rocks, the present data, if the geologic map by Sabidulla *et al.* (1978) is correct, indicate the lowermost geologic unit for it (Fig. 3). The accurate stratigraphic position of the Mogod and Bugad/Baruunblen formations remains to be confirmed when more age data from these formations become available. Besides, age-constraint of the lower part of the Khanui Group, Khustai and Khargana formations, will give a clearer view of the stratigraphy and magmatic history of the Permian–Triassic igneous rocks.

Conclusion

1. The intermediate lava of the Bugat/Baruunburen Formation from the Jargalant area (Amgalan *et al.*, 2017) gives zircon U-Pb age of 257.9 ± 3.8 Ma.

2. The intermediate lava of the Mogod Formation from the Mogod area (Sabidulla *et al.*, 1978) gives hornblende K-Ar age of 292.9 ± 14.1 Ma.
3. If previously published geologic map is correct, the volcanic rocks of the Permian–Triassic igneous rocks can be divided into the Lower Permian Mogod Formation, the Lower –Upper Permian Khanui Group, and the Upper Permian Bugat/Baruunburen Formation.

Acknowledgements

We would like to gratitude to Dr. K. Yagi at the Hiruzen Institute for Geology and Chronology for his helpful advice. We thank Dr. O. Munkhtsetseg at Mongolian University of Science and Technology for useful discussion. We would like to thank Profs. M. Takeuchi and H. Yoshida at Nagoya University for valuable comments. We are grateful to Prof. K. Yamamoto of the Nagoya University and S. Davaanyam at Institute of Geology, Mongolian Academy of Science for their technical support. Special thank goes to Dr. Munkhtsengel, B. at Mongolian University of Science and Technology for her reviewing this paper. We would like to thank Enago (www.enago.jp) for the English language review. A part of this study was supported by the Daiko Foundation, Japan.

References

Amgalan, Ch., Munkhnasan, Ch., Adiyaragchaa, L., Davaasuren, J., Lkhagvajav, M., Mungunshagai, S., Munkhsukh, B., Badral, A., and Otgonbaatar, B. (2017) *Report on Results of General Prospecting and Geological Mapping Works with the Scale of 1:50,000 Conducted in "Ulaan Tolgoi-50" Project Area, Covering Bayan-Undur and Jargalant Soums of Orkhon Aimag; and Bugat, Selenge and Khangal Soums of Bulgan Aimag in 2014–2017. Code: UT-50. Location: M-48-100-A, B, V, G, M-48-101-A, B, V, G., Report No. 8460*. Mineral Resource Authority of Mongolia, Ulaanbaatar, 577p.

Badarch, G., Cuninham, W. D., and Windley, B. F. (2002) A new terrane subdivision for Mongolia: Implications for the Phanerozoic crustal growth of central Asia. *Journal of Asian Earth Sciences*, **21**, 87–110.

Batbayar, N., Tumursukh, N., Bayar, B., Byambazaya, T., and Batrom, B. B. (2014) *Report on Results of General Prospecting and Geological Mapping Works with the Scale of 1:50,000 Conducted in Serven Uul Field, Covering Saikhan and Mogod Soums of Bulgan Aimag and Khairkhan Soum of Arkhangai Aimag in 2012–2014. (M-48-121-A, B, V, G, M-48-122-A, B, V, G). Report No. 7645*. Mineral Resource Authority of Mongolia, Ulaanbaatar, 192p.

Berzina, A. P., Gimon, V. O., Nikolaeva, I. V., Palesskii, S. V., and Travin, A. V. (2009) Basites of the polychronous magmatic center with the Erdenetiin Ovoo porphyry Cu-Mo deposit (northern Mongolia): petrogeochemistry, $^{40}Ar/^{39}Ar$ geochronology, geodynamic position, and related ore formation. *Russian Geology and Geophysics*, **50**, 827–841.

Dejidmaa, G., Oyuntuya, N., Tuya, Sh., Soyolmaa, G., Otgonbaatar, B., *et al.* (2011) *State Geological Mapping -200" Project of the Central Mongolia. Brief Report on Results of "Project To Compile State Geological Mapping at Scale 1:200000 on the Sheet of Nomenclature M-48-XXV, M-48-XXVI, M-48-XXVII, L-48-VII, L-48-VIII, L-48-XIII, L-48-XIV, L-48-XV and L-48-XVI conducted in Bulgan, Tuv, Orkhon-Uul, Selenge, Uvurkhangai and Arkhangai Aimags. Report No. 6320*. Mineral Resource Authority of Mongolia, Ulaanbaatar. 14908p.

Gabcho, B., Klinets, A., and Petran, M. (1967) *Report on Geological Mapping at Scale 1:200000 on the Middle Part of Selenge River Area in the Selenge Aimag. Report No. 1811*. Mineral Resource Authority of Mongolia, Ulaanbaatar.

Gerel, O. and Munkhtsengel, B. (2005) Erdenetiin Ovoo porphyry copper-molybdenum deposit in central Mongolia. Porter, T.M. (ed.), *Super Porphyry Copper & Gold Deposits –A Global Perspective v. 2*, 525–543, PGC Publishing, Adelaide.

Itaya, T., Doi, M., and Ohira, T. (1996) Very low potassium analysis by flame photometry using ultra low blank chemical lines: an application of K-Ar method to ophiolites. *Geochemical Journal*, **30**, 31–39.

Itaya, T., Nagao, K., Inoue, K., Honjou, Y., Okada, T., and Ogata, A. (1991) Argon isotope analysis by a newly developed mass spectrometric system for K-Ar dating. *Mineralogical Journal*, **15**, 203-221.

Izawa, T. and Ohsawa, H. (2004) *Basic Research Report on the Cooperation for the Development of Resources Exploration in the Western Erdenet Area, Mongolia*. Japan International Cooperation Agency and Japan Oil, Gas and Metals National Corporation, Tokyo, 213p.

Kaneoka, I. (1998) *Numerical Dating*. University of Tokyo Press, Tokyo, 315p.

Kepezhinskas, B. B. and Luchitsky, I. B. (1974) *Continental Volcanic Associations of Central Mongolia*. Nauka, Moscow, 69p.

Kouchi, Y., Orihashi, Y., Fujimoto, T., Haruta, Y., and Yamamoto, K. (2015) Zircon U–Pb dating by 213 nm Nd: YAG laser ablation inductively coupled plasma mass spectrometry: optimization of the analytical condition to use NIST SRM 610 for Pb/U fractionation correction. *Chikyukagaku (Geochemistry)*, **49**, 1–17.

Kovalenko, V. I., Yarmolyuk, V. V., Kovach, V. P., Kotov, A. B., Kozakov, I. K., Salnikova, E. B., and Larin, A. M. (2004) Isotope provinces, mechanisms of generation and sources of the continental crust in the Central Asian mobile belt: geological and isotopic evidence. *Journal of Asian Earth Science*, **23**, 605–627.

Kurihara, T., Tsukada, K., Otoh, S., Kashiwagi, K., Minjin, C., Dorjsuren, B., Boijir, B., Sersmaa, G., Manchuk, N., Niwa, M., Tokiwa, T., Hikichi, G., and Kozuka, T. (2008) Upper Silurian and Devonian pelagic deep-water radiolarian chert from the Khangai–Daur belt of Central Mongolia: Evidence for Middle Paleozoic subduction-accretion activity in the Central Asian Orogenic Belt. *Journal of Asian Earth Sciences*, **34**, 209–225.

Ludwig, K. R. (2008) *Isoplot 3.70: Geochronological Toolkit for Microsoft Excel*. Berkeley Geochronology Center, USA.

Mossakovsky, A. A. and Tomurtogoo, O. (1976) *Upper Paleozoic of Mongolia*. Nauka, Moscow, 125p.

Munkhtsengel, B. (2007) *Magmatic and Mineralization Processes of the Erdenetiin Ovoo Porphyry Copper-molybdenum Deposit and Environmental Assessment, Northern Mongolia*. PhD Thesis, Graduate School of Engineering, Tohoku University, Sendai, Japan.

Munkhtsengel, B., Gerel, O., Tsuchiya, N., and Ohara, M. (2007a) Petrochemistry of igneous rocks in area of the Erdenetiin Ovoo porphyry Cu-Mo mineralized district, northern Mongolia. In Tohji, K., Tsuchiya, N., and Jeyadevan, B. (eds.), *Water Dynamics: 4th International Workshop on Water Dynamics*, 63–65, American Institute of Physics, New York.

Munkhtsengel, B., Tsuchiya, N., Dan, D., and Gerel, O. (2007b) SHRIMP U-Pb zircon age of the intrusive and host rocks in Erdenet district, and their relationship between ore mineralization age of Erdenetiin Ovoo deposit. *Mongolian Geoscientist*, **34**, 120–125.

Nagao, K. and Itaya, T. (1988) K-Ar age determination. *Memoir of Geological Society of Japan*, **29**, 5–21.

Nagao, K., Nishido, H., Itaya, T., and Ogata, K. (1984) An age determination by K-Ar method. *Bulletin of the Research Institute of Technology, Okayama University of Science*, **9**, 19–38.

Onon, G. and Tsukada, K. (2017) Late Paleozoic low-angle southward-dipping thrust in the Züünharaa area, Mongolia: tectonic implications for the geological structures in the Sayan–Baikal and Hangai–Daur belts. *International Journal of Earth Science*, **106**, 2549–2573.

Sabidulla, B., Jamsranjav, Ts., Togookhuu, D., Tudev, S., and Chultemjamts, T. (1978) *Report on Geological Mapping at Scale 1:200000 on the Middle Part of Orkhon River Basin. Report No. 2765*. Mineral Resource Authority of Mongolia, Ulaanbaatar. 23p.

Sengör, A. M. C., Natal'In, B. A., and Burtman, V. S. (1993) Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia. *Nature*, **364**, 299–307.

Sotnikov, V. I., Ponomarchuk, V. A., Berzina, A. P., and Travin, A. V. (1995) Geochronological borders of magmatism of Cu-Mo-porphyry Erdenetuin-Obo deposit. *Russian Geology and Geophysics*, **36**, 78–89.

Sotnikov, V. I., Ponomarchuk, V. A., Shevchenko, D. O., and Berzina, A. P. (2005) The Erdenetiyn-ovoo porphyry Cu-Mo deposit, northern Mongolia: $^{40}Ar/^{39}Ar$ geochronology and factors of large-scale mineralization. *Russian Geology and Geophysics*, **46**, 620–631.

Tomurtogoo, O. (1998) *Geological Map of Mongolia at the Scale of 1:1 000000*. Mineral Resources Authority of Mongolia and Mongolian Academy of Science, Ulaanbaatar.

Tomurtogoo, O. (2003) *Tectonic Map of Mongolia at the Scale of 1:1000000 and Tectonics of Mongolia (Brief Explanatory*

Notes of the Map). Mineral Resources Authority of Mongolia, Ulaanbaatar.

Tomurtogoo, O. (2014) Tectonics of Mongolia. Petrov, O. V., Leonov, Y. G., and Pospelov, I. I. (eds.), *Tectonics of Northern, Central and Eastern Asia. Explanatory Note to the Tectonic Map of Northern– Central–Eastern Asia and Adjacent Areas at Scale 1:2500000*. SPb. 110–126, VSEGEI Printing House, St. Petersburg.

Tovuudorj, D., Ponomarev, B., and Baljinnyam, D. (1971) *Report on Geological Mapping at Scale 1:200000 on Orkhon-Selenge Basin Area. Report No. 2035*. Mineral Resource Authority of Mongolia, Ulaanbaatar.

Tsukada, K., Nuramkhaan, M., Purevsuren, N., Kabashima, T., Kondo, T., Gantumur, O., Hasegawa, H., and Yamamoto, K. (2018) Permian adakitic magmatism in the Khanui Group, Northern Mongolia –Late Paleozoic slab-melting of subducted oceanic plate beneath the "Siberian continent." *Journal of Geodynamics*, **121**, 49–63.

Umeda, K. (2018 MS) *Geochemistry of the Andesitic Rocks at the Ulaan Tolgoi Area in Jargalant, Eastern Erdenet, Mongolia*. Bachelor Thesis, School of Science, Nagoya University, Nagoya, Japan.

Vural, A. (2017) K-Ar dating for determining the age of mineralization as alteration product: a case study of antimony mineralization vein type in granitic rocks of Gümüshane area, Turkey. *Acta Physica Polonica A*, **132**, 792–795.

Yagi, K., Okada, T., Honjou, Y., and Itaya, T. (2015) Argon analyses by isotopic dilution method using argon 38 spike with HIRU –Reproducibility and reliability in 25 years K-Ar dating–. *Bulletin of the Research Institute of Technology, Okayama University of Science*, **33**, 42–52.