Geochronology and tectonic implications of the Urgamal eclogite, Western Mongolia

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The Urgamal eclogite in western Mongolia, described here for the first time, occurs in the Altai allochthon (also known as the Urgamal subzone) in the Zavkhan terrane of the Central Asian Orogenic belt. The eclogite consists of garnet, omphacite, white mica, quartz, epidote, rutile, and barroisite. We measured zircon U–Th–Pb ages in a barroisite–rich sample of the eclogite using an electron probe microanalyzer, which yielded an age of 1113 +31/−52 Ma. This suggests that the eclogite protolith is slightly older than the recorded metamorphic and igneous activity in the Zavkhan autochthon (880–780 Ma). To constrain the timing of eclogite facies metamorphism, K–Ar geochronology was applied to white mica separates, yielding an age of 395 ± 7.9 Ma. This Devonian age is much younger than the time at which the Lake terrane and the Zavkhan terrane collided (545–525 Ma). After the collisional event, the Zavkhan terrane was subjected to extensional tectonics, resulting in alkaline volcanism until the beginning of the Silurian (440 Ma). The Urgamal eclogite records a subduction or collision event at 440–395 Ma, which has not been recognized before. This convergent tectonic environment may have been the result of collision between the Zavkhan terrane and the eastern Tarvagatai terrane. During collision, part of the Altai allochthon may have been subducted beneath the Zavkhan autochthon, thereby forming the Urgamal eclogite.

Keywords: Eclogite, Central Asian Orogenic Belt, Zavkhan terrane, K–Ar geochronology, U–Th–total Pb zircon geochronology

INTRODUCTION

The Central Asian Orogenic Belt (CAOB), which is one of Earth’s largest ancient mountain belts, formed adjacent to the Siberian craton between 1250 and 220 Ma (Fig. 1a) (Xiao et al., 2015). The CAOB is composed mainly of Precambrian cratons, island arcs, accretionary complexes, and ophiolites (Xiao et al., 2015). Tectonic activity in the CAOB started with the opening of the Paleo-Asian Ocean, when oceanic arcs formed in response to plate subduction (Xiao et al., 2015). During this time, the CAOB produced immense amounts of juvenile crust (Jahn, 2004) that today makes up ~20 vol% of the Eurasian continent (Schulmann and Paterson, 2011). As the Paleo-Asian Ocean closed, numerous arcs were amalgamated to form the CAOB during the latest Permian (Xiao et al., 2003) or Jurassic (Van der Voo et al., 2015) (Fig. 1b).

Mongolia is located in the CAOB, and its oldest tectonic unit consists of Proterozoic cratonic terranes that are surrounded by Paleozoic arcs and accretionary zones (Xiao et al., 2015). In southwestern Mongolia, Proterozoic crust occurs within the Tuva-Mongolia, Zavkhan, Baidrag, and Tarvagatai terranes (Fig. 1a). These terranes were amalgamated with the Lake terrane during the early Paleozoic, with the Gobi-Altaï terrane and Trans-Altaï terranes during the Ordovician-Carboniferous, and finally with the South Gobi terrane during the Permian (Gibson et al., 2013; Xiao et al., 2015). The autochthon and allochthon units in the Zavkhan terrane are separated by a
key geological boundary, yet the structure and geological history of these units are poorly constrained (Fig. 1a) (e.g., Bold et al., 2016). The autochthonous part of the Zavkhan terrane (hereafter referred to as the Zavkhan autochthon) is located in the northeast. The allochthonous part occupies the southwest part of the Zavkhan terrane, and it borders the Lake terrane to the west. The allochthonous part is also referred to as the ‘Urgamal subzone’ by Badarch et al. (2002) and the ‘Altai allochthon’ by Bold et al. (2016). In this study, ‘Altai allochthon’ is used hereafter. It is not clear whether the Zavkhan autochthon and Altai allochthon share the same Proterozoic basement (Bold et al., 2016). These two units are separated by a large Cambrian fault, which named as ‘Fault–1’ by Bold et al. (2016) where they have suggested the reactivation of the fault after Middle Devonian. We have revised position of ‘Fault–1’ in the middle latitude part (~ N48°) to fit the terrane subdivision by Kozakov et al. (2017).

In the middle latitude part of the Zavkhan terrane (Fig. 1b), previous studies on U–Pb zircon geochronology has suggested that the regional metamorphism and folding ended at 786 ± 6 Ma (Kozakov et al., 2014, 2017). However, we discovered an eclogite in the Altai allochthon that may indicate a different timing of events. This paper aims to constrain the timing of high-P metamorphism of the Urgamal eclogite, to identify a previously unknown subduction event recorded by the Zavkhan terrane and its bearing on tectonic evolution of CAOB.

**TECTONIC SETTING**

The Lake terrane, which has previously been described as an island arc, consists of ophiolite and a volcanic arc complex that formed during the early Paleozoic (Xiao et al., 2015). The oldest event recorded by the Lake terrane is the emplacement of plagiogranites in the Dariv–Khantaishir ophiolite (568 ± 4 Ma, Gibsher et al., 2001; 573 ± 6 Ma, Kozakov et al., 2012). At the SE margin of the Lake terrane, the Chandmani (Ch.) eclogite is closely related to the Erdene–Uul ophiolite (Fig. 1a; Burianek et al., 2017). The Ch. eclogite experienced major prograde metamorphism from blueschist to amphibole eclogite facies (22–24 kbar at 520–570 °C) at ~ 600 Ma, followed by a medium–P/T overprint (10 kbar at ~ 600 °C) during the collision between the Baidrag and Lake terranes at ~ 540 Ma (Štípská et al., 2010; Javkhlan et al., 2014, 2019). Granitoid magmatism in the Lake terrane started at ~ 530 Ma (Rudnev et al., 2009).

The Zavkhan terrane has been described as a cratonic terrane (e.g., Badarch et al., 2002) and a microcontinent (e.g., Lehmann et al., 2010; Bold et al., 2016) that formed mostly at the margin of the Rodinia supercontinent. The basement of the Zavkhan terrane consists of migmatic orthogneiss. The Khavchig complex in the Altai allochthon yields a U–Pb zircon age of 840 ± 9 Ma for zircon rims that formed during anatexis (Zhao et al., 2006) and 1967 ± 13 Ma for the cores of migmatic zircons (Bold et al., 2016). In the Zavkhan allochthon, samples of granite and trondhjemite near Zavkhan–Mandal village yield U–Pb zircon ages of 856 ± 2, 786 ± 6, and 862 ± 3 Ma (Kozakov et al., 2014, 2017). Two distinct magmatic events are recognized in this area. The older igneous rock is gabbrodiorite that cuts the migmatic gneiss in the northern part of the Budun Formation (Kozakov et al., 2014). The zircon U–Pb age of the Budun Formation (~ 860 ± 3 Ma) is interpreted to represent the start of regional metamorphism (Kozakov et al., 2014). During or following this regional metamorphic event, granitic magmatism produced the Zavkhan batholith. Zircon U–Pb dating of trondhjemites from the Zavkhan batholith yielded an age of 786 ± 6 Ma (Kozakov et al., 2014). Kozakov et al. (2014, 2017) postulated that magmatism and metamorphism in the Zavkhan terrane occurred mainly between 880 and 780 Ma. Accretion–collision between the Lake terrane and the Zavkhan terrane took place between 545 and 525 Ma (Bold et al., 2016). After the collision, the Zavkhan terrane was subjected to extension until the early Silurian (~ 440 Ma). Finally, the Zavkhan terrane was intruded by the Hangai batholith between 270 and 240 Ma (Yarmolyuk et al., 2011).

The area targeted in this study has a complex structure (Fig. 1b), comprising geologically distinct fault-bounded units of the Zavkhan autochthon and the Altai allochthon that were covered by Tsagaan Oloom Formation which deposited from Cryogenian to Ediacaran. In this area, Urgamal–Shubun and Tsagannur Formations are classified as part of the Altai allochthon (Samozvantsov et al., 1982). The allochthon includes garnet–biotite–muscovite gneiss and muscovite gneiss of sedimentary origin (Kozakov et al., 2014), intercalated with garnet amphibolite, quartzite, and marbles. The allochthon has been metamorphosed to the epidote amphibolite and amphibolite facies (Kozakov et al., 2017). Kozakov et al. (2014) estimated that M1 metamorphism of rocks in the Altai allochthon took place at 810–785 Ma. These allochthonous units unconformably overlay Budun Formations of the Zavkhan autochthon.

We discovered an eclogite in the Shubun Formation which is located in the eastern Urgamal–Shubun Formation of the Altai allochthon. Shubun Formation made up of metabasite–siliceous–terrigenous rock association (Yarmolyuk et al., 2017). Kozakov et al. (2017) reported 960–930 Ma ages for zircon from granitic and gabbroic gneiss from the Urgamal–Shubun Formation (rocks types
Figure 1. (a) Simplified geological map of Western Mongolia (modified after Bold et al., 2016). The eclogite localities are indicated as stars. The Zavkhan autochthon is bounded by the Altai allochthon across a regional tectonic boundary (‘Fault 1’ of Bold et al., 2016). We have revised the shape of the tectonic boundary based on geological sketch map of Kozakov et al. (2017) (see text for more information). (b) Simplified geological map of the Urgamal eclogite locality, after Kozakov et al. (2017), which is based on the geological map of Samozvantsov et al. (1982). Characters in circles represent first few letters of three villages: U, Urgamal; ZM, Zavkhan-Mandal; Dur, Durvuljin. Star represents a location of the Urgamal eclogite. Some geological terranes are labelled by Formation names.
were not given in the original article and were provided by one of our authors, Erdenjargal, C.). Enormous quartzite blocks (~ 4 km width) are exposed at Mt. Tsakhir, which lies along the Zavkhan river at the SE margin of the Shubun Formation. On the east side of Mt. Tsakhir (47.6°N, 95.6°E), there are 15 occurrences of layers and lenses in 9 outcrops along the valley. The quartzite shows a weak foliation defined by alignment of white mica. At the sampled outcrop, quartzite displays a N–S trending and E dipping (~ 60°) foliation that is overprinted by crenulations. Thin eclogite layers are generally parallel to the foliation in the quartzite, whereas larger eclogite layers are sometimes discordant to the foliation. Eclogite sample for this study came from the largest lens (~ 20 × 60 m), whose long axis is nearly parallel to the foliation in the host quartzite. The lens has been variably retrogressed to black-colored amphibolite via the transformation of omphacite to hornblende and plagioclase. Investigated samples are representative of the eclogite in this area: (1) light-brown amphibolitized eclogite (sample 8028, Fig. 2a), in which omphacite grains were variably replaced by hornblende and plagioclase, and (2) green-colored eclogite (sample 2602, Fig. 2b), which occurs as a 20 cm–wide lens (the length is not traceable beyond 1 m) surrounded by dark-colored amphibolite.

Eclogite facies minerals in sample 8028 consist of garnet, omphacite, quartz, epidote, white mica, rutile, and green-blue barroisite (Fig. 2a), which have been variably retrogressed to an amphibolite facies mineral assemblage. Detailed petrography, mineral compositions, and P–T estimates for the eclogite will be reported in a subsequent study. Coarse-grained, typically euhedral zircons, whose

Figure 2. Photomicrographs, back-scattered electron (BSE) image, and a concentration map of potassium of the Urgamal eclogite. (a) Photomicrograph of a moderately retrogressed eclogite sample 8028. Garnet (Grt) coexists with omphacite (Omp), rutile (Rt), epidote (Ep), barroisite (Brs), white Mica (Wm), and quartz (Qtz), which have been retrogressed into a symplectite of hornblende (Hb), albite (Ab), and biotite (Bt). (b) Photomicrograph of eclogite sample 2602, in which well-preserved Omp coexists with Grt, Qtz, and Wm, with accessory Ep, Brs, and Rt. (c) BSE image of zircon (Zrn) crystals in a thin section of sample 8028. Ilm Ilmenite. (d) K2O concentration map of eclogite sample 2602, showing the distribution of Wm.
The main aim of this study was to use K–Ar geochronology to determine the metamorphic age of white mica in the Urgamal eclogite. We also determined U–Th total Pb ages for relict zircons to constrain their igneous protoliths. The results are presented below.

**AGE DETERMINATIONS FOR THE URGAMAL ECLOGITE**

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**K–Ar geochronology of white mica**

Sample 2602 was sliced and crushed using a stamp mill. The fragments were sieved (75–150 µm), and after removing magnetic minerals, the white mica fraction was separated. See Yagi (2006) for details of the mineral separation procedure. We chose the most abundant, purest fractions for K and Ar analyses. Analyses and calculation of ages and errors followed Nagao et al. (1984) and Itaya et al. (1991). Potassium was analyzed by flame photometry using a 2000 µg g⁻¹ Cs buffer with an analytical error of 2% at a 2σ confidence level. Argon isotopes were analyzed on a 15 cm-radius sector type mass spectrometer with a single collector system which called as HIRU (Itaya et al., 1991), using the isotopic dilution method with a 38Ar spike. Multiple runs of the standard (JG-1 biotite, 91 Ma) gave an error of 1% at a 2σ confidence level (Itaya et al., 1991). The decay constants of 40K to 40Ar, 40Ca, and the ratio of 40K to total K used in the age calculations are 0.581 × 10⁻⁹ year⁻¹, 4.962 × 10⁻¹⁰ year⁻¹, and 0.0001167, respectively (Steiger and Jäger, 1977). The K–Ar age result for white mica in eclogite is 395 ± 7.9 Ma (at a 2σ confidence level) (Table 1). Because argon retention temperatures in white mica is generally assumed to be ~350–430 °C (e.g., Kelley, 2002), the measured K–Ar age value of high-grade metamorphic rocks, including eclogite, have been interpreted as cooling ages when the radiogenic Ar diffusion in white mica was closed. However, Itaya (2020) proposed the closure temperature of argon diffusion in white mica is much higher, approximately 600 °C. Adopting the latter value, it is critical important whether metamorphic peak temperature of the Urgamal eclogite exceed more than 600 °C or not. The absence of lawsonite and glaucophane suggests that the peak eclogite metamorphic temperature exceeded ~550–600 °C. Thus, the K–Ar age likely reflect the timing of eclogite facies metamorphism. If excess argon still remains in muscovite due to insufficient recrystallization, the obtained K–Ar age is served as an upper limit of the eclogite facies metamorphism.

**U-Th-total Pb age for zircon**

A high degree of metamictization makes it difficult to apply conventional laser ablation ICP-MS technique, due to the large beam diameter (generally >10 um). Chemical U-Th-total Pb Isochron method of dating (CHIME) with an electron microprobe (EMP) makes it possible to determine an age for a microvolume of the zircon domain (Suzuki and Adachi, 1991; Suzuki and Kato, 2008). Although CHIME zircon ages generally have large errors (up to 100 Ma at 2σ precision for low Pb concentrations), the method is precise enough to distinguish whether the relict zircons formed after 880 Ma as part of the Zavkhan autochthon, or formed as part of the Altai allochthon whose basement granitic gneiss sometimes records old history prior to 1000 Ma.

Zircon grains in conventional thin sections of sample 8028 were analyzed using an EMP (JCM-733; JEOL, Tokyo) with five wavelength-dispersive spectrometers (radius of the Rowland circle = 140 mm) at the Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Japan. The instrument operating conditions were 15 kV accelerating voltage, 500 nA probe cur-

| Sample | Grain size in Long dimension | K2O concentration (wt%) | Radiogenic 40Ar (10⁶cc STP/g) | K–Ar age (Ma) | Nonradiogenic 40Ar (%) |
|--------|-----------------------------|-------------------------|-------------------------------|--------------|-----------------------|
| 2602   | White mica 75–150 µm         | 7.911 ± 0.158           | 13554 ± 133                  | 395.0 ± 7.9  | 0.6                   |
rent, and 3 µm probe diameter. Matrix correction was performed using the method of Bence and Albee (1968) with the $\alpha$-factor table from Kato (2005) modified for U M$\beta$ line emission. The procedure for calculating CHIME ages from concentrations of Pb, Th, and U is described by Suzuki and Adachi (1991) and Suzuki and Kato (2008).

We selected the two least-metamictized grains of zircon and identified 21 points that do not contain inclusions or holes when viewed under an optical microscope and in secondary electron images. However, among the 21 analyses, 12 yielded a significant amount (0.1–0.3 wt%) of CaO (Fig. 3a). Large calcium cations (ionic radius = 1 Å) cannot be partitioned into the zircon structure, in which both Zr and Si have small ionic radii (0.59 and 0.26 Å, respectively). Suzuki and Kato (2008) attributed similar Ca-rich zones to secondary xenotime (YPO$_4$)-rich domains in zircon grains. Xenotime easily degrades into a metamict state, so Suzuki and Kato (2008) concluded that zircon analyses with higher CaO content should be avoided due to the potential loss of Pb. We used the remaining nine zircon analyses for age calculations, each of which contain <0.1 wt% CaO and can be plotted on the Cocherie plot (Fig. 3) (Cocherie and Albarede, 2001). The protolith age is constrained to 1113 ± 52/±31 Ma (1σ). The age suggests that the protolith of the Urgamal eclogite formed at the end of the Mesoproterozoic.

**DISCUSSION**

New U–Th–Pb ages for zircon grains in the Urgamal eclogite suggest that the protolith formed before ~1000 Ma (at the 95% confidence interval). This age is slightly older than U–Pb zircon ages from the Urgamal–Shubun Formation (960–930 Ma from granitic and gabbroic gneisses, Kozakov et al., 2017). The Urgamal–Shubun ages, including our zircon age, are generally older than the Zavkhan autochthon in the NE Zavkhan terrane, which formed between 880 and 780 Ma (Kozakov et al., 2014). U–Pb age data obtained by Bold et al. (2016) (their Table 1) also suggest that the oldest magmatic ages of the granitic gneiss in the Altai allochthon (1967 ± 13 Ma) are much older than those of the Zavkhan autochthon (839 ± 11 Ma). This age difference may indicate that the Altai allochthon was formed separately to the Zavkhan autochthon, and that the two were later juxtaposed through collision.

The newly discovered eclogite in the Urgamal–Shubun Formation can be taken as evidence for subduction. An obtained white mica K–Ar age suggests that the Urgamal eclogite formed during the early Devonian (~395 ± 8 Ma). To put this age result into context, previous geochronological data are described. Bold et al. (2016) reported ages from the Altai allochthon granites, using the metamorphic rims of zircon grains. In their study, granite gneiss from the Urg Sharga Gorge records a metamorphic age of 529 ± 22 Ma, and an unnamed granitic gneiss from the Dung Sharga Gorge also records a metamorphic age of 507.07 ± 0.66 Ma. This metamorphism was prob-

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**Figure 3.** Results of Th–U–total Pb geochronology of zircon from the Urgamal eclogite. (a) CaO versus Th–U–total Pb age diagram for zircon analyses of sample 8028. Note that CaO-poor (<0.1 wt%) spots indicate older ages than CaO-rich spots. (b) Th/Pb versus U/Pb diagram for zircon crystals from the eclogite sample 8028. Error ellipsoids represent age data for Ca-poor spots in (a). The best-fit regression line (heavy line) for the ellipsoids has the slope of 1113 Ma. The 1σ error curves are shown as parabolas. The age is calculated at the weighted mean point (X bar, Y bar) of the best-fit line, and the error is calculated on the hyperbolas, close to the weighted mean point, where the distance between the hyperbolas is smallest.
ably the result of collision between the Zavkhan terrane and the Lake terrane, which occurred from 545 to 525 Ma. One of the aim of our study was to investigate whether eclogite facies metamorphism took place in response to this collision. The Ch. eclogite in the southeastern part of the Lake terrane records 547.9 ± 2.6 Ma (1σ) age (Štípská et al., 2010) and likely record this collision event. In contrast, the K–Ar age of the Urgamal eclogite is much younger than the collision between the Lake and Zavkhan terranes. Thus, it is highly unlikely that the Urgamal eclogite formed as a result of collision between these terranes.

After the collision with the Lake terrane, the Zavkhan terrane was subjected to extensional tectonics. This resulted in the formation of graben that were filled with bimodal igneous rocks and sediments of the late Ordovician-Silurian Teel Formation (Bold et al., 2016). Syn-rift igneous activity resulted in the emplacement of the Numrug granite (442.10 ± 0.19 Ma), which lies in the Khasagt Khairkhán range of the Zavkhan autochthon (Bold et al. 2016). Rift-related igneous activity has also been reported in the adjacent Lake zone (Yarmolyuk et al., 2011; Soejono et al., 2017). Rifting is thought to have lasted until at least the early Silurian (~ 440 Ma), so it is also unlikely that the Urgamal eclogite formed in relation to this event.

It is difficult to explain the formation of Devonian eclogite within the Neoproterozoic cratonic terrane. During the Devonian, subduction-related arc volcanism took place in the Zavkhan area, but the driving force behind the volcanism remains unknown (e.g., Bold et al., 2016). Our working hypothesis is that a previously unrecognized subduction/collision event produced the eclogite and magmatism during the Devonian. A possible driving force for the convergence was the collision between the Zavkhan and the Tarvagatai terranes. During convergence, part of the Altai allochthon may have subducted beneath the Zavkhan autochthon. At present, there is no convincing explanation for the eclogite in the Zavkhan terrane. Thus, the Zavkhan terrane’s tectono-metamorphic history, as it is currently understood, may require major revisions.

**CONCLUSION**

Kozakov et al. (2014, 2017) suggested that the basement rocks of the Zavkhan terrane were mainly formed during the Neoproterozoic, that magmatic and metamorphic activity ended prior to 786 ± 6 Ma, and that the Zavkhan terrane was metamorphosed to the epidote-amphibolite to amphibolite facies. Contrary to these views, we discovered eclogite in the Urgamal-Shubun Formation of the Altai allochthon. The Zavkhan terrane was in an extensional environment until 440 Ma, so eclogite-forming high-pressure metamorphism must have taken place between 440 and 395 Ma. We speculate that part of the Altai allochthon was subducted beneath the Zavkhan autochthon, resulting in the formation of eclogite. This convergence could have been driven by collision of the Zavkhan and the Tarvagatai terranes. To test this hypothesis, it is necessary to carry out detailed field mapping of metamorphic rocks in the Zavkhan terrane.

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