Zircon age and occurrence of the Adaatsag ophiolite and Muron shear zone, central Mongolia: constraints on the evolution of the Mongol–Okhotsk ocean, suture and orogen

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Abstract: The Adaatsag ophiolite in eastern Mongolia is situated in the Mongol–Okhotsk suture zone, which extends from central Mongolia through Transbaikalia to the Sea of Okhotsk and separates the Siberian and Amurian (Mongolian) plates. The ophiolite sequence passes upwards from serpentinite mélangé and serpentinitized dunite and harzburgite, through layered gabbro (with leucogabbro pegmatite dykes), wehrlite and clinopyroxenite, to isotropic gabbro and leucogabbro, sheeted mafic dykes, and olivine-rich basaltic lavas, overlain by red chert and meta-clastic sediments. A single-zircon mean 207Pb/206Pb evaporation age of 325.4 ± 1.1 Ma for a leucogabbro pegmatite dyke records the time of igneous crystallization of the plutonic suite, and thus the time of formation of oceanic crust in the Mongol–Okhotsk ocean that gave rise to the ophiolite. A U–Pb secondary ionization mass spectrometry (SIMS) and evaporation zircon age of 172 Ma for a mylonitized granite provides a maximum age for the left-lateral Muron shear zone, which occurs close to the left-lateral Mongol–Okhotsk suture, and indicates that the suture in eastern Mongolia formed at least by the mid-Jurassic. We review the evidence and models for subduction tectonics that gave rise to major calc-alkaline batholiths along active continental margins of the bordering plates and to extensive, post-collisional, alkaline to peralkaline magmatism. Whereas the magmatic history of the orogen is better known, the age of the ocean, and the time of formation and deformation of the suture zone are not. Our new data on the Adaatsag ophiolite and Muron shear zone provide key constraints on the early and late stages of development of the Mongol–Okhotsk ocean and orogen.

Keywords: Mongolia, Adaatsag ophiolite, Muron shear zone, orogenic belts, absolute age.

The long-lived Palaeo-Asian ocean began to form near Lake Baikal in Siberia by at least 1000 Ma (Khain et al. 2002) and terminated in Inner Mongolia, northern China, in the Permian (Xiao et al. 2003). There appears to be a remarkable and consistent decrease in ophiolite ages from north (near the margin of the Siberian craton) to south (near the margin of the North China craton), consistent with the idea that the Central Asian Orogenic Belt formed by accretion from north to south (present coordinates) (Sengör et al. 1993). However, a triangular remnant embayment of the Palaeo-Pacific remained in eastern Asia in the mid–late Palaeozoic (Zorin et al. 1998; Zorin 1999) and is known as the Mongol–Okhotsk ocean. Sengör et al. (1993) termed it the Khangay-Khetey ocean and Scotese (2001) the Amurian Seaway. Closure of the ocean gave rise to the Mongol–Okhotsk suture zone, which extends for about 3000 km from the present-day Sea of Okhotsk southwestwards as far as central Mongolia between the Siberian and Amurian (Mongolian) continents (Fig. 1), and led to the bordering Mongol–Okhotsk orogen (Fig. 2) that formed in the late Palaeozoic to mid–late Mesozoic (Zonenshain et al. 1990; Parfenov et al. 2001). Undated glauconophe schists in the suture zone in Transbaikalia confirm the operation of subduction processes (Dobretsov et al. 1989).

Because of the paucity of structural studies and isotopic data the age of the Mongol–Okhotsk ocean and the time of formation of the suture zone and of the Mongol–Okhotsk orogen are poorly known. The aim of this paper is to present new geological information and zircon ages to help constrain the early and late stages in the development of this ocean and orogen.

Previous studies and geological setting

It has been difficult to constrain the age of formation of the Mongol–Okhotsk ocean. Sengör et al. (1993) suggested that it existed since the Vendian (610–570 Ma) to Cambrian (Harland et al. 1989) and therefore considered that a large part of the Mongol–Okhotsk orogen formed during accretion of the Neoproterozoic to Palaeozoic Altai orogen, and the Central Asian Orogenic Belt (Jahn et al. 2000; Badarch et al. 2002). The history of the ocean margins was traced back to the Devonian by Zorin (1999) and to the latest Neoproterozoic and Cambrian by Parfenov et al. (2001). Palaeomagnetic (Zhao et al. 1990; Enkin et al. 1992; Pruner 1992; Scotese 2001) and palaeobiogeographical data (Nie et al. 1990) provide information back to only the Permian.

The suture zone contains the Adaatsag ophiolite in eastern Mongolia and the Onon island arc associated with Devonian–Carboniferous marine turbidites in Siberia (Fig. 2) (Zorin 1999). The presence in Mongolia of late Permian to early Triassic fossiliferous marine sediments in the suture zone confirms the existence of marine conditions at these times (Kovalenko et al. 1995). Radiolaria NE of Adaatsag were identified in 2001 as late
Permian in age (I. Remkina, pers. comm., on samples provided by O. Tomurtogoo).

The suture zone is bordered on both sides by abundant calc-alkaline to peralkaline plutons and lavas that extend from central Mongolia to the Sea of Okhotsk (Fig. 2). Fersman (1926) first outlined the vast belt related to Mesozoic magmatism and mineralization, which is about 3000 km long and 1000 km wide and contains over 900 granitic intrusions that occupy over 150,000 km² or nearly 10% of the entire belt (Kovaleno et al. 1999). Kovalenko et al. (1995) documented in detail the magmatic rocks and mineralization of the belt. The tectonic and magmatic events developed during two main phases at 250–170 Ma and 170–100 Ma (Kovalenko et al. 1995; Koval et al. 1999; Koval 2003). Geological relationships suggest that two continental margin magmatic arcs formed as a result of subduction to the NW and SE (present coordinates) during closure of the ocean. Kovalenko et al. (1995, fig. 35) showed how the two Triassic–early Jurassic, Andean-type, volcanic and plutonic belts closed symmetrically and joined each other to the west at longitude c. 102° forming a half-circle centred on the suture zone. The inner volcanic rocks are predominantly calc-alkaline basalts that are bordered by sub-alkaline basalts in the outer zone. Correspondingly, the inner plutonic complexes are dominated by calc-alkaline granites and granodiorites, and the outer ones by alkaline granites.

The fact that the intrusions young from west to east along the line of the suture suggests that the ocean closed in a scissor-like movement from the late Carboniferous–Permian in central Mongolia, to Triassic–early Jurassic in southwestern Transbaikalia, late Jurassic in NE Transbaikalia and Cretaceous in the Amur province (Fig. 2) (Kravchinsky et al. 2002). There is disagreement about the closure time: according to Zonenshain et al. (1990) and Sengör & Natal’in (1996), the Mongol–Okhotsk ocean closed in the Triassic in the west (Mongolia) and in the late Jurassic in the east (Amur). However, Enkin et al. (1992) and Scotese (2001) concluded from palaeomagnetic results that the ocean was still open in the late Jurassic and closed only in...
the early Cretaceous. From geophysical and geological data Zorin (1999) suggested that it closed at the early–mid-Jurassic boundary. With new palaeomagnetic data Kravchinsky et al. (2002) concluded that the ocean closed largely during the Jurassic, with final closure at its eastern end in the late Jurassic to earliest Cretaceous.

Identifying the many metalogenic zones associated with the Mongol–Okhotsk belt, Obolenskiy et al. (1999) distinguished two main ages of mineralization: late Jurassic related to granitoid magmatism (Sn–W, Ta–Nb–Li, Cu–Mo, Au), and early Cretaceous volcano-hydrothermal (Sb–Hg, U, CaF₂). Gordienko & Kuz’mín (1999) reported commercial Mo and W deposits localized in Permian leucogranites and granites. The highest concentration of gold occurrences in Transbaikalia is in the Mongol–Okhotsk suture (Zorin et al. 1998). Yakubchuk & Edwards (1999) pointed out that gold mineralization in the eastern section of the suture is concentrated in black shales within accretionary wedges, auriferous sulphides being remobilized by metamorphism associated with thrusting during the period 425–380 Ma. Mineralization associated with Mesozoic granitic intrusions and lavas is documented in a database in Irkutsk and records the ore potential of this major metallogenic Mongol–Okhotsk belt (Koval et al. 1999). Gusev & Khain (1996) outlined a possible geodynamic evolution of the orogen.

The Adaatsag ophiolite

Adaatsag is situated some 180 km SSW of Ulaanbaatar (Fig. 1) on the Mongol–Okhotsk suture. The ophiolite has a complete stratigraphy, according to the definition of Anonymous (1972), that from bottom to top is as follows. The lowermost rocks are serpentinized dunite and harzburgite, which are best exposed in the NE of the ophiolite (Fig. 3). Similar rocks occur as separate blocks in a serpentinite mélangé in the east. The cumulate sequence is represented by interlayered clinopyroxenite, wehrlite and pegmatitic layered gabbro. Leucogabbro pegmatite dykes (our dated sample NM 53) up to 2 m wide occur within the layered gabbro (Figs. 3 and 4). Ultramafic rocks were found as lensoid roof pendants in a granitic pluton 2 km NNE of the sample locality. In the main outcrop of the ophiolite, layered gabbro is overlain by isotropic hornblende gabbro that passes upwards into leucogabbro that contains rare lenses of plagiogranite. Hornblende-bearing leucogabbro pegmatite dykes reach 2 m in width. The upper isotropic gabbro contains fresh clinopyroxene, many ductile shear zones, up to 2 m wide plagiograniyte dykes and sills and dykes of amygdaloidal, plagioclase- and olivine-phyric dolerite, which increase in abundance upwards until they reach 100% and constitute a sheeted dyke complex. The sheeted dykes are up to 2 m wide, mostly strike between...
010° and 030°, and have local screens of gabbro and harzburgite. These dykes are overlain by variolitic, plagioclase- and olivine-phryic basaltic lavas that reach about 300 m in thickness.

Oceanic sediments on top of the basalts crop out on the northern margin of the ophiolite. According to Safronov & Ivliev (1999), the sediments have the following stratigraphy (from bottom to top): red chert, siliceous arkose sandstone, hydrothermal sediments enriched in Fe₂O₃ (17.8–22.8%), MnO (0.6–1.5%) and P₂O₅ (1.6–2.5%), high-titanium schists containing mica–carbonate–plagioclase and quartz–mica–carbonate–plagioclase, and sericite–quartz–plagioclase schists enriched in alkalis. We interpret these sediments to represent a lateral progression from deep ocean floor where cherts were deposited to a trench that received clastic material from a continent or arc. These sediments are overlain by greenschist-facies, calc-alkaline basalt, andesite and dacite, which probably represent an island arc developed on the Adaatag ocean floor. The arc rocks are overlain by 20 m thick, mid-Carboniferous sediments rich in Bryozoa, which provide a minimum age constraint for the ophiolite.

On its southern side the Adaatag ophiolite was thrust over marine fossiliferous Carboniferous sandstones and siltstones, and there are subaerial, continental lavas associated with giant-crystal porphyry dykes of presumed Permian age that we interpret to have formed in an intra-continental rift.

The Muron shear zone

About 320 km east of Ulaanbaatar and 50 km NNE of the Muron River (Fig. 1) a batholith of coarse homogeneous porphyritic biotite granite contains layers and lenses of biotite schist, has K-feldspar phenocrysts, locally garnet, and garnet-bearing aplite and pegmatite layers and veins. At 47°51′N, 110°32′E the granite is cut by a 400 m wide mylonitic shear zone with an internal foliation striking east–west and dipping c. 35°S. A strong pervasive stretching lineation on shear zone foliation surfaces dips consistently about 10°W. Sigmoidal feldspar–quartz lenses and rotated K-feldspar phenocrysts on surfaces perpendicular to the lineation define a left-lateral sense of movement, indicating that overall this is a left-lateral shear zone. Granitic mylonite sample MO 01/98 was collected near the middle of this shear zone (Fig. 2).

Analytical procedures, geochemistry and zircon ages

Whole-rock powders and heavy mineral separates of leucogabbro pegmatite sample NM 53 and mylonitized granite sample MO 01/98 were prepared in the laboratory of the Mongolian Ministry of Mines and Energy, Ulaanbaatar. Zircons were then concentrated at Mainz University, using a Frantz magnetic separator and heavy liquids, and were hand-picked for isotopic analysis during optical inspection under a binocular microscope.

Major oxides and trace elements were determined on whole-rock fused glass discs and powder pellets, respectively, using a Phillips PW 1404 X-ray fluorescence spectrometer at Mainz University. Analytical details have been given by Laskowski & Kröner (1985). Loss on ignition (LOI) was determined after heating to 1050°C, and Table 1 shows the geochemical data.

Table 1. Chemical composition of dated samples NM 53 and MO 01/98

|       | NM 53  | MO 01/98 |
|-------|--------|----------|
| SiO₂  | 57.45  | 71.28    |
| TiO₂  | 0.16   | 0.33     |
| Al₂O₃ | 20.78  | 14.07    |
| Fe₂O₃* | 2.39   | 3.80     |
| MnO   | 0.05   | 0.03     |
| MgO   | 3.75   | 0.37     |
| CaO   | 7.83   | 1.14     |
| Na₂O  | 5.84   | 3.10     |
| K₂O   | 0.16   | 6.02     |
| P₂O₅  | 0.02   | 0.13     |
| LOI   | 1.03   | 0.60     |
| Total | 99.47  | 99.19    |

Mean (2σm) errors. Mean ages

Major elements in wt.%, trace elements in ppm. Fe₂O₃*, total iron given as Fe₂O₃.

Analytical ages and uncertainties are based on the means of all ratios evaluated and their 2σm (2σm) errors. Mean ages and errors for several zircons from the same sample are presented as weighted means of the entire population. In the case of combined datasets the 2σm error may become very low, and whenever this error was less than the reproducibility of the internal standard error we have used the latter value (i.e. an assumed 2σm error of 0.000026).

The analytical data are presented in Table 2, and the 207Pb/206Pb spectra are shown in the histograms of Figure 5 and Figure 6, inset, which permit visual assessment of the data distribution from which the mean ages are derived. The evaporation technique provides only Pb isotopic ratios; consequently, all 207Pb/206Pb ages determined by this method are necessarily minimum ages. However, many studies have demonstrated that there is a very strong likelihood that these data represent true zircon crystallization ages when (1) the 207Pb/206Pb ratio does not change with rising temperature of evaporation and/or (2) repeated analyses of grains from the same sample at high evaporation temperatures yield the same isotopic ratios within error. Comparative studies by evaporation, conventional U–Pb dating, and ion-microprobe analysis have shown this to be correct (Kröner et al. 1991, 2001; Cocherie et al. 1992; Jaekel et al. 1997; Karabinos 1997).

Zircons from mylonitized granite sample MO 01/98 were also analysed on the SHRIMP II ion microprobe of the Chinese Academy of Geological Sciences, Beijing, which has technical specifications identical to those of SHRIMP II at Perth, Australia (De Laeter & Kennedy 1998). Analytical procedures have been described by Compston et al. (1992) and Nelson (1997). The reduced 206Pb/238U ratios were normalized to the Perth Consortium CZ3 standard value of 0.09432, which is equivalent to an age of 564 Ma. The error in the ratio Pb*/U during analysis of all standard zircons during this study was 1.01%. Primary
Sensitivity was about 23 c.p.s. ppm to allow assessment of Pb\(^{+}\)zircon CZ3. Analyses of samples and standards were alternated to follow the method described by Nelson (1997). Common-

\[ \text{Mean age: } 325.4 \pm 1.1 \text{ Ma} \]

Discussion and geological history

The Adaatsag ophiolite provides key information on the Mongol–Okhotsk ocean, but we do not know where it was derived from in this wide ocean. The ophiolite age of 325 Ma demonstrates...
strates that new oceanic crust was being generated in the early Carboniferous. Within the Mongol–Okhotsk suture zone, largely in Russia, is the Onon island arc (Fig. 2) that formed during the Devonian–early Carboniferous (Zorin 1999). Further magmatic development of the arc in the late Permian probably took place in an Andean phase after the arc had accreted to one of the continental margins. From preliminary palaeomagnetic data Kuzmin & Kravchinsky (1996) concluded that the Onon island arc was distant from the Siberian and Amurian continental margins in the late Carboniferous and early Permian.

Passive margin sediments and lavas on the two continental margins of the Mongol–Okhotsk ocean are poorly developed or preserved. They are best seen east of longitude 120°E, where, on the northern margin, shallow marine carbonate sediments of 6000–9000 m thickness range in age intermittently from Cambrian to early Carboniferous (Parfenov et al. 2001). North of Adaatsg, on the northern continental margin, a low-grade carbonate–shale sequence contains Vendian (c. 600 Ma) microphytoliths and early Cambrian algae (Parfenov et al. 2001). In eastern Mongolia late Permian marine sediments with brachiopods, crinoids and Bryozoa and Triassic marine sediments with ammonites occur in the suture zone, indicating that marine conditions existed during these times. On the south side of Adaatsg extensive marine sandstones and siltstones reach a thickness of 1500–2500 m, contain brachiopods, Bryozoa and crinoids of Mississippian age, and are overthrust by serpentinites of the Adaatsg ophiolite. We suggest that these terrigenous sediments were deposited on the southern passive continental margin of the Carboniferous ocean.

Farther west, at c. longitude 100°E, the NW-trending Bayankhongor ophiolite with a Sm–Nd whole-rock formation age of 569 ± 21 Ma (Kepezhinskas et al. 1991) was obducted northwards at c. 540 Ma (Buchan et al. 2002) onto turbiditic sediments, which now are chlorite–muscovite schists and minor marbles, that were deposited on a deep-water passive margin or continental rise (Buchan et al. 2001). The thrust-imbricated ophiolite zone contains minor thrust slices of fossiliferous Carboniferous shallow-water marine limestones and mudstones (Buchan et al. 2001), which were probably deposited on a passive continental margin. Several Russian researchers have considered that the Mongol–Okhotsk suture extends westwards as far as the Bayankhongor ophiolite zone (Zorin 1999). For example, the 100 000 km² Hangay batholith, composed of granodiorites to leucogranites, has conventional multigrain U–Pb zircon ages of 252 ± 3 and 253 ± 2 Ma (Budnikov et al. 1999; Jahn et al. 2004) and contains ilmenite- and magnetite-series granitic rocks that Takahashi et al. (2001) regarded as comparable with arc-related granites in Japan.

The Mongol–Okhotsk suture is bordered on both sides (Fig. 2)
by extensive Carboniferous–Cretaceous volcanic–plutonic belts (Kovalenko et al. 1995; Wickham et al. 1995; Zanvilevich et al. 1995; Litvinovsky et al. 1999). Prominent on the northern side of the suture is the 120 000 km² Angara–Vitim batholith (Fig. 2), which was emplaced at 320–280 Ma (U–Pb and Rb–Sr data of Yarmolyuk et al. 1997; Litvinovsky et al. 2002) and comprises predominantly calc-alkaline biotite–hornblende tonalites, granodiorites and granites generated by subduction-related processes below the active continental margin of Siberia throughout much of the Carboniferous (Zorin 1999; Parfenov et al. 2001). On the southern side of the batholith the contemporaneous mid-Carboniferous to early Triassic Selenga volcano-plutonic belt is 200–300 km wide and extends for 2000 km on the north side of the suture from northern Mongolia (longitude 96°E) to NE Transbaikalia (longitude 122°E) (Figs. 1 and 2). The belt comprises subalkaline andesites, trachyandesites, dacites, rhyolites, trachy-rhyolites, and granodiorites, granites, granosyenites and monzonites, and developed along an active continental margin (Parfenov et al. 2001; Litvinovsky et al. 2002). Calc-alkaline rocks near the suture increase in alkalinity northwards and southwards towards the Siberian and Amurian (Mongolian) continents, respectively (Kovalenko et al. 1995). In the Permian, Triassic and early Jurassic subduction-related, volcanic and plutonic, calc-alkaline magmatic arcs continued to form on the major, northern (west of longitude 122°E) and minor, southern (west of longitude 115°E) sides of the suture (Kovalenko et al. 1995; Zorin 1999) (Fig. 2).

East of about longitude 120°E the calc-alkaline arc is replaced by post-collisional, late Triassic to early Cretaceous A-type magmatic rocks (Fig. 2). Eby (1990, 1992) defined two groups of A-type granites related to specific tectonic environments: A1 granites are differentiates of magmas derived from high-temperature mantle sources like those of oceanic island basalts, but emplaced in either pre-orogenic continental rifts or anorogenic intra-plate rifts. The A2 group is derived from sources chemically similar to those of island arcs or active continental margin basalts and emplaced into continental crust that has been through a cycle of island arc magmatism or continent–continent collision (these two groups will be further considered below).

According to Litvinovsky et al. (2002), formation of the peralkaline–syenite–granite series in Transbaikalia occurred during two discrete phases: in the early Permian (c. 280 Ma) and at the end of the Triassic (220–210 Ma). Near the centre of the Carboniferous–Permian plutonic (granitic) belt on the northern side of the suture at 49°N, 109°E (Fig. 2) the Bryansk complex consists largely of peralkaline syenites and granites that have yielded U–Pb and Rb–Sr emplacement ages of 285–279 Ma (Litvinovsky et al. 2002). Trace element data, the presence of high-temperature melt inclusions in quartz phenocrysts, and ($^{206}$Pb/$^{238}$U) values of ~1.9 to ~3.0 suggest that the magma formed at the base of thickened (up to 60–70 km) continental crust. A magma source containing an older, enriched component may have involved magmatically overthickened Andean-type crust.

New palaeomagnetic data of Kravchinsky et al. (2002) suggest that the Mongol–Okhotsk ocean was as wide as 4700 km in the late Permian and that it closed relatively fast at the end of the Jurassic. Those workers calculated that, if the width of the ocean in the late Jurassic was 2650 km, and if it closed in the period 160–140 Ma, then the average speed of closure was 13.3 cm a⁻¹. As indicated above, the igneous rocks of the Mongol–Okhotsk orogen generally young eastwards from Permian to early Cretaceous (Fig. 2). In the far east of Transbaikalia the ocean closed either in the late Jurassic (Zonenshain et al. 1990; Sengör & Natal’ in 1996) or in post-early Cretaceous times (Halim et al. 1998; Kravchinsky et al. 2002). Accordingly, it is commonly accepted that the ocean closed in a scissor-like fashion from west to east (Zhao et al. 1990; Zonenshain et al. 1990).

This closure involved oblique convergence of the Amurian continent with the Siberian continent, giving rise to left-lateral movements along the suture zone (Parfenov et al. 2001). From their palaeomagnetic data Kravchinsky et al. (2002) concluded that large tectonic rotations around local vertical axes were due to left-lateral shear along the suture zone and the eastward extrusion of Mongolia resulting from the collision of India with Asia. According to Kimura et al. (1990), left-lateral movement on the suture in the early Cretaceous was caused or accentuated by the northward collision of the Indochina block with Eastern Asia, with consequent transient faulting caused by extrusion. Despite all the above work there is still very little information on structures created by the collisional processes. Our zircon age of 172 Ma for molybrite sample MO 01/98 reflects the time of emplacement of the granitic batholith. Therefore, the 400 m wide Muron shear zone is younger, perhaps late Jurassic. The ENE orientation, left-lateral movement pattern, and proximity to the suture zone all suggest that it may be a subsidiary shear zone contemporaneous with movement along the suture.

Van der Voo et al. (1999) postulated a subducted slab of presumed Jurassic age of relatively high seismic velocity descending northwards under the Baikal region to at least 2500 km depth, which they suggested is a remnant of the subducted oceanic lithosphere of the Mongol–Okhotsk ocean. By Permian time, southern and eastern Mongolia had stabilized and underwent a period of rifting, accompanied by bimodal, basalt–peralkaline granite–comenditic magmatism in a mature continental setting (Parfenov et al. 2001). Apatite fission-track ages of 140–100 Ma from the Baikal region were ascribed by Van der Beek et al. (1996) to rapid cooling in the early Cretaceous, contemporaneous with the final closure of the Mongol–Okhotsk ocean and collision of the Siberian and Amurian (Mongolian) cratons.

The mantle plume hypothesis has been applied to the Mongol–Okhotsk orogen in two ways.

(1) Dobretsov (1997), Yarmolyuk et al. (2000, 2001) and Jahn (2002) suggested that the Permo-Triassic granites of the orogen were derived from the Siberian mantle plume or superplume, in particular because of their synchronicity with the Permo-Triassic Siberian continental flood basalts. According to Kovalenko et al. (2004), Yarmolyuk & Kovalenko (2000) concluded that the Permo-Triassic intraplate magmatic activity of the Central Asian Orogenic Belt (which includes the Mongol–Okhotsk granites) was controlled by mantle sources with similar composition to those of the Perman–Triassic Siberian traps. The plume centre of the Siberian basalts is located at a triple junction of continental rifts 300 km west of Noril’sk (Schissel & Smail 2001), which is c. 3000 km NW of Ulaanbaatar (Fig. 1). Dobretsov (1997) proposed a new plume centre near Ulaanbaatar that would be nearer to and responsible for the granites; no data have been forthcoming that support this proposal.

However, the Mongol–Okhotsk granites played an integral part in the continuous evolution of the Carboniferous–Jurassic granites in the orogen. They typically have calc-alkaline chemistry, and are widely regarded as having formed along an active continental margin (Kovalenko et al. 1995; Dergunov 2001; Parfenov et al. 2001, and references therein). Calc-alkaline granites are located closer to the suture, whereas more potassic granites in the continental margin are farther from the suture, a spatial relationship common in many subduction-generated continental margins, such as the Andes (Pitcher et al. 1985). Also,
the Permian A-type syenitic–granitic Bryansky complex in Transbaikalia was derived from a high-temperature silicic magma from the base of thickened (up to 60–70 km) continental crust and underlying mantle, and was generated by remelting and mixing of continental and lithospheric mantle material (Litvinovsky et al. 2002). In our opinion, the Permo-Triassic granites cannot be taken out of their geological context and separated from their temporally related Carboniferous and early Jurassic calc-alkaline granites, and spatially related, contemporaneous, more potassic granites. The Permo-Triassic basalts belong to a plume-generated large igneous province, and the Permo-Triassic granites to a distant subduction-generated, collisional orogen.

(2) As the ocean closed progressively eastwards with time from the Permian to the Jurassic an active continental margin developed especially on the northern side, and alkaline–peralkaline, plutonic and volcanic rocks of intra-plate type including A-type granites evolved particularly in eastern Transbaikalia and Amur (Fig. 1). According to the model of Kovalenko et al. (1995, 2004) and Dergunov (2001), the active continental margin migrated northwards from the Permian to the early Cretaceous and progressively overrode a mid-oceanic ridge of Palaeo-Tethys centred on a sublithospheric mantle plume, a tectonic situation comparable with that in California with respect to the overridden East Pacific Rise, and this led to the intraplate, rift-related magmatism within a Basin-and-Range-type province. For example, Yarmolyuk et al. (1997) suggested that alkaline rocks associated with the calc-alkaline Angara–Vitim batholith require a within-plate, sub-lithospheric, high-temperature heat source of a mantle plume and consequently argued that the continental margin was transported over a mantle plume.

The fundamental point of the model of Kovalenko et al. (1995, 2004), Yarmolyuk et al. (1997), Gordienko & Kuz’min (1999) and Dergunov (2001) is that all post-orogenic and anorogenic alkaline magmatism, including A2-type granites (Eby 1992), requires a high-temperature mantle source, which must be a mantle plume. However, plumes are derived from either the 660 km phase boundary or the 2700 km deep core–mantle boundary. Consideration of the geological history and structure of the Mongol–Okhotsk orogen suggests that the delamination model is applicable for the generation of the abundant post-collisional magmatic rocks.

Conclusions

(1) The Adaatsag ophiolite is situated in east–central Mongolia on the Mongol–Okhotsk suture, which separates the Siberian and Amurian (Mongolian) continents. The ophiolite stratigraphy passes upwards from serpentinite mélange, serpentinized dunite and harzburgite, through layered gabbro, wehlrite and clinopyroxenite, to isotropic gabbro and leucogabbro, sheeted mafic dykes, basaltic lavas, red chert and meta-clastic sediments.

(2) A leucogabbro pegmatite dyke cutting layered gabbro has a mean 206Pb/238U Pb single-zircon evaporation age of 325.4 ± 1.1 Ma, which records the time of igneous crystallization of the leucogabbro, and of that part of the Mongol–Okhotsk ocean that gave rise to the ophiolite.

(3) The major Muron shear zone must post-date the 172 Ma host granitic batholith, dated on single zircons by SHRIMP and evaporation. This constrains the age of formation of the adjacent Mongol–Okhotsk suture zone to at least the mid-Jurassic in eastern Mongolia.

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