Early Cambrian eclogites in SW Mongolia: evidence that the Palaeo-Asian Ocean suture extends further east than expected

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ABSTRACT

Newly discovered eclogites, Early Cambrian carbonates and chloritoid-bearing metapelites form the Tsakhir Uul accretionary wedge, which was thrust during the Early Cambrian over the Mesoproterozoic Dzabkhan-Baydrag continent. The rock association of the wedge forms a tectonic window emerging through the hangingwall Khantaishir ophiolite unit, which preserves a typical Tethyan-type ophiolitic sequence. The eclogites correspond geochemically to T-MORB modified by fluid circulation. They are composed of garnet, omphacite, amphibole, rutile ± muscovite ± quartz ± epidote and exhibit well-equilibrated matrix textures. Jadeite content of the omphacite reaches up to 45 mol.%, the Si content of muscovite is between 3.40 and 3.45 p.f.u., amphibole is winchite to barroisite, but reaches tschermakitic composition at some rims, and garnet composition is grS340-0.36 alm0.43–0.56 pSps0.05–0.18 χ[0.05–0.18 F0.75–0.81]. The peak assemblage, together with the composition of garnet rims, omphacite, amphibole and muscovite, correspond in a pseudosection to 20–22.5 kbar and 590–610 °C. The tschermakitic rim of amphibole is interpreted as partial reequilibration on decompression below 16 kbar and ~600–630 °C. Two muscovite separates from the eclogite yielded an Ar–Ar plateau age of 536.9 ± 2.7 Ma (1σ) and a mean age of 547.9 ± 2.6 Ma (1σ), whereas muscovite from an interbedded garnet-chloritoid micaschist yielded an Ar–Ar plateau age of 536.9 ± 2.7 Ma (1σ); these ages are interpreted as cooling ages. The P–T data, geochemistry of eclogites and cooling ages suggest an affinity between the Tsakhir Uul wedge and the Gorny Altai and the north Mongolian blueschist belt, which are believed typical for subduction of warm oceanic lithosphere and closure of small oceanic basins. Thus, the discovery of the Tsakhir Uul eclogites represents an important finding suggesting extension of the Early Cambrian subduction system of the Central Asian Orogenic Belt far to the east in a region where it was not expected.

Key words: Cambrian eclogite; Central Asian Orogenic Belt; Mongolia; Palaeo-Asian Ocean; Tsakhir Uul accretionary wedge.

INTRODUCTION

Since the end of the Late Proterozoic till the Mesozoic, the Central Asian Orogenic Belt (CAOB), also known as Altaids (Šengör et al., 1993; Šengör & Nataliin, 1996), has been the largest region of crustal growth on the Earth (Jahn et al., 2009). The CAOB evolved through accretion of magmatic arcs, back-arc terranes, accretionary complexes and continental blocks. Accretion is considered to have lasted from the latest Mesoproterozoic to the late Permian (Kröner et al., 2007; Windley et al., 2007; Xiao et al., 2009). Two main periods of continental growth related to accelerated accretion in the CAOB are recognized (Zonenshain et al., 1976): (i) the Late Proterozoic to Early Palaeozoic period (reported also as ‘Caledonian’), when Late Proterozoic ophiolites of the Palaeo-Asian Ocean have been accreted to the Siberia craton and to Proterozoic continental basement fragments; and (ii) the Late Palaeozoic to Mesozoic period, when a vast Siluro-Devonian oceanic domain of the ‘south Mongolian’ ocean was accreted during the so-called ‘Hercynian’ phase. The first accretion period is evidenced by a number of ophiolitic bodies and high-pressure rock occurrences, namely in the central Kazakhstan, Gorny Altai and North Mongolia (Khain et al., 2003; Volkova & Sklyarov, 2007). However, the shape of the Palaeo-Asian Ocean suture is unknown because of the scattered character of ophiolitic and high-pressure units developed during a long period of time between 760 and 490 Ma (Volkova & Sklyarov, 2007). In contrast, the Late Palaeozoic to Mesozoic suture of the south Mongolian ocean is well defined, being parallel to the northern termination of the North Chinese and Tarim cratons (e.g. Xiao et al., 2009).
The eclogites of this study occur in an area located at the contact of Palaeozoic oceanic rocks and the Dzabkhan-Baydrag continent, which belongs to the group of basement blocks located south of the Siberian craton (Fig. 1). The eclogites are associated with ophiolitic rocks corresponding to the easternmost extremity of an ophiolitic nappe system thrust northwards (present coordinates) over the Dzabkhan-Baydrag continent, namely the Khantaishir (Zonenshain & Kuzmin, 1978) and the Dariv (Khain et al., 2003; Dijkstra et al., 2006) ophiolites, both dated as Late Proterozoic (c. 570 Ma). Thus, the occurrence of

Fig. 1. (a) Location of the Central Asian Orogenic Belt (CAOB) and adjacent tectonic elements. Age assignment: V: Vendian (650–543 Ma). (b) Simplified tectonic map of the eastern part of the CAOB showing main lithotectonic zones and location of Fig. 2 (modified from Şengör & Natal’In, 1996; Parfenov et al., 2001; Badarch et al., 2002; Parfenov et al., 2003; Xiao et al., 2004; Kuzmichev et al., 2005; Volkova & Sklyarov, 2007; Xiao et al., 2008; De Boisgrollier et al., 2009; Kröner et al., 2010). Numbers in top-right corner of each box refer to geochronological constraints from: (1) Khain et al. (2002), (2) Kuzmichev et al. (2007), (3) Kuzmichev et al. (2005), (4) Sklyarov & Postnikov (1990), (5) Pfänder et al. (1998), (6) Kröner et al. (2010), (7) Lehmann et al. (2010), (8) Badarch et al. (2002), (9) Khain et al. (2003), (10) Dijkstra et al. (2006), (11) Kovalenko et al. (1996), (12) Kröner et al. (2001), (13) Uchio et al. (2004), (14) Buslov & Watanabe (1996), Buslov et al. (2001), (15) Volkova et al. (2005).
ophiolites and the newly discovered eclogite belt may constrain the existence of the Palaeo-Asian Ocean suture far to the east along the southern edge of the Dzabkhan-Baydrag continent (Fig. 2). In addition, the newly discovered eclogite belt may be correlated with other high-pressure Neoproterozoic belts (Hugeyn and Oka) located at the western edge of the Tuva Mongol basement block (Sklyarov, 2006; Kuzmichev et al., 2007).

In this article, we present petrological and geochronological data for the eclogites and associated schists that suggest subduction of the Early Cambrian passive margin sequences of the Palaeo-Asian Ocean in SW Mongolia. Major and trace element geochemistry is used to discuss the character of the eclogite protolith and the geodynamic setting of formation. Thermodynamic modelling is used to characterize P–T conditions and the metamorphic field gradient of the eclogite and 40Ar–39Ar geochronology on muscovite is applied to date exhumation of the high-pressure rocks and by inference the age of the Palaeo-Asian Ocean suture. Finally, we discuss the significance of the newly discovered eclogites for the geographic extension of the Palaeo-Asian Ocean far to the east compared to the existing model of Zonenshain & Kuzmin (1978), which may have important consequences for established tectonic models for the evolution of the CAOB by Şengör et al. (1993) and Windley et al. (2007).

FIELD SETTING

SW Mongolia is a region affected by both Early Palaeozoic (also called ‘Caledonian’) and late Palaeozoic (‘Hercynian’) tectonic events (Mossakovsky et al., 1993). In agreement with the early models for the tectonic evolution of the CAOB (Zonenshain, 1973; Ruzhentsev & Pospelov, 1992; Ruzhentsev, 2001), the geology of Mongolia is divided into two major tectonic domains that differ in tectonic style and ages of geological formation: (i) the Mesoproterozoic northern domain (the Mongolian continent of Zonenshain, 1973), corresponding to the Dzabkhan-Baydrag continent of Badarch et al. (2002) that was predominantly affected by Early Palaeozoic orogenesis; and (ii) the Early Palaeozoic, southern, mostly oceanic domain (south Mongolian Ocean domain) that was predominantly affected by late Palaeozoic orogenesis (Fig. 1). The two domains are separated by the...
Main Mongolian deep fault, later renamed the Main Mongolian Lineament (Tomurtogoo, 1997).

The study area is located in the Zamtyyn range belonging to the Dzabkhan-Baydrag continent in the northern Mesoproterozoic domain, which forms a large mountain crest ~20 km NE from the village of Chandman (Fig. 3). It is flanked in the north by a Cretaceous basin and in the south by the E–W trending Main Mongolian Lineament. The newly discovered eclogite belt belongs to the so called ‘Lake Zone’ of Rauzer (1987), which shows the following geological units and formations from bottom to top.

The structurally lowest and eastern part is represented by coarse-grained augen-gneiss, banded amphibolites, amphibolitic gneisses and marbles of the Zamtyyn Nuuru complex, which was recently dated as late Mesoproterozoic and attributed to the Dzabkhan basement (c. 950 Ma, Kröner et al., 2010). These Dzabkhan basement rocks are affected by amphibolite facies metamorphism and are locally thermally reworked by Late Cambrian (c. 500 Ma) magmatic and migmatitic event (Hrdličková et al., 2008; Kröner et al., 2010).

The Dzabkhan basement rocks are tectonically overlain by the Tsakhir Uul formation (Fig. 3), composed of fossiliferous volcano-sedimentary, sedimentary, and tuffaceous siliceous schists and marbles, which were dated in the studied area, and in the type locality of the Khantaishir ridge some 120 km to the west, as Early Cambrian by Archaeocyatha macrofossils (Markova, 1975; Hanžl & Aichler, 2007). The Tsakhir Uul formation in the study area essentially consists of marble, enclosing large boudins of eclogite and metapelites up to hundreds of metres across in the north. The central part of the unit is composed of a NE-SW trending belt of metagabbro and amphibolite, overlain by a large body of peridotite, whereas the southern part is dominated by marble and metapelites. The eclogites of this study are associated with garnet- and chloritoid-bearing metapelites. However, metagabbros show only amphibolite facies mineral assemblages, suggesting that the unit did not reach eclogite facies conditions as a whole. The metasedimentary rocks in the southern part of the Tsakhir Uul formation (south of the peridotite body) have amphibolite facies assemblages.

Further north occurs an ophiolitic unit composed of serpentinitized peridotites, a tonalite-trondhjemite suite, and abundant tholeiitic to calc-alkaline mafic to intermediate volcanic rocks (Hanžl & Aichler, 2007). This unit is interpreted as a lateral equivalent of the Khantaishir ophiolite unit (Zonenshain & Kuzmin, 1978), which was dated at 568 ± 4 Ma using U–Pb method on zircon from a plagiogranite (Gibsher et al., 2001). The uppermost part of the section studied is represented by clastic sequences recently dated as Devonian and Early Carboniferous (Kröner et al., 2010). On the southwestern foothill of the Zamtyyn Range, a volcanioclastic formation of bimodal volcanic rocks and volcanioclastic sediments was dated as Permian (Hanžl & Aichler, 2007).

The Tsakhir Uul formation was thrust over the Zamtyyn Nuuru basement complex as a mélangé of eclogite, gabbro and high- to medium-pressure pelite, surrounded by carbonate matrix (Lehmann et al.,

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**Fig. 3.** Interpretative geological cross-section and associated simplified stratigraphic column show structural relationships between the Early Devonian molasse, Khantaishir ophiolitic domain, Tsakhir Uul accretionary complex and underlying basement. Horizontal and vertical scales of the profile are the same.

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2010). The basement metamorphic foliation S1 was determined as Late Proterozoic based on 40Ar–39Ar cooling ages of c. 570 Ma on intrafolial coarse muscovite (Lehmann et al., 2010). The eclogites and marbles reveal polyphase deformation marked by an eclogite facies fabric (S2) reworked by a dominant amphibolite facies fabric (S2) developed in impure marbles and metapelites, and by heterogeneous amphibolite facies shear zones in the eclogites. This metamorphic foliation shows variable dip indicating an early steep folding event probably associated with emplacement of the Tsakhir Uul eclogites. This early D2 thrusting event is marked by shear fabrics in metavolcanics underlying peridotite sheet in the Erdene Uul mountains suggesting that the Khantasihir ophiolites experienced a similar thrusting event. Although kinematic data are scarce, a SE-NW shortening direction is likely based on a few L2 lineations and the orientation of F2 fold hinges.

The whole sequence of the Tsakhir Uul accretionary wedge is deformed by major E–W trending large scale folds. In the metasedimentary rocks, these folds are associated with a very low grade but intense, steep E–W-trending cleavage. The same cleavage affects also the Khantaishir ophiolite and basement rocks thereby modifying the original emplacement geometry of the eclogite-ophiolite system.

ANALYTICAL PROCEDURES AND ABBREVIATIONS

The whole-rock inductively coupled plasma mass spectrometry analyses were performed in the Acme laboratories, Canada. Mineral analyses were performed on an electron microprobe CAMECA SX-100 at the Institute of Mineralogy at the University of Stuttgart in point beam mode at 15 kV and 15 nA. The petrography is documented in Figs 5 and 6, representative mineral analyses are summarized in Tables 1 and 2, and the petrography is documented in Figs 5 and 6. The sign /C212 = > /C213 is used for a trend in mineral composition or for zoning and the sign /C212 – /C213 for a range of mineral compositions; p.f.u. = per formula unit. For the amphibole, the variables and isopleth notations are used as in Dale et al. (2005) and Diener et al. (2007) to compare the chemical variability of the amphibole with the modelled pseudosections.

Mineral abbreviations: g = garnet, cpx = diopсидic clinopyroxene, o = omphacitic clinopyroxene, jd = jadeitic clinopyroxene, am = amphibole, hb = hornblende, act = actinolite, gl = glaucophane, ep = epidote, chl = chlorite, mu = muscovite, pl = plagioclase, q = quartz, ilm = ilmenite, ru = rutile; alm = Fe/(Ca + Fe + Mg + Mn), prp = Mg/(Ca + Fe + Mg + Mn), grs = Ca/(Ca + Fe + Mg + Mn), sps = Mn/(Ca + Fe + Mg + Mn), XFe = Fe/(Fe + Mg), an = Ca/(Ca + Na + K), ab = Na/(Ca + Na + K), Z = xNa(M4) = Na(M4)/2, Y = xAl(M2) = AlVI/2, A = xNa(A) = Na(A), C = xCa(M4) = Ca/2. The isopleth notation used is: x(g, cpx) = Fe/(Fe + Mg), z(g) = Ca/(Ca + Fe + Mg) × 100, j(cpx) = Na/(Na + Ca) × 100, z(am) = xNa(M4) = Na(M4)/2 × 100, y(am) = xAl(M2) = AlVI/2 × 100, a(am) = xNa(A) = Na(A) × 100.

PETROGRAPHY

Macroscopically, the eclogites appear as isotropic, fine-grained massive rocks, with rarely distinguishable foliation. They are composed of a light to dark greenish, fine-grained matrix that may have dark green
to black patches, with ~40 vol.% of garnet porphyroblasts, usually ~2–4 mm in size. Some eclogites contain macroscopically visible muscovite. Locally, the eclogites show compositional layering at centimetric to decimetric scale marked essentially by variable amount and size of garnet.

Under the microscope the common assemblage is garnet, clinopyroxene, colourless to light blue amphibole that may be light to dark green at the rims, garnet, rutile and quartz. Some samples contain also epidote and/or muscovite. In thin section, a majority of the eclogites show a strong foliation that is defined by the preferred orientation of clinopyroxene and amphibole, and sometimes by muscovite. Some of the rocks sampled are garnetiferous amphibolites as they contain no pyroxene or only very small amounts and have a matrix dominated by colourless to light blue amphibole; these rocks were
not included in this study. Two samples of the most typical eclogites were chosen for this petrological study, the muscovite-bearing eclogite M133p17/06 (45°24.276′N, 98°13.828′E) and the muscovite-absent, epidote-bearing eclogite M134p45/06 (45°24.597′N, 98°14.902′E). These samples were chosen for their well-equilibrated matrix textures to determine peak conditions of metamorphism.

Eclogites contain on average ($n = 5$) 48 wt% SiO$_2$, 2.17 wt% Na$_2$O and 0.54 wt% K$_2$O, which corresponds to a basaltic composition according to the SiO$_2$ v. K$_2$O + Na$_2$O relation. Primitive mantle normalized multi-element patterns (plotted with GCDkit, Janoušek et al., 2006) are very similar to the pattern for T-MORB, transitional between E-MORB and OIB (Geist et al., 1995), except for highly fluid-mobile large ion lithophile element as Cs, Rb and K (Fig. 4). Therefore, the precursor of the eclogite is interpreted to have the composition of T-MORB basalt modified by fluid circulation.

Sample M133p17/06

Sample M133p17/06 is composed of garnet (40%), clinopyroxene (40%), colourless or pale blue to pale green amphibole (10%), muscovite (3%), accessory rutile, quartz, calcite, titanite, albite and zircon (Fig. 5). Garnet (2 mm) has an inclusion-rich core with numerous amphibole and quartz, and some titanite, calcite and albite grains, and an inclusion-poor rim with rare rutile, amphibole and muscovite grains (Fig. 5a,b). Strongly oriented and elongated pyroxene (1 mm), amphibole (1 mm) and muscovite (0.5 mm) together with amphibole-bearing pressure shadows around garnet define the foliation (Fig. 5a,c). These minerals in the foliation together with rutile exhibit mutual contacts and straight boundaries pointing to textural equilibrium attained at peak metamorphic conditions. Locally, pyroxene is decomposed along cracks into symplectite formed by albite and amphibole or more rarely by albite and clinopyroxene (Fig. 5d).

Fig. 6. Backscattered electron (BSE) images of epidote-bearing eclogite M134p45/06. (a) Garnet with inclusions of amphibole, rutile, plagioclase, epidote and matrix of clinopyroxene, amphibole and small amount of epidote and plagioclase. (b) Detail of strongly oriented matrix of clinopyroxene, rutile and amphibole located in garnet pressure shadow. (c) Garnet with profile indicated. (d) Detail of amphibole aggregate and rutile in garnet pressure shadow with profile indicated.
Table 1. Representative mineral analyses. Muscovite-bearing eclogite M133p17-06.

| Position | g-r | g-spikes | g-e | cpxs-m | cpxs-mx | am-mx-c | am-mx-r | am-in-c | am-mx-ir | mu-mx | mu-in |
|----------|-----|----------|-----|--------|--------|--------|---------|---------|----------|--------|--------|
| Analysis | st5-L16-125 | st5-L16-141 | st5-L17-169 | st5-L13-46 | st5-L13-86 | st5-L12-64 | st3-p18 | st5-L2-11 | st5-L2-10 | st3-46 | st3-56 |
| SO2      | 37.91 | 37.62 | 37.38 | 56.00 | 56.14 | 55.00 | 48.66 | 51.71 | 46.02 | 51.17 | 50.98 |
| TiO2     | 0.12 | 0.15 | 0.27 | 0.04 | 0.03 | 0.06 | 0.24 | 0.14 | 0.34 | 0.29 | 0.26 |
| Cr2O3    | 0.03 | 0.04 | 0.02 | 0.02 | 0.01 | 0.02 | 0.01 | 0.03 | 0.05 | 0.04 | 0.01 |
| Al2O3    | 1.98 | 1.99 | 2.16 | 0.00 | 0.01 | 0.00 | 0.00 | 0.08 | 0.08 | 0.00 | 0.01 |
| SiO2     | 2.37 | 2.39 | 2.84 | 1.89 | 1.89 | 18.00 | 13.04 | 13.27 | 9.84 | 19.58 | 19.17 |
| Total    | 99.85 | 100.21 | 99.97 | 100.81 | 100.31 | 98.12 | 97.88 | 97.87 | 97.74 | 95.18 | 94.92 |

Sample M123p45/06

Sample M123p45/06 is composed of garnet (40%), clinopyroxene (30%), colourless to pale blue amphibole (20%) that is in places pale green at the rim, minor epidote (3%), and accessory quartz, albite, rutile and zircon (Fig. 6). Garnet (3 mm) commonly includes amphibole, rutile, quartz, and rarely epidote and albite (Fig. 6a). Clinopyroxene and amphibole in the matrix are strongly preferentially oriented parallel to the foliation (Fig. 6b), they exhibit mutual contacts and straight boundaries with garnet, epidote and rutile that is interpreted as textural equilibrium attained at peak metamorphic conditions.

Garnet zoning is marked by a flat plateau in the core, a shoulder and a rim with the following compositions grs0.25 => 0.33 => 0.27, alm0.50 => 0.56, py0.12 => 0.08 => 0.14, sps0.06 => 0.00, and Fe0.78 = 0.88 = 0.86 (Figs 5a & 7a). Clinopyroxene is omphacite with 35–45% of jadeite, 3–5% of acmite and XFe varying between 0.11 and 0.16 in the inclusions and 0.14 and 0.12 in the matrix. Amphibole composition ranges from actinolite to hornblende sensu lato, with winchitic to barroisitic core (Z = xNa(M4) = NaM4/2 = 0.2–0.28, Y = xAl(M2) = AlIV/2 = 0.15–0.25, A = xNa(A) = NaA(1) = 0.02–0.15, AlIV = 0.25–0.70) and commonly thin barroisitic rims that exceptionally reach tschermakitic composition (Z = 0.20–0.33, Y = 0.26–0.42, A = 0.15–0.40, XFe = 0.15–0.40, F = 0.12–0.4, AlIV = 0.70–1.10) (Figs 8a–c & 9a,b). The compositional range and zoning pattern of amphibole included in garnet is similar to the matrix amphibole (Figs 8b & 9a,b), but amphibole inclusions tend to have higher XFe and a higher amount of Fe2+ (YFe = YFe(Fe + Mg) = 0.20–0.60, F = XFe+F2+/(M2) = Fe2+/2 = 0.15–0.30) compared to the matrix amphibole (XFe = 0.08–0.40, F = 0.12–0.40). Muscovite has maximum Si (p.f.u.) = 3.40–3.45 and 4–8% of paragonite. The composition of pyroxene and muscovite points clearly to high-pressure metamorphism. However, the variability in the amphibole composition shows that even if the matrix amphibole is in textural equilibrium with the high-pressure minerals, its rim is locally compositionally modified.
Table 2. Representative mineral analyses. Epidote-bearing eclogite M134p45–06.

| Mineral | g-c | g-r | cpx-mx | am-mx-c | am-mx-r | am-in | am-in | ep-in | ep-mx |
|---------|-----|-----|--------|---------|---------|-------|-------|-------|-------|
| Analysis | st2-L14-240 | st2-L14-166 | st2-L8-89 | st2-L16-326 | st2-L16-341 | st1-p35 | st1-p54 | st1-p58 | st1-p60 |
| SiO₂ | 37.55 | 37.87 | 55.78 | 53.77 | 40.58 | 42.25 | 43.46 | 37.87 | 38.26 |
| TiO₂ | 0.17 | 0.04 | 0.08 | 0.08 | 0.15 | 0.48 | 0.56 | 0.17 | 0.07 |
| Cr₂O₃ | 0.02 | 0.01 | 0.04 | 0.02 | 0.05 | 0.03 | 0.02 | 0.00 | 0.00 |
| Al₂O₃ | 1.98 | 2.01 | 0.43 | 0.80 | 3.24 | 2.31 | 2.56 | 2.46 | 2.46 |
| Cr | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| TiO₂ | 0.12 | 0.12 | 0.18 | 0.12 | 0.18 | 0.08 | 0.19 | 0.00 | 0.00 |
| Na₂O | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CaO | 10.62 | 9.28 | 13.25 | 9.32 | 9.49 | 9.63 | 8.70 | 22.87 | 22.91 |
| MgO | 1.22 | 4.55 | 8.67 | 17.43 | 8.43 | 7.19 | 9.61 | 0.04 | 0.04 |
| MnO | 8.06 | 0.26 | 0.00 | 0.00 | 0.05 | 0.05 | 0.00 | 0.29 | 0.24 |
| FeO | 20.72 | 25.58 | 4.68 | 7.67 | 13.85 | 20.07 | 14.49 | 7.14 | 6.33 |
| SiO₂ | 3.01 | 2.98 | 1.98 | 7.60 | 6.10 | 9.88 | 9.88 | 9.88 | 9.88 |

in, inclusion in garnet; mx, matrix; c, core; r, rim; ox, oxygen; cat, cation; g, garnet; cpx, diopsidic clinopyroxene; am, amphibole; ep, epidote.

in, inclusion in garnet; mx, matrix; c, core; r, rim; ox, oxygen; cat, cation; g, garnet; cpx, diopsidic clinopyroxene; am, amphibole; ep, epidote.

= 0.90–2.20; Figs 8c,d & 9c,d). Amphibole inclusions do not show systematic zoning and the compositional range is from barroisitic to tschermakitic hornblende (Z = 0.20–0.30, Y = 0.30–0.55, A = 0.22–0.55, X₉Fe = 0.30–0.55, F = 0.15–0.40, AlIV = 0.9–1.7; Figs 8c & 9c,d). Pyroxene composition results clearly from high-pressure metamorphism, however, even if the matrix amphibole is in textural equilibrium with pyroxene, some amphibole rims are chemically modified.

PSEUDOSECTION MODELLING

Calculation methods

The pseudosections were calculated using THERMOCALC 3.3 (Powell et al., 1998; 2009 version) and the data set 5.5 (Holland & Powell, 1998; November 2003 upgrade), in the system Na₂O–CaO–K₂O–FeO–MgO–Al₂O₃–SiO₂–H₂O–TiO₂–O (NCKFMASHTO) and in the system Na₂O–CaO–FeO–MgO–Al₂O₃–SiO₂–H₂O–TiO₂–O (NCFMASHTO) with the amphibole model from Diener et al. (2007), clinopyroxene from Green et al. (2007), garnet from White et al. (2007) modified by Diener et al. (2008), feldspar from Holland & Powell (2003), paragonite-muscovite from Coggon & Holland (2002), chlorite from Holland et al. (1998), epidote from Holland & Powell (1998) and ilmenite from White et al. (2000). Calculations for a Mid-Ocean Ridge Basalt (MORB) composition showed that with garnet and clinopyroxene fractionating, the bulk composition changes little (Štípka & Powell, 2005), so even though the garnet and amphibole in the eclogites are zoned, bulk composition fractionation calculations are not presented and the analysed whole-rock compositions of the samples are used in the mineral equilibria modelling. The Fe₂O₃ was set to represent 9–12% of the total FeO, a mean value obtained for ocean floor basalts (Sun & McDonough, 1989; Rebay et al., 2010). Calculations showing the effect of H₂O-undersaturation on the relative stability of minerals, their quantities and mineral chemistry (Štípka & Powell, 2005; Štípka et al., 2006; Baldwin et al., 2007; Rebay et al., 2010) are not presented and therefore, the prograde evolution of the eclogites, including the significance of the mineral inclusions in garnet, their chemistry or garnet zoning are not discussed. In the pseudosections, where the composition of supra-solvus clinopyroxene varies through the composition of the solvus top, the boundary is shown by a dashed line labelled di/o, similarly, the solvus top of coexisting hornblende and actinolite is extended into the supra-solvus region by a line labelled hb/act (Štípka & Powell, 2005; Štípka et al., 2006). The range of P–T conditions shown is chosen to discuss the peak P–T conditions and the retrogression of the eclogite (Figs 8 & 10). The pseudosections are contoured with the calculated compositional isopleths for muscovite, clinopyroxene, garnet and amphibole.

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An H₂O-saturated pseudosection for the whole-rock composition of sample M133p17/06 (in wt%: SiO₂ = 48.00, Al₂O₃ = 14.26, Fe₂O₃ = 14.63, MgO = 6.23, CaO = 11.38, Na₂O = 2.48, K₂O = 0.54, TiO₂ = 1.21, P₂O₅ = 0.11, MnO = 0.22, Cr₂O₃ = 0.02) is shown in Fig. 10. The major features involve the stability of muscovite over the whole calculated P–T range, epidote stability below 21 kbar and at maximum temperature of 640 °C at 16 kbar, lawsonite stable above 19.5 kbar and below 620 °C at 25 kbar.
Amphibole stability is up to 660 °C at 17 kbar and up to 585 °C at 25 kbar. Glauconite is stable below ~580 °C and between 1 and 20 kbar, hornblende above 575 °C at 16 kbar and to a maximum pressure of 18 kbar at 630 °C, actinolite up to 590 °C at 25 kbar and to the maximum temperature of 630 °C at 18 kbar.

The observed well-equilibrated peak assemblage for the eclogite M133p17/06 is muscovite, garnet, clinopyroxene, amphibole, rutile and quartz that corresponds to the narrow field between the epidote-out and actinolite-out lines, outside the stability of lawsonite. The composition of muscovite with Si = 3.40–3.45 (p.f.u.) and composition of clinopyroxene with 35–45% of jadeite corresponds closely to the calculated compositional ranges in the upper pressure part of the g–o–act–ru field. The x(o) isopleths range in this region between 0.17 and 0.19 (not shown) differing slightly from the measured $X_{Fe} = 0.04–0.12$ of the matrix pyroxene. Garnet rim composition with ~27–29% of grossular are close to the calculated $Z(g)$ values in the upper pressure part of the g–o–act–ru field. $X_{Fe}$ at the rim (0.78) is close to calculated range of $x(g)$ between 0.73 and 0.74 in the same region (not shown). The compositional isopleths of amphibole in the upper pressure part of the g–o–act–ru field correspond closely to the winchitic to barroisitic amphibole cores [$Z = NaM4/2 = 0.20–0.28$, $Y = Al^{VI}/2 = 0.15–0.25$, $A = Na(A) = 0.02–0.15$], therefore, these amphibole compositions are considered to correspond to the pressure peak. By comparing the observed assemblage and mineral compositions with the calculated model, the peak P–T conditions for the eclogite sample M133p17/06 may be estimated at 21–22.5 kbar and 590–600 °C. The compositional variables of the thin barroisitic to tschermakitic rims ($Z = 0.20–0.33$, $Y = 0.26–0.42$, $A = 0.15–0.40$, $X_{Fe} = 0.1–0.45$) tend to be close to the calculated isopleths ~18 kbar and 630 °C and are therefore interpreted as modified on decompression.

**Pseudosection for epidote-bearing sample M134 p45/06**

An H2O-saturated pseudosection for the whole-rock composition of the sample M134p45/06 (in wt%: SiO2 = 48.80, Al2O3 = 12.85, Fe2O3 = 14.78, MgO = 7.46, CaO = 11.23, Na2O = 2.58, K2O = 0.16, TiO2 = 1.45, P2O5 = 0.04, MnO = 0.22, Cr2O3 = 0.02) is shown in Fig. 11. The major features of the pseudosection are similar to the pseudosection of the sample M133p17/06 (Fig. 10), except that muscovite is not stable, glauconite is stable to slightly higher temperature of ~600 °C, epidote is stable to slightly higher temperature, from 635 °C at 16 kbar to 635 °C

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at 19 kbar and to 600 °C at 22 kbar, which is its upper pressure limit. Actinolite and hornblende are also stable to higher temperature, from 650 °C at 19 kbar to 610 °C at 25 kbar.

The observed well-equilibrated assemblage of garnet, clinopyroxene, amphibole, epidote, rutile and quartz corresponds to the calculated field g–o–act–ep–ru, situated between the glaucophane-out and epidote-out lines. The composition of pyroxene with up to 42% of jadeite and garnet rim compositions with grossular between 24% and 27% are close to the calculated isopleths j(o) and z(g) in the upper pressure part of the g–o–act–ep–ru field. X_{Fe} of pyroxene (0.06–0.15) and garnet rims (0.74) are close to the calculated values of x(o) = 0.15–0.16 and x(g) = 0.68–0.70 in the same region (not shown). The winchitic to barroisitic core compositions of the amphibole (Z = 0.23–0.30, Y = 0.18–0.38, A = 0.00–0.35) tend to be close to the calculated values in the upper pressure part of the g–o–act–ep–ru field and are considered as peak pressure compositions. The peak P–T conditions of the eclogite sample M134p45⁄06 are therefore estimated to 20–21.5 kbar at 590–610 °C. Barroisitic to tschermakitic rims of the matrix amphibole (Z = 0.13–0.31, Y = 0.25–0.70, A = 0.25–0.78) may be compared with the isopleths calculated in the lower pressure part

Fig. 10. H₂O-saturated pseudosection for the composition of muscovite-bearing eclogite M133p17/06 contoured for compositional isopleths. (a–f) See chapter Analytical procedures and abbreviations for notation and abbreviations. The ellipse in (f) shows peak P–T conditions. For discussion see text.

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of the g–o–hb–ep–ru field and are therefore interpreted as compositions modified on decompression at 600–630 °C and below 16 kbar.

40Ar–39Ar GEOCHRONOLOGY

40Ar–39Ar dating procedure

Mineral separates of single mica grains ranging in size from 0.160 to 500 mm were obtained after sample crushing by handpicking under a binocular microscope. After acetone, alcohol and distilled water washing, single muscovite grains were irradiated in the nuclear reactor of McMaster University in Hamilton, Canada. The total neutron flux density during irradiation was $8.8 \times 10^{18}$ n cm$^{-2}$ with a maximum flux gradient estimated at 0.2% in the volume where the samples were included. Irradiation lasted for 70 h, corresponding to a total of nearly 110 MWh. Hb3gr hornblende was used as neutron flux monitor. J-values were calculated relative to an age of 1072 Ma for Hb3gr (Turner et al., 1971) and the decay constants of Steiger & Jäger (1977) were used. The irradiated separates were measured in the Geosciences Azur Laboratory at Nice University. The step-heating procedure is described in detail by Ruffet et al. (1991).
Heating was carried out by a CO₂ Synrad 48-5 laser, and isotopic measurements were performed in a VG 3600 mass spectrometer equipped with a Daly detector system. Blanks of the extraction and purification laser system were measured after every third heating step and subtracted from each argon isotope from the subsequent gas fraction. Typical blank values were in the range of 6–18, 0.3–2.0, 0.4–1.2 and 0.6–1.4 × 10⁻¹³ccSTP for masses 40, 39, 37 and 36, respectively. The criteria for defining a plateau age were as follows: (i) a plateau age should contain at least 70% of the released \(^{39}\)Ar; (ii) there should be at least three successive heating steps in the plateau; and (iii) the integrated age of the plateau should agree with each apparent age of the plateau within the 1σ error confidence interval. Errors on plateau ages are given at the 1σ level and do not include the errors on the age of the monitor. However, the error in the \(^{40}\)Ar*/\(^{39}\)Ar ratio of the monitor is included in the calculation of the plateau age error bar.

\(^{40}\)Ar–\(^{39}\)Ar results

The sample M134p47/06 (45°24.597N, 98°14.902E) is a foliated eclogite composed of garnet, clinopyroxene, amphibole, muscovite, rutile, quartz and epidote (Fig. 12). Duplicates of large grains of muscovite yielded a plateau age of 543.1 ± 3.9 Ma (1σ) and a mean age (which is the average value of two consecutive steps where ~65% of the \(^{39}\)Ar is released) of 547.9 ± 2.6 Ma (1σ) (Fig. 13, Table 3).

The sample M134p31/06 is a quartzitic micaschist that contains garnet, muscovite, chloritoid, chlorite, quartz, rutile and ilmenite (Fig. 12). The metamorphic foliation is defined by bands dominated by muscovite (up to 3 mm) containing minor chlorite, that alternate with recrystallized quartz bands of infinite length.

DISCUSSION AND CONCLUSIONS

In this work, new geological, geochemical, petrological and \(^{40}\)Ar–\(^{39}\)Ar geochronological data are presented from an eclogite bearing Tsakhir Uul unit in southwestern Mongolia. The Tsakhir Uul unit, spatially associated with Khantaishir ophiolites overlying the Dzabkhan-Baydrag Mesoproterozoic basement, may represent a type tectonic assemblage for accretionary complexes of the eastern part of the CAOB. We discuss the lithotectonic position of the Tsakhir Uul eclogite bearing unit, \(P–T\) evolution and \(^{40}\)Ar–\(^{39}\)Ar geochronology of the eclogites and associated micaschists in comparison with other high-pressure units of the CAOB. Finally, the geographic position of the eclogites is discussed as a marker of the major suture zone of the Palaeo-Asian Ocean in its easternmost extremity.

Structure of the Tsakhir Uul accretionary wedge and the Khantaishir ophiolite

The eclogite boudins and marbles are enclosed in a metapelite bearing unit that is overlying a continental Mesoproterozoic basement. The carbonate rocks
locally contain Archeocyatha fossils of Early Cambrian age providing an important chronological boundary for onset of the subduction process. These carbonates constitute continuous sequences east and west of the study region, being deposited on Precambrian granitoids and high-grade rocks. The metasedimentary rocks are rich in K2O (20 wt%) and Al2O3 (20 wt%) and contain chloritoid, suggesting an Al-rich pelitic composition with high content of continental material. Within the metapelites dark schists and fine-grained quartzites also occur locally, which may indicate minor intercalations of deep marine sediments. The MORB chemistry of the eclogites suggests that these rocks originated in oceanic environment, probably formed at a mid-ocean ridge.

The whole sequence can be interpreted as follows. The Early Cambrian carbonate rocks probably represent relicts of a platform, which rimmed an Early Cambrian passive margin of the Dzabkhan-Baydrag continent (Rauzer, 1987). The eclogites represent subducted, slightly differentiated MORB incorporated within the metasedimentary wedge during exhumation. Therefore, this complex unit can be interpreted as an accretionary wedge, which contains both continental and oceanic elements. The Tsakhir Uul accretionary wedge constitutes a tectonic nappe overlying para-autochthonous continental margin represented by orthogneiss and migmatites belonging to the Dzabkhan-Baydrag continent (Fig. 3). The structural mapping of Lehmann et al. (2010) also suggests that the Khantaishir ophiolite resides structurally above the high-pressure unit. This inference is based on the existence of the Khantaishir ophiolite in lowlands north of the Tsakhir Uul accretionary wedge, which occupies topographic highs, and on the existence of a peridotite and amphibolite sheet located structurally above the southern part of the wedge. Therefore, we suggest that the Dzabkhan basement is covered by part of the Tsakhir Uul accretionary wedge, which itself is overlain by the Khantaishir ophiolite nappe. Based on

Table 3. 40Ar/39Ar step-heating release spectra.

| Sample          | Laser power (mW/μC) | Pow. cont. (%) | %39Ar (wt%) | %39Ar/39K | Age (Ma) ± error (1σ) |
|-----------------|---------------------|----------------|-------------|-----------|-----------------------|
| M134-P31-06     | 383                 | 0.00           | 1.76        | 0.00      | 15.93                 |
|                 | 403                 | 51.83          | 5.16        | 0.00      | 15.36                 |
|                 | 424                 | 10.00          | 0.00        | 15.14     | 540.26 ± 3.54         |
|                 | 445                 | 14.99          | 64.40       | 0.00      | 535.54 ± 1.39         |
|                 | 480                 | 15.08          | 16.20       | 0.00      | 538.30 ± 3.91         |
|                 | fuse                | 14.74          | 2.39        | 0.00      | 527.80 ± 11.01        |
| M134-P47-06 Muscovite A | 352 | 1.46        | 3.06        | 0.00      | 16.99                 |
|                 | 415                 | 16.41          | 2.48        | 0.00      | 578.80 ± 12.16        |
|                 | 437                 | 15.57          | 26.00       | 0.00      | 553.50 ± 2.09         |
|                 | 475                 | 15.32          | 64.98       | 0.00      | 547.71 ± 1.30         |
|                 | 515                 | 15.46          | 2.56        | 0.00      | 549.96 ± 22.66        |
|                 | fuse                | 15.32          | 0.93        | 0.00      | 545.82 ± 42.66        |
| M134-P47-06 Muscovite B | 347 | 0.00        | 0.21        | 0.00      | 23.02                 |
|                 | 446                 | 0.00           | 11.51       | 0.00      | 15.93                 |
|                 | 455                 | 0.00           | 81.23       | 0.00      | 15.22                 |
|                 | 460                 | 0.00           | 2.14        | 0.00      | 15.49                 |
|                 | 509                 | 0.00           | 1.51        | 0.00      | 15.50                 |
|                 | 1111                | 0.00           | 3.40        | 0.00      | 15.33                 |

Fig. 13. 40Ar/39Ar step-heating release spectra for (a) eclogite sample M134p47/06 and (b) micaschist sample M134p31/06.
lithology and geochemical data, the rock assemblage of the Khantaishir ophiolite in its type section was interpreted as a supra-subduction island arc complex (Zonenshain & Kuzmin, 1978; Khain et al., 2003). In the section of the Khantaishir ophiolite nappe studied here, it is represented by rocks of the southeastern Erdene Mountain piedmont where serpentinized peridotites, a tonalite-trondhjemite suite, and abundant tholeiitic to calc-alkaline mafic to intermediate volcanic rocks were interpreted as an arc assemblage (Hanžl & Aichler, 2007).

This tectonic sequence shows a number of similarities with Tethyan-type ophiolites, which may be best exemplified by the Oman ophiolitic sequence, such as: similar ages for the ophiolites (c. 570 Ma) and the high-pressure rocks (c. 540 Ma), the presence of an amphibolite sole underneath peridotite (southern peridotite sheet and associated amphibolites) and metamorphic units exhibiting different pressure histories (northern eclogitic and southern non-eclogitic part of the wedge). The Tethyan model implies subduction of an oceanic domain together with a continental margin, forming eclogites and high-pressure metapelites, and thrusting of these units back over the continent, which is then followed shortly after by thrusting of an ophiolite unit over the continental margin units (Goffe et al., 1988; Yamato et al., 2007; Agard et al., 2009). Based on the Tethyan ophiolite analogue, it is possible that the exhumation of the eclogite bearing Tsakhir Uul accretionary wedge and emplacement of the Khantaishir ophiolitic nappe are quasi-synchronous processes (Montigny et al., 1988).

**P–T gradients and age of metamorphism of the CAOB high-pressure rocks**

There are three major regions in the CAOB containing blueschist and eclogite bearing sequences of Mesoproterozoic and Early Palaeozoic age. The westerly Kokchetav subduction–collision zone (Kazakhstan) is characterized by the presence of diamond (40–70 kbar, 1000–1200 °C, in the Kumdy-Kol and Barchi units) and coesite (30 kbar, 700 °C, in the Kulet unit) in gneisses and eclogites, and records an exceptionally steep P–T gradient of 6–7 °C km⁻¹ (see Dobretsov et al., 2006; for review; Fig. 14). The formation of ultra high pressure and high pressure rocks in the Kokchetav subduction–collision zone is interpreted as a result of subduction of the Palaeo-Asian Ocean lithosphere and blocks of continental crust underneath the Ediacaran to Early Cambrian island arc system at c. 535 Ma. The high-pressure rocks have been exhumed at c. 528 Ma to mid-crustal depths and reached the base of the accretionary wedge. Subsequently, the subduction zone sequences were interleaved with micaschists, mylonites and schists, forming together the Kokchetav subduction–collision zone. The second area of high-pressure rocks is represented by numerous occurrences of blueschists and eclogites in the Gorny and Rudny Altai and in northern Mongolia, where protoliths have common Normal Mid-Ocean Ridge Basalt (N-MORB) tholeiitic chemistry (Volkova & Sklyarov, 2007). These rocks are represented by thrust slices associated with mélangé zones and common olistostromes containing blueschist blocks with P–T conditions of 6–9 kbar and 380–520 °C (Fig. 14), and ophiolite slices, for example in the Oka and the Kurtushiba units from the Sayan mountains, the Uimon unit from the Gorny Altai mountains and the Huegyn unit from the north Mongolia (Volkova & Sklyarov, 2007). Less common eclogite blocks are contained in a serpentinite mélange and show P–T conditions of 15–20 kbar and 660–770 °C in the Chagan-Uzun unit from the Gorny Altai or in the Chara unit from the NE Kazakhstan (Fig. 14) (Volkova & Sklyarov, 2007). These high-pressure rocks are characterized by warmer P–T gradients of ~8–20 °C km⁻¹ compared to the colder Kokchetav subduction zone (Fig. 14). Geochronological data show that the subduction started at 700 Ma with formation of eclogites at c. 650–630 Ma (Sm–Nd ages, Buslov et al., 2001) and exhumation and cooling at c. 535 Ma (K–Ar ages, Buslov & Watanabe, 1996). In the Gorny Altai, separate basins were closed during the Ordovician as shown by numerous ⁴⁰Ar–³⁹Ar ages on phengite and Na-amphibole (Volkova et al., 2005). The blueschists are interpreted to result from
subduction of an oceanic plate beneath an island arc in an intraoceanic fore-arc environment (Volkova & Sklyarov, 2007).

The Tsakhir Uul accretionary wedge shows remarkable lithological similarity with typical Gorny Altai blueschist bearing units that are composed of siliceous rocks, carbonate rocks and N-MORB basalts (the Uimon unit in the Gorny Altai and the Chara unit in the Rudny Altai). Recorded $P$–$T$ conditions of $\sim 21$ kbar and $600 ^\circ C$ and mineral assemblage of the Tsakhir Uul eclogites are similar to eclogites associated with serpentinite mélanges of the Gorny Altai and plot on a $P$–$T$ gradient of $\sim 8 ^\circ C \ km^{-1}$ (Fig. 14). These data suggest that the Tsakhir Uul accretionary wedge eclogites originated by subduction of a young and ‘warm’ oceanic crust (Volkova et al., 2005). It is suggested that the eclogites of the SW Mongolia are connected to the same closure of small oceanic basins typical for the Gorny Altai subduction system, while the major subduction system operated to the west in the region of Kokchetav subduction–collision zone. The $\text{^{40}Ar/^{39}Ar}$ cooling ages of c. 540 Ma reported in this study show that the Tsakhir Uul accretionary wedge was cooled earlier than the Gorny Altai-Mongolian blueschists but at the same time as some eclogites of the Gorny Altai accretionary complex (Buslov & Watanabe, 1996) and at the same time as the high-pressure rocks of the Kokchetav subduction system. The true age of eclogites facies metamorphism remains presently unknown but we speculate that it is not older than the c. 570 Ma age of type locality of the Khantaishir ophiolite close to Altai city (Gibsher et al., 2001). This is also the Ar–Ar cooling age of muscovite from a greenschist facies orthogneiss basement underlying the Tsakhir Uul eclogite and Khan-taishir ophiolite nappe pile (Lehmann et al., 2010).

**Palaeo-Asian Oceanic suture in Mongolia**

Our study shows that the eclogites from SW Mongolia show geochemical, structural and $P$–$T$ affinity to the Gorny Altai blueschist and eclogite belts. These belts are aligned along the Tuva Mongol continental fragment in the Gorny Altai. However, so far no high-pressure rocks were reported to occur along the Dzabkhan-Baydrag continental block. The discovery of the Tsakhir Uul eclogites thus represents an important finding suggesting extension of the Early Cambrian subduction system far to the east in the region where it was not expected (Zonenshain, 1973). The lithological character of the accretionary wedge associated with ophiolites, the chemistry of the eclogite protoliths and the cooling ages of the Tsakhir Uul accretionary wedge indicate the existence of a subduction system rimming both the Dzabkhan and the Tuva Mongol continental blocks and filling a gap in knowledge of the extension of the Proterozoic to the Cambrian Palaeo-Asian Ocean in the eastern part of the CAOB. Coeval exhumation of the Tsakhir Uul accretionary wedge and the Kokchetav high-pressure rocks may indicate a common tectonic evolution of the eastern and western terminations of the Palaeo-Asian Ocean in the Early Cambrian.

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**REFERENCES**

Agard, P., Yamato, P., Jolivet, L. & Burov, E., 2009. Exhumation of oceanic blueschists and eclogites in subduction zones: timing and mechanisms. *Earth-Science Reviews*, 92, 53–79.

Badarch, G., Cunningham, C.W. & 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.

Baldwin, J.A., Powell, R., Williams, M.L. & Goncalves, P., 2007. Formation of eclogite, and reaction during exhumation to mid-crustal levels, Snowbird tectonic zone, western Canadian Shield. *Journal of Metamorphic Geology*, 25, 953–974.

Buslov, M.M. & Watanabe, T., 1996. Intrasubduction collision and its role in the evolution of an accretionary wedge: the Kurai Zone of Gorny Altai (Central Asia). *Geologiya i Geofizika (Russian Geology and Geophysics)*, 37, 82–93 (74–84).

Buslov, M.M., Saphonova, I.V., Watanabe, T. et al., 2001. Evolution of the Paleo-Asian Ocean (Altai-Sayan Region, Central Asia) and collision of possible Gondwana-derived terranes with the southern marginal part of the Siberian continent. *Journal of Asian Earth Sciences*, 3, 203–224.

Coggon, R. & Holland, T.J.B., 2002. Mixing properties of phengitic micas and revised garnet-phengite thermobarometers. *Journal of Metamorphic Geology*, 20, 683–696.

Dale, J., Powell, R., White, R.W., Elmer, F.L. & Holland, T.J.B., 2005. A thermodynamic model for Ca-Na clinopyroxenes and clinopyroxene Na$_2$O-CaO-MgO-Al$_2$O$_3$-SiO$_2$-H$_2$O-O for petrological calculations. *Journal of Metamorphic Geology*, 23, 771–791.

De Boisgrollier, T., Petit, C., Fournier, M. et al., 2009. Palaeozoic orogeneses around the Siberian craton: structure and evolution of the Patom belt and foredeep. *Tectonics*, 28, 18.

Diener, J.F.A., Powell, R., White, R.W. & Holland, T.J.B., 2007. A new thermodynamic model for clinopyroxene and orthopyroxene in the system Na$_2$O-CaO-FeO-MgO-Al$_2$O$_3$-SiO$_2$-H$_2$O-O. *Journal of Metamorphic Geology*, 25, 631–656.

Diener, J.F.A., White, R.W. & Powell, R., 2008. Granulite facies metamorphism and subsoluid fluid-absent reworking, Strangways Range, Arunta Block, central Australia. *Journal of Metamorphic Geology*, 26, 603–622.

Dijkstra, A.H., Brouwer, F.M., Cunningham, W.D., Buchan, C., Badarch, G. & Mason, P.R.D., 2006. Late Neo-protorozoic proto-arc ocean crust in the Dariv Range, Western Mongolia: a supra-subduction zone end-member ophiolite. *Journal of the Geological Society*, 163, 363–373.

Dobretsov, N.L., Buslov, M.M., Zhimulev, F.I., Travin, A.V. & Zayachkovsky, A.A., 2006. Vendian-Early Ordovician
geodynamic evolution and model for exhumation of ultrahigh and high-pressure rocks from the Kokchetav subduction-collision zone (northern Kazakhstan). *Russian Geology and Geophysics*, **47**, 424–440.

Geist, D., Howard, K.A. & Larson, P., 1995. The generation of oceanic melts by crystal fractionation – the basalt – rhyolite association at volcano-Alcedo, Galapagos archipelago. *Journal of Petrology*, **36**, 965–982.

Gibsher, A.S., Khain, E.V., Kotov, A.B., et al., 2001. Late Vendian age of the Han-Taishiri ophiolite complex in western Mongolia. *Russian Geology and Geophysics*, **42**, 1110–1117.

Goff, H., Michard, A., Kienast, J.R. & Lemer, O., 1988. A case of obduction-related high-pressure, low-temperature metamorphism in upper crustal nappes, Arabian continental margin, Oman. P-T paths and kinematic interpretation. *Tectonophysics*, **151**, 363–386.

Green, E., Holland, T. & Powell, R., 2007. An order-disorder model for omphacite pyroxenes in the system jadeite-diopside-hedenbergite-actinolite, with applications to eclogitic rocks. *American Mineralogist*, **92**, 1181–1189.

Hanzl, P. & Aichler, J., 2007. *Geological Survey of the Mongolian Altay at a Scale 1:50,000* (Zamyn nura – 50). Final Report, Czech Geological Survey, Prague, Czech Republic, 389 pp.

Holland, T.J.B. & Powell, R., 1998. An internally consistent thermodynamic data set for phases of petrological interest. *Journal of Metamorphic Geology*, **16**, 309–343.

Holland, T.J.B. & Powell, R., 2003. Activity-composition relations for phases in petrological calculations: an asymmetric multicomponent formulation. *Contributions to Mineralogy and Petrology*, **145**, 492–501.

Holland, T.J.B., Baker, J. & Powell, R., 1998. Mixing properties and activity-composition relationships of chlorites in the system MgO-FeO-Al2O3-SiO2-H2O. *European Journal of Mineralogy*, **10**, 395–406.

Hrdlicková, K., Bolormaa, K., Burianek, D., Hanžl, P., Gerdes, A. & Janoušek, V., 2008. Petrology and age of metamorphosed rocks in tectonic slices inside the Palaeozoic sediments of the eastern Mongolian Altay, SW Mongolia. *Journal of Geosciences*, **53**, 139–165.

Jahn, B.M., Litvinovsky, B.A., Zanvilevich, A.N. & Reichow, M., 2009. Peralkaline granitoid magmatism in the Mongolian-Okhotsk orogenic belt. *Geology of the Pacific Ocean*, **16**, 797–800.

Jahn, B.M., Litvinovsky, B.A., Zanvilevich, A.N. & Reichow, M., 2009. Peralkaline granitoid magmatism in the Mongolian-Okhotsk orogenic belt. *Geology of the Pacific Ocean*, **16**, 797–800.

Janoušek, V., Farrow, C.M. & Erban, V., 2007. The generation of oceanic melts by crystal fractionation – the basalt – rhyolite association at volcano-Alcedo, Galapagos archipelago. *Journal of Petrology*, **36**, 965–982.

Khain, E.V., Bibikova, E.V., Kotov, A.B., et al., 2001. Late Vendian age of the Han-Taishiri ophiolite complex in western Mongolia. *Russian Geology and Geophysics*, **42**, 1110–1117.

Kovalenko, V.I., Pukhtel, I.S., Yarmolyuk, V.V., Zhuravlev, G.M., Litvinovsky, B.A., Zanvilevich, A.N. & Reichow, M., 2001. New zircon ages and significance for Rodinia Supercontinent: Evidence From South Siberia (ed. Kozakov, I.K.), pp. 142–145. Guidebook and Abstract Volume, Workshop IGCP-440, Irkutsk.

Kuzmin, V.I., Pukhtel, I.S., Yarmolyuk, V.V., Zhuravlev, G.M., Litvinovsky, B.A., Zanvilevich, A.N. & Reichow, M., 2001. New zircon ages and significance for Rodinia Supercontinent: Evidence From South Siberia (ed. Kozakov, I.K.), pp. 142–145. Guidebook and Abstract Volume, Workshop IGCP-440, Irkutsk.

Lehmann, J., Schulmann, K., Léxa, O. et al., 2010. Structural constraints on the evolution of the Central Asian Orogenic Belt in Southern Mongolia. *American Journal of Science*, (in press).

Markova, N.G., 1975. Stratigraphy of the Lower and Middle Paleozoic of Western Mongolia. *Transactions of Joint Soviet-Mongolian Scientific Research Geological Expedition*, Vol. 12. Nauka Press, Moscow, 119 pp. (in Russian).

Montigny, R., Lemer, O., Thuitaz, R. & Whitechurch, H., 1988. K-Ar and Ar-40/Ar-39 study of metamorphic rocks associated with the Oman ophiolite – tectonic implications. *Tectonophysics*, **151**, 345–362.

Mossakovsky, R.A., Samygin, S.G. & Kherskova, T.N., 1993. Central Asian fold belt: geodynamic history and evolution of formations. *Geotectonics*, **6**, 3–33.

Parfenov, L.M., Popeko, L.I. & Tomurtogoo, O., 2001. Problems of tectonics of the Mongol-Okhotsk orogenic belt. *Geology of the Pacific Ocean*, **16**, 797–800.

Parfenov, L.M., Khanchuk, A.I., Badarch, G. et al., 2004. NE Asia Geodynamics Map at a scale of 1:5,000,000. In: *Digital Files for Northeast Asia Geodynamics, Mineral Deposit Location Maps, and Metamorphic Belt Maps, Stratigraphic Columns, Descriptions of Map Units, and Descriptions of Metamorphic Belts* (eds Nokleberg, W.J., Badarch, G., Berzin, N.A., Diggles, M.F., Hwang, D.H., Khanchuk, A.I., Miller, R.J., Naumova, V.V., Oblenskii, A.A., Ogasawara, M., Parfenov, L.M., Prokopiev, A.V., Rodionov, S.M. & Yan, H.), U.S. Geological Survey Open-File Report 2004-1252, Version 1.0. http://pubs.usgs.gov/of/2004/1252/.

Pländer, J.A., Jochum, K.P., Kröner, A., Kazakov, I., Oidup, C. & Todt, W., 1998. Age and geochemical evolution of an early Cambrian ophiolite-island arc system in Tuva, South Central Asia. *Geological Survey of Finland, Special Paper*, **26**, 42 pp.

Powell, R., Holland, T. & Worley, B., 1998. Calculating phase diagrams involving solid solutions via non-linear equations, with examples using THERMOCALC. *Journal of Metamorphic Geology*, **16**, 577–589.

Rauzer, A.A., Zhanchiv, D.I., Golyakov, V.I. et al., 1991. Comparison of *Rauzer, A.A., Zhanchiv, D.I., Golyakov, V.I. et al., 1991. Comparison of* 

Ruzhentsev, S.V. & Pospelov, I.I., 1992. The South Mongolian Variscan belt. *Geological Survey of Finland, Special Paper*, **26**, 329–358.

Ruzhentsev, S.V., 2001. The Variscan belt of south Mongolia. *Tectonics, Magmatism, and Metallogeny of Mongolia* (ed. Dergunov, A.B.), pp. 61–94. Routledge, London.

Ruzhentsev, S.V. & Pospelov, I.I., 1992. The South Mongolian Variscan belt. *American Journal of Science*, (in press).

Šengör, A.M.C. & Natal’ in, B.A., 1996. Paleotectonics of Asia: fragments of a synthesis. In: *The Tectonic Evolution of Asia* (ed. Rubey Colloquium), pp. 486–640. Cambridge University Press, Cambridge.

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Çengör, A.M.C., Natal’in, B.A. & Burtman, V.S., 1993. Evolution of the Altai tectonic collage and Paleozoic crustal growth in Eurasia. Nature, 364, 299–307.

Sklyarov, E.V., 2006. Exhumation of metamorphic complexes: basic mechanisms. Russian Geology and Geophysics (Geologiya i Geofizika), 47, 68–72.

Sklyarov, E.V. & Postnikov, A.A., 1990. Hugeyn high-pressure belt of Northern Mongolia. Doklady AN SSSR, 315, 950–954.

Steiger, R.H. & Jäger, E., 1977. Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology. Earth and Planetary Science Letters, 36, 359–362.

Štípska, P. & Powell, R., 2005. Constraining the P-T path of a MORB-type eclogite using pseudosections, garnet zoning and garnet-chloropyroxene thermometry: an example from the Bohemian Massif. Journal of Metamorphic Geology, 23, 725–743.

Štípska, P., Pitra, P. & Powell, R., 2006. Separate or shared metamorphic histories of eclogites and surrounding rocks? An example from the Bohemian Massif. Journal of Metamorphic Geology, 24, 219–240.

Sun, S.S. & McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Magmatism in the Ocean Basins (eds Saunders, A.D. & Norry, M.J.), pp. 313–345. Geological Society Special Publication, 42.

Tomurtogoo, O., 1997. A new tectonic scheme of the Paleozoïdes in Mongolia. Mongolian Geoscientist, 3, 12–17.

Turner, G., Hjñeke, J.C., Podosek, F.A. & Wasserburg, G.J., 1971. 40Ar/39Ar ages and cosmic ray exposure ages of Apollo 14 samples. Earth and Planetary Science Letters, 12, 19–35.

Uchio, Y., Isozaki, Y., Ota, T., Usunomiyà, A., Buslov, M.M. & Maruyama, S., 2004. The oldest mid-oceanic carbonate buildup complex: setting and lithofacies of the Vendian (Late Neoproterozoic) Baratal limestone in the Gorny Altai Mountains, Siberia. Proceedings of the Japan Academy Series B: Physical and Biological Sciences, 80, 422.

Volkova, N.I. & Sklyarov, E.V., 2007. High-pressure complexes of Central Asian Fold Belt: geologic setting, geochemistry, and geodynamic implications. Russian Geology and Geophysics, 48, 83–90.

Volkova, N.I., Stupakov, S.I., Tret’ yakov, G.A., Simonov, V.A., Travin, A.V. & Yudin, D.S., 2005. Blueschists from the Uimon zone as evidence for Ordovician accretionary-collisional events in Gorny Altai. Geologiya i Geofizika (Russian Geology and Geophysics), 46, 367–382. (361–378).

White, R.W., Powell, R., Holland, T.J.B. & Worley, B.A., 2000. The effect of TiO2 and Fe2O3 on metapelitic assemblages at greenschist and amphibolite facies conditions: mineral equilibria calculations in the system K2O-FeO-MgO-Al2O3-SiO2-H2O-TiO2-Fe2O3. Journal of Metamorphic Geology, 18, 497–511.

White, R.W., Powell, R. & Holland, T.J.B., 2007. Progress relating to calculation of partial melting equilibria for metapelites. Journal of Metamorphic Geology, 25, 511–527.

Windley, B.F., Alexeev, D., Xiao, W., Kroner, A. & Badarch, G., 2007. Tectonic models for accretion of the Central Asian Orogenic Belt. Journal of the Geological Society, 164, 31–47.

Xiao, W.J., Zhang, L.C., Qin, K.Z., Sun, S. & Li, J.L., 2004. Paleozoic accretionary and collisional tectonics of the Eastern Tianshan (China): implications for the continental growth of central Asia. American Journal of Science, 304, 370.

Xiao, W., Han, C., Yuan, C. et al., 2008. Middle Cambrian to Permian subduction-related accretionary orogenesis of Northern Xinjiang, NW China: implications for the tectonic evolution of central Asia. Journal of Asian Earth Sciences, 32, 102–117.

Xiao, W.J., Windley, B.F., Yuan, C. et al., 2009. Paleozoic multiple subduction-accretion processes of the southern Altaiids. American Journal of Science, 309, 221–270.

Yamato, P., Acard, P., Cofﬁe, B., De Andrade, V., Vidal, O. & Jolivet, L., 2007. New, high-precision P-T estimates for Oman blueschists: implications for obduction, nappe stacking and exhumation processes. Journal of Metamorphic Geology, 25, 657–682.

Zonenshain, L.P., 1973. The evolution of Central Asiatic geosynclines through sea-floor spreading. Tectonophysics, 19, 213–232.

Zonenshain, L.P. & Kuzmin, M.I., 1978. Khantaishir ophiolite complex in western Mongolia and ophiolite problem. Geotectonics, 1, 19–42.

Zonenshain, L.P., Kuzmin, M.I. & Moralev, V.M., 1976. Global Tectonics, Magmatism and Metallogeny. Nedra, Moscow (in Russian).

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