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Zircon U–Pb dating of jadeitite from the Syum-Keu ultramafic complex, Polar Urals, Russia: Constraints for subduction initiation

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ABSTRACT

High-pressure, low-temperature metamorphic rocks record subduction of oceanic crust and sediments into the mantle, but the timing of subduction initiation is commonly difficult to determine. However, the appearance of fluid activity in the mantle wedge above a subduction zone can be correlated with incipient subduction. Here we describe jadeitite veins up to 5 m wide, which are hosted in serpentinites of the Syum-Keu ultramafic complex, Polar Urals, Russia. The jadeitites consist of both jadeite (86–88 mol% jd) and omphacite (54–75 mol% jd). Multi-stage growth of the jadeite is indicated by variations in color and structure, such as growth zoning and the distribution of fluid inclusions. We consider that the jadeitite veins formed from Na–Al–Si-rich fluids under HP/LT conditions during active subduction, and that the source material was subducted ocean crust. SHRIMP U–Pb dating of zircons from the jadeitite yielded a concordant weighted mean $^{206}Pb/^{238}U$ age of 404 ± 7 Ma, which we interpret as the age of peridotite serpentinization and jadeitite formation in the suprasubduction zone mantle. This age indicates that subduction was initiated about 40 Ma earlier than peak metamorphism (360–355 Ma) of eclogite in the Polar Urals.

1. Introduction

Jadeitites that contain 90 vol.% jadeite are very rare. They occur only within serpentinite as tectonic enclaves or veins associated with blueschists, eclogites and ophiolites, and are usually considered to be subduction related (e.g., Harlow and Sorensen, 2005; Shi et al., 2008). Thus, these rocks are distributed along orogens where they are associated with remnants of oceanic lithosphere (Shi et al., 2000, 2001; Li and Zhang, 2004; Harlow and Sorensen, 2005).

High-pressure (HP) veins in blueschists and eclogites, which formed by subduction and dehydration of oceanic crust, provide evidence of fluid activity in suprasubduction zones (Gao and Klemd, 2001; Gao et al., 2007; Glodny et al., 2003). The formation of jadeitite in serpentinite is clearly related to fluid-rock interaction in these zones (Johnson and Harlow, 1999; Harlow and Sorensen, 2005; Morishita et al., 2007; Shi et al., 2008). Because the formation of jadeitite is closely related to serpentinization of ultramafic rocks, the timing of jadeitite formation may constrain the timing of serpentinization (Tsujimori et al., 2005; Shi et al., 2008).

In this paper we discuss the occurrence of jadeitite in ultramafic rocks of the Polar Urals, consider the implications of zircon crystallization in the jadeitite and use the zircon ages to constrain the age of serpentinization in the associated subduction zone.

2. Geologic settings

The Urals orogenic belt resulted from closure of the Paleo-Urals ocean, which was situated between the East European and Siberian plates in the Ordovician to Silurian (Savelieva and Nesbitt, 1996; Savelieva et al., 2002). The Polar Urals are the northernmost part of this orogenic belt, where remnants of both the East European plate, and West Siberian plate are preserved. The Polar Urals are subdivided into four tectonic units, labeled A to D from west to east in Fig. 1.

A-West Uralian zone consisting of a mixture of Ordovician to Carboniferous shallow water shelf sedimentary rocks and deeper water turbidites with mafic volcanic rocks. The zone is dominated by strong deformation with westward-directed thrusting onto shallow water continental margin rocks. B-Allochthonous Paleozoic shelf sedimentary rocks and volcanic rocks with greenschist facies metamorphism in the eastern side of the zone. C-Central Uralian zone, where the Precambrian basement of the Urals crops out (Puchkov, 2009). D-Easternmost zone, which is an oceanic lithosphere sequence containing ophiolites with ages ranging from Upper Ordovician to Devonian. This zone contains major outcrops of ultramafic rocks (Syum-Keu, Rai-iz and Voykar), gabbros and

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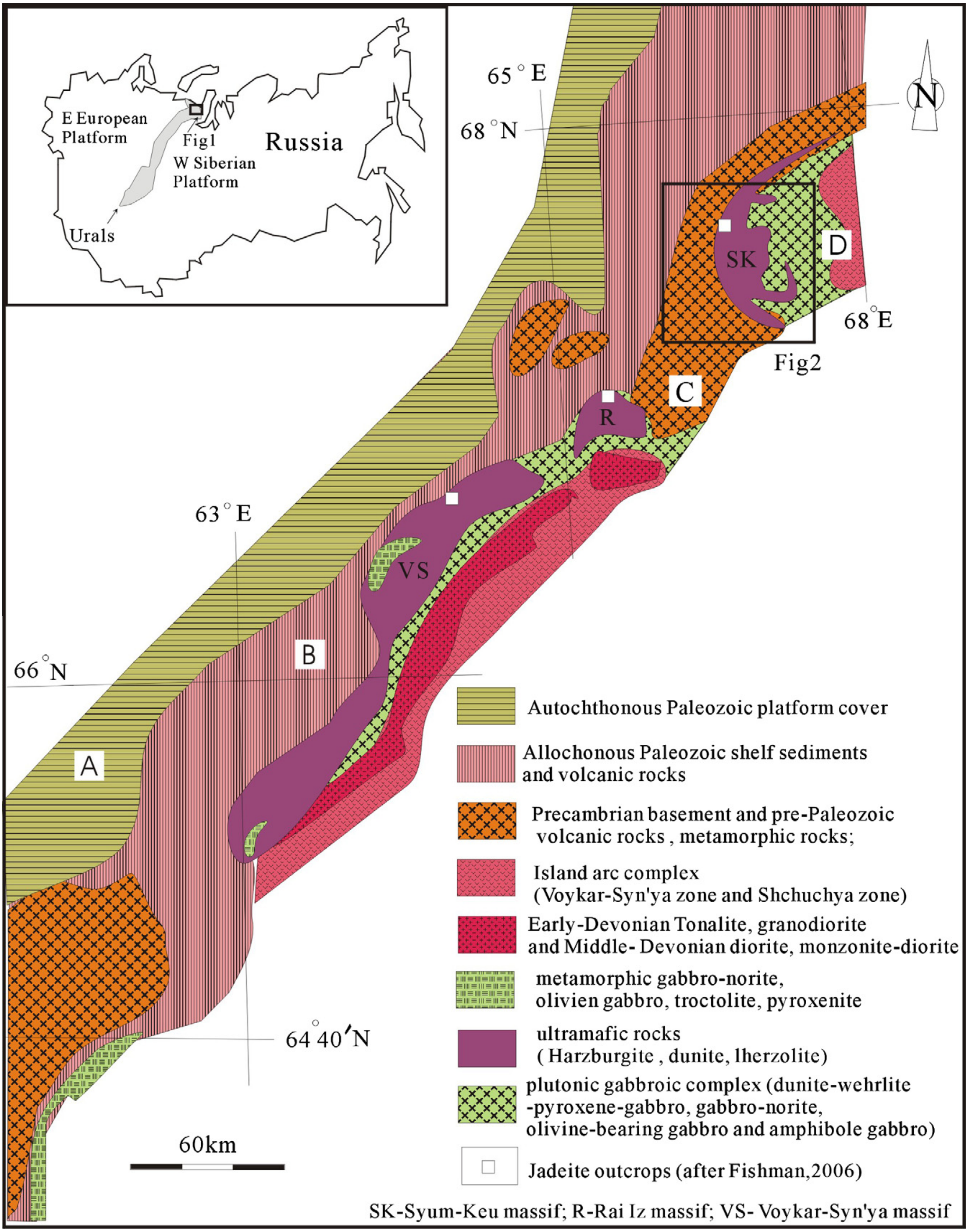

Fig. 1. Simplified geological map of the Polar Urals (modified after Savelieva et al. (2002).

island arc volcanic rocks (Savelieva and Nesbitt, 1996; Puchkov, 1997, 2009; Sharkov et al., 1999; Savelieva et al., 2002).

The study area lies at the northern end of the Polar Urals, where the western portion consists of Paleozoic sedimentary rocks (P_Z), greenschist facies metasedimentary rocks (Niaroveyskaya Suite) and high-pressure gneiss (Marun-Keu complex-MK) with eclogite and blueschists. The eastern part of the orogen contains an ophiolite assemblage composed of mafic–ultramafic rocks (Syum-Keu complex-SK), gabbro, early Paleozoic volcaniclastic sedimentary rocks (P_{Z1}), and Paleozoic quartz diorites and granites (Udovkina, 1985; Savelieva and Nesbitt, 1996; Savelieva et al., 2002; Glodny et al., 2004) (Fig. 2).

2.1. The Marun-Keu (MK) complex

The MK complex is considered to be the product of collision between the passive East European plate and the subducted Paleo-Urals Ocean (Fig. 2 and Table 1). This suite of HP metamorphic rocks mainly consists of blueschists, felsic gneisses, garnet amphibolites and eclogites (Udovkina, 1971, 1985; Dobretsov, 1984, 1991; Molina et al., 2002, 2004; Glodny et al., 2003). Both the blueschists in the northern segment of the unit and the eclogites in the central and southern segments of the unit formed under low temperature–high pressure conditions, up to 600–650 °C and 14–17 kbar (Udovkina, 1971, 1985; Dobretsov, 1984, 1991; Molina et al., 2002). Although the blueschists and eclogites are not spatially

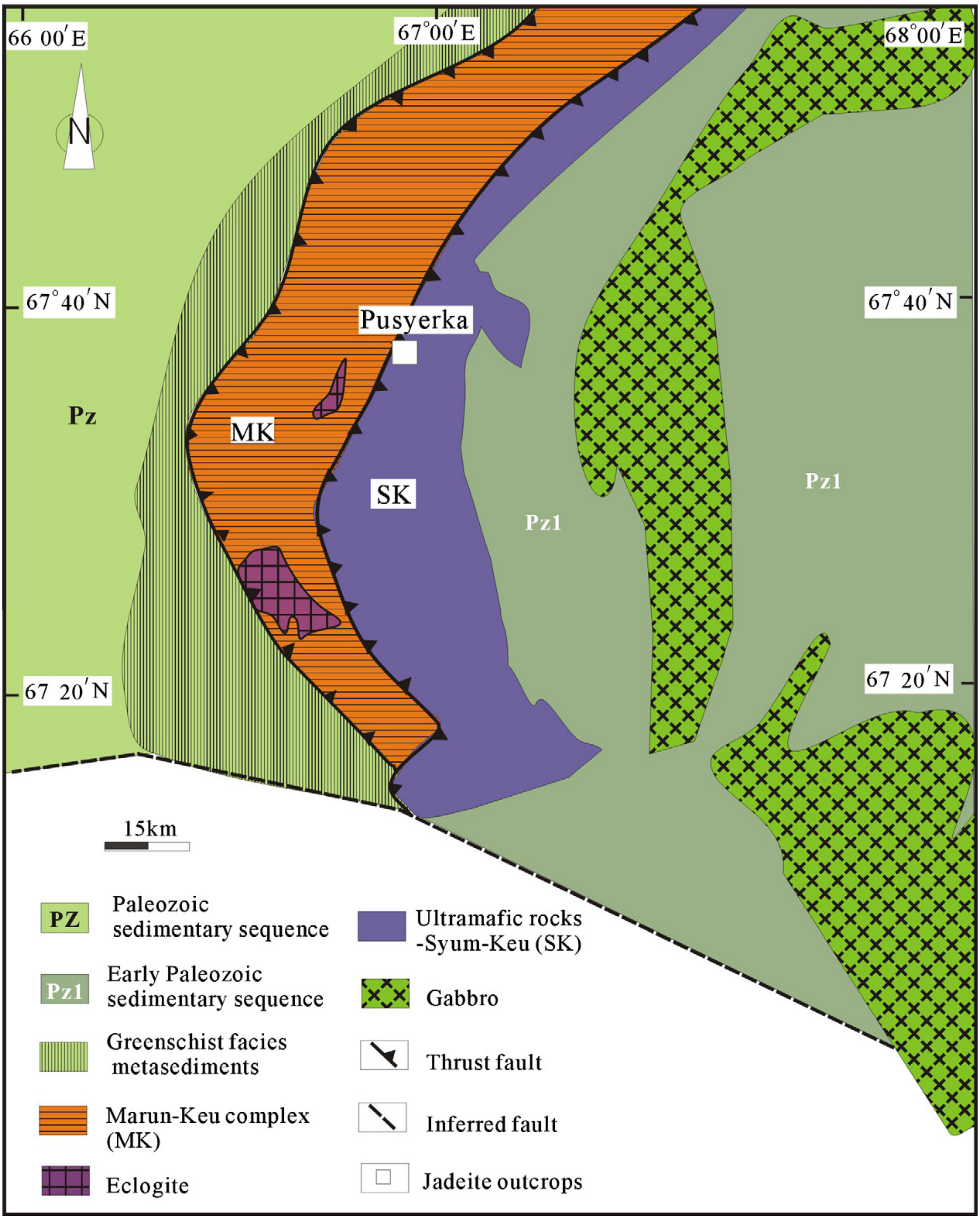

Fig. 2. Simplified geological map of the Marun-Keu complex and Syum-Keu massif in the Polar Urals (modified after Udovkina, 1985 and Remizov, 2004).

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Table 1
High pressure (HP) metamorphic rocks and ophiolite from the north end of the Polar Urals, Russia.

Complex	Marun-Keu	Syum-Keu
Rock type	Amphibolites and gneisses with eclogites and blueschists	Harzburgite, dunite with variably serpentinzed
T-P	Eclogites: 600–650 °C, 1.4–1.7 GPa	900 ± 50 °C 1.2 ± 0.7 GPa
Timing of formations	Metamorphic age: 360–355 Ma (Zircon, U–Pb; Sm–Nd method)	523 ± 10 Ma (Sm–Nd method)

related, they both represent the subducted products of the same oceanic lithosphere (Dobretsov, 1991). The metamorphic ages of the high-pressure eclogites are 360–355 Ma (Glodny et al., 1999, Glodny et al., 2003; Glodny et al., 2004; Shatsky et al., 2000).

2.2. The Syum-Keu (SK) complex

The SK complex crops out in a NE-trending block about 60 km long and 12–15 km wide, exposed over approximately 600 km^2 (Fig. 2). It is composed mainly of dunite and harzburgite (Makeyev, 1992; Gurskaya and Smelova, 2003), but is partly encircled by a harzburgite–lherzolite complex of variable width on the north, west and east sides. The exposed proportions of harzburgite, dunite–harzburgite and dunite are about 73:25:2. A narrow (2–3 m wide) dunite–wehrlite–clinopyroxenite assemblage is exposed along the east slope of the complex at its northern end (Makeyev, 1992; Makeyev and Braynchaninova, 1999). Sm-Nd isochron ages of harzburgite are 523 ± 10 Ma for the Syum-Keu block (Andreichev, 2004). Based on its outcrop pattern and geophysical data, the block consists of several flat lenses with thicknesses of 1–3 km, which were deformed during emplacement, and are concordantly distributed with the host rock (Fig. 2 and Table 1). The entire complex is variably serpentinzed (45–65 vol.%).

Two gabbro complexes, the Malycko and Maclov magmatic bodies, crop out along the east side of the Syum-Keu complex (Fig. 2). These are believed to have formed at high and low pressures, respectively (Efimov and Potapova, 1992; Kulikova, 2005), in island arc or back arc settings (Kulikova, 2005). It has been suggested that an early Paleozoic arc-continent belt existed in the Polar Urals, similar to that in the South Urals (Brown and Spadea, 1999; Leech and Ernst, 2000; Dobretsov, 1991; Savelieva and Nesbitt, 1996; Shatsky et al., 2000).

2.3. Jadeitite

There are three major occurrences of jadeitite in the Polar Urals, all of which occur in ultramafic rocks (Fig. 1): (1) the Levoketchpel deposit in the northwest Voykar-Synisky block or so-called Pay-Yer block (Morkovkina, 1960; Dobretsov and Ponomareva, 1965; Kovalenko and Sviridenko, 1981; Dobretsov, 1984; Harlow and Sorensen, 2005); (2) three mineralized points (Obraztsov, Karovoe and Zapadnoe) in the northeastern Rai-Iz block; and (3) the Pusyerka jadeitite deposit in the western side of Syum-Keu complex (Fishman, 2006).

The Pusyerka jadeite deposit is located on the west side (67°36.56′N, 66°46.82′E, H556 m) of the Syum-Keu complex (Fig. 2). Jadeite mineralization in the serpentinized dunite was controlled by two faults, dipping 50–70° SE (Fig. 3). The mineralized belt between the two faults is about 300 m wide and is composed mainly of antigorite serpentinite (Makeyev, 1992; Bryanchaninova et al., 2004). In the strongly serpentinized segment, there are numerous jadeitite veins, which strike N30°E and increase in jadeite content from NE to SW. These veins extend intermittently for about 10 km along strike and range in thickness from 20 to 100 m. More than 70 ore bodies occur in the belt, 11 of which were evaluated as early as 1980 (Fishman, 2006). The ores are mainly eluvial or slope deposits of brecciated blocks, but the primary veins are exposed locally.

One of the jadeite ore bodies, which is 10 m long, 5 m wide and 50 m deep (Fig. 4a), yielded over 10 kg of top grade transparent jade and over 200 t of gray jade. The jadeitite ores are hosted directly in dark serpentinite composed mainly of antigorite, brucite and magnetite (Makeyev and Braynchaninova, 1999). Gangue minerals are chiefly anthophyllite and phlogopite. The jadeitite ore bodies are essentially the same as those in Levoketchpel at Voykar-Synisky, also in the Polar Urals (Morkovkina, 1960; Kovalenko and Sviridenko, 1981; Dobretsov, 1984; Harlow and Sorensen, 2005). They are also similar to those in the Borus mélange of west Sayan, Russia (Dobretsov, 1984; Ouyang and Qu, 1999), and at Itrmurundy near Balkhash Lake, Kazakstan (Kovalenko and Sviridenko, 1981). The only significant difference is an absence of albite jadeitite in the Pusyerka deposit, whereas it is common in the Levoketchpel deposit and the Rai-Iz block.

Most of the jadeite ore bodies are visibly zoned, with three generations of jadeitite formation. The earliest phase (stage I) occurs in the vein center and the latest phase (stage III) occurs along the margins. Stage II jadeitite is intermediate in age and lies between the other phases. The first generation is always light gray, dense, massive, fine- to coarse-grained, and composed only of jadeite. This phase makes up the main part of the ore body and is associated with phlogopite. The second generation forms narrow veinlets, lenses and pockets of green to light green, fine-grained jadeite, several centimeters thick, along the boundary with the first

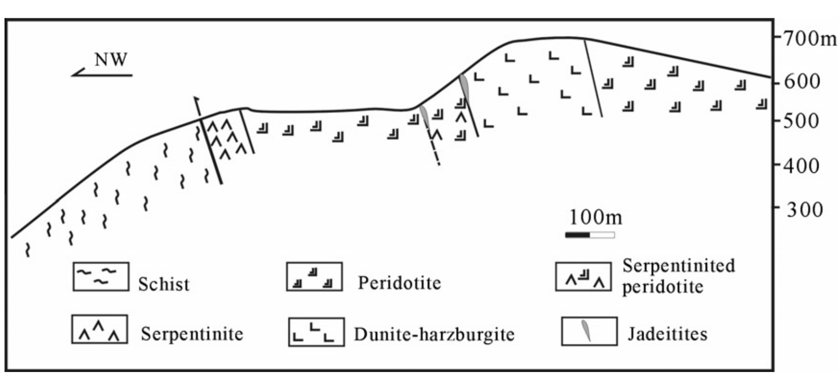

Fig. 3. A representative cross-section of the jadeitite-bearing Syum-Keu ultramafic rocks (after Fishman, 2006).

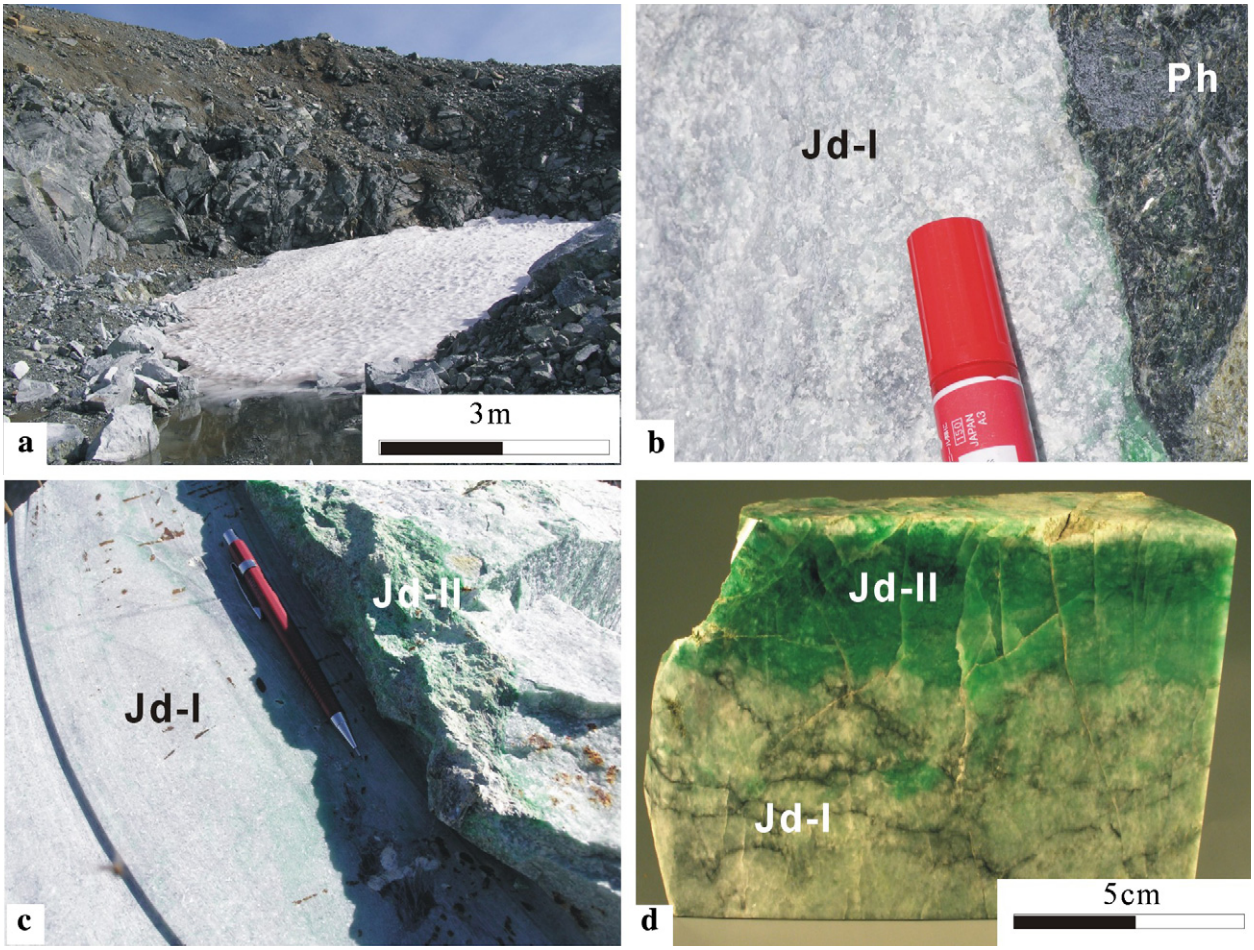

Fig. 4. Occurrence and texture of jadeitite from the Polar Urals: (a) jadeitite quarry or pit; (b) the early jadeitite (Jd-I) and its host phlogopite (Ph); (c and d) the second generation of green jadeite (Jd-II), growing within the grayish-white first generation (Jd-I) (after Fishman, 2006). (a) Jadeitite quarry or pit; (b) the early jadeitite (Jd-I) and its host phlogopite (Ph); (c and d) the second generation of green jadeite (Jd-II,) growing within the grayish-white first generation (Jd-I) (after Fishman, 2006).

generation (Fig. 4c and d). The third generation of the jadeitite is green, sometimes dark green, medium-grained, transparent or translucent, and typically occurs as crusts or nodules with a radiating structure. The first generation occurs as blocks of about 40 × 30 × 20 cm, containing jadeite with an average of 33 mol.% Jd. The second and third generations, which are classified as bijouterie, occur in masses of about 10 × 10 × 10 cm, in which small amounts (~0.5% of the total) are equal to the Myanmar emerald in quality. The second generation of jadeitite has a cryptocrystalline texture, a greasy luster and ranges from yellow–green, apple green, dark green or aquamarine in color. It is transparent in slices up to ~10 mm thick. The estimated reserves of this type are about 100 kg (Makeyev, personal communication).

3. Analytical methods

Samples of jadeitite were collected from the Pusyerka deposit in the Syum-Keu complex on the east slope of the Polar Urals. Mineral chemical compositions were obtained using a JXA8800 microprobe at the Mineral Resources Institute, CAGS with an accelerating voltage of 20 keV, a beam current 2×10^{-8} A, and beam diameters of 5 μm, or 2 μm for some small inclusions. Small minerals and fluid inclusions in jadeite and zircons were analyzed using a RENISHOW-1000 Raman spectrum instrument.

Zircons were separated from jadeitite sample Y5-100, which was crushed, rinsed and treated with heavy liquids. Individual grains were carefully selected under a binocular microscope, mounted with standard Temora zircons (TEM zircons with an age of 417 Ma, Black et al., 2003) on a double adhesive tape, and embedded in epoxy. The mounted zircons were polished to approximately half of their thickness and photographed under transmitted and reflected light. The U–Th–Pb zircon dating was performed at the Beijing ion probe center with a SHRIMP II following the procedures described by Zhang et al. (2005). Before carrying out the analyses, cathodoluminescence images were obtained in order to determine the inner textures of the zircons. Standard SL13 zircon, having an age of 572 Ma and a U content of 238 μg/g, was used to determine the U, Th and Pb contents of the TEM standard zircon and sample zircons. TEM was used to calibrate the corrected values of Pb/U and UO/U ratios, and the sample ages were calculated with the ISOPLOT program (Ludwig, 2003). Common lead was corrected through the actual measured values of ^{204}Pb.

4. Results

4.1. Petrography and mineral chemistry

In this paper we focus on the first and second generations of jadeitite. The studied samples consist of grayish-white to locally emerald colored, massive jadeite with a grain size of 1–2 mm (Fig. 4b–d). Some crystals show oscillatory zoning (Fig. 5a) typical of crystallization from a fluid or melt (Harlow and Sorensen, 2005; Sorensen et al., 2006). The chemical compositions of both the grayish-white (Jade-I) and green (Jade-II) jadeitite are given in Table 2. Jade-I is high in Jd (~88 mol%) and is classified as jadeite, but a few grains are omphacite with Jd as low 54 mol%. Crystals of Jade-II show clear oscillatory zoning and vary from 85.6 to 74.6 mol% Jd, indicating that both jadeite and omphacite are present (Fig. 6). Emerald jadeite is usually thought to contain high Cr^{3+}, e.g., Kosmochlor with 12.08 wt.% Cr_2O_3 (Ouyang and Qu, 1999). However, Cr_2O_3 is consistently low in our samples, ranging from about 0.01% to 0.24 wt.%, and shows no obvious differences in amount between the two generations of jadeitite. Jade-II of the Polar Urals contains much higher Fe^{2+} than Fe^{3+} (Table 2), which probably accounts for its green color.

Whole-rock compositions of the jadeitites, obtained by wet chemical analysis, contain 8.24–8.37 wt.% Na_2O, 15.74–18.46 wt.% Al_2O_3, and 51.64–54.76 wt.% SiO_2. Calculated Jd contents range from 58 to 69 mol%, which are much lower than those based on microprobe analyses (cf. Table 2), suggesting that these jadeitites should be classified as omphacite. Two samples with relatively high H_2O^+ suggest that hydrous minerals (e.g., phlogopite) are locally present in the jadeitite (see Fig. 4b).

Fluid inclusions are well developed in the jadeitite and tend to cluster in poorly transparent areas (Fig. 5b). A few relative large

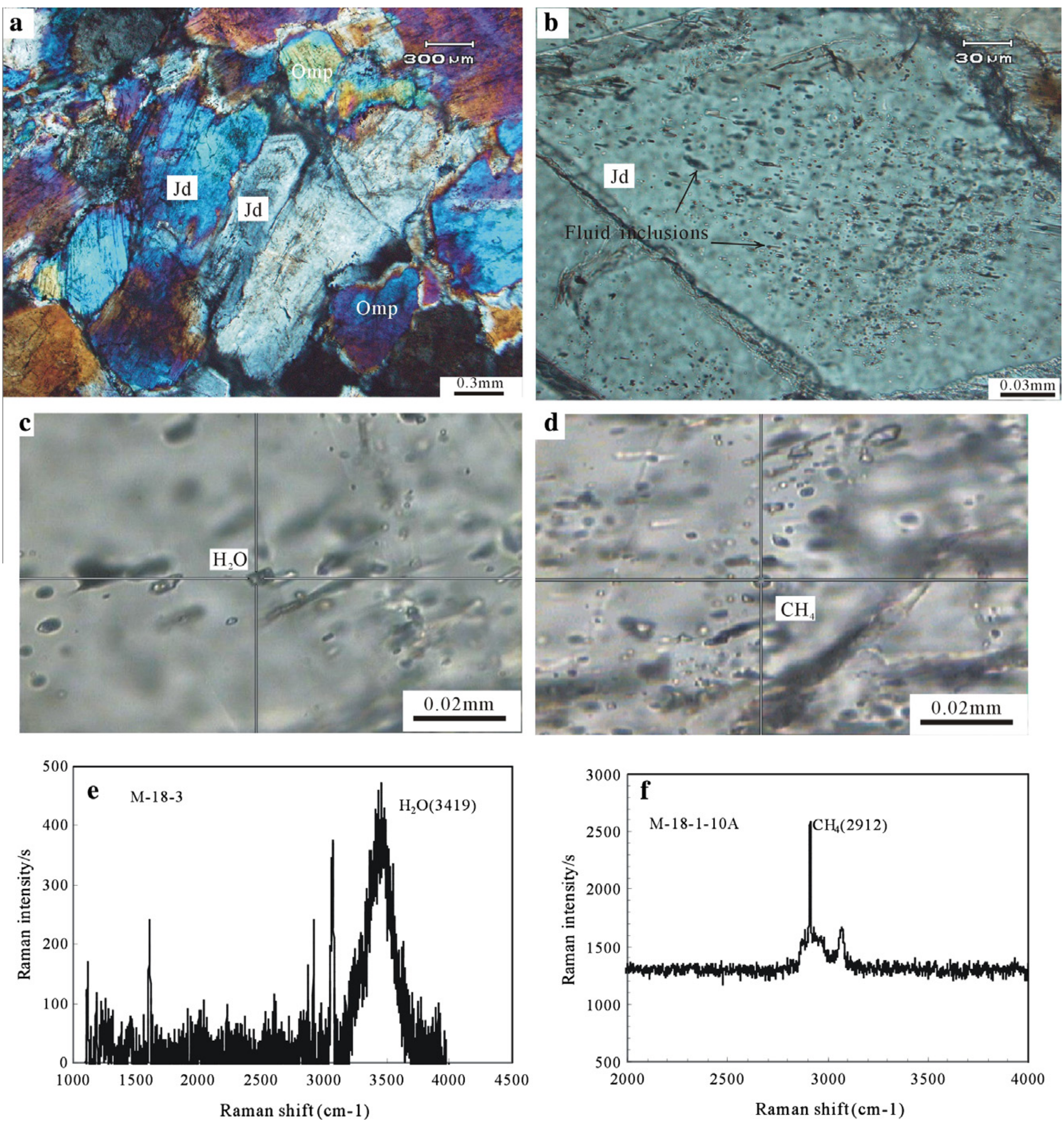

Fig. 5. Photomicrographs of various jadeite grains: (a) well-developed oscillatory zoning; (b) abundant fluid inclusions; (c) H_2O-rich fluid inclusions and their Raman spectrum (e); (d) CH_4-rich fluid inclusions and their Raman spectrum (f).

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Table 2
Representative microprobe analyses of pyroxenes (6 O basis).

Sample	M-18 Jade-I			Jade-II	
Mineral	Omphacite	Jadeite	Jadeite	Jadeite	Omphacite
Analyses point	2-2-Omp	2-2-Jd	2-2-Jd	2-1-Jd	2-1-Omp
SiO_2	56.66	58.16	58.98	58.25	57.82
TiO_2	0.09	0.03	0.06	0.04	0.02
Al_2O_3	12.38	21.25	20.80	20.81	17.58
Cr_2O_3	0.04	0.01	0.24	0.02	0.08
FeO	1.84	1.09	1.21	1.02	1.11
MnO	0.05	0.01	0.00	0.00	0.05
MgO	8.31	2.10	1.96	2.75	4.77
NiO	0.04	0.00	0.04	0.03	0.00
CaO	11.86	2.97	2.99	3.60	6.87
Na_2O	8.22	13.79	13.43	13.54	11.69
K_2O	0.01	0.00	0.00	0.00	0.00
CoO	0.00	0.01	0.00	0.04	0.02
Total	99.51	99.42	99.70	100.09	100.00
Si	1.99	1.99	2.02	1.98	1.98
Al^{IV}	0.01	0.02	0.00	0.02	0.02
Al^{VI}	0.50	0.84	0.84	0.81	0.69
Ti	0.00	0.00	0.00	0.00	0.00
Fe^{3+}	0.00	0.00	0.01	0.00	0.00
Fe^{2+}	0.05	0.03	0.03	0.03	0.03
Cr	0.00	0.00	0.01	0.00	0.00
Mg	0.43	0.11	0.10	0.14	0.24
Ni	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00
Ca	0.45	0.11	0.11	0.13	0.25
Na	0.56	0.91	0.89	0.89	0.78
K	0.00	0.00	0.00	0.00	0.00
Total	4.00	4.00	4.00	4.00	4.00
WEF	45.54	11.91	11.84	14.37	25.39
JD	54.46	88.09	87.68	85.63	74.61
AE	0.00	0.00	0.49	0.00	0.00

Mineral symbols after Kretz (1983), WEF-(Wo + En + Fs), JD-Jadeite, AE-Aegirine, Omp-Omphacite.

(5–8 μm) inclusions are present, but most are <3 μm. Raman spectrum analyses indicate that the fluid inclusions are water (Fig. 5c and e) or methane (Fig. 5d and f), and are all single phase. This suggests that the jadeite crystallized from hydrothermal fluids (c.f., Harlow and Sorensen, 2005).

4.2. Zircon dating of the jadeite

4.2.1. Character of zircons

The zircons are smaller than 100 μm, mostly 50–70 μm in length, colorless to light yellow, transparent, and granular. In plane polarized light, two types of zircon can be recognized: one is long prismatic and transparent, with length/width ratios of 2; the other is short prismatic, cracked, translucent, and partially metamict. Observations of over 500 zircons show that most have inclusions, all smaller than 10 μm in size, and commonly 3–5 μm. Raman spectrum analyses indicate that the mineral inclusions are pyroxene, rutile, muscovite (phengite?), feldspar, quartz and zeolite, and fluid inclusions are mainly water.

Morphologically, these zircons are quite similar to those from magma or hydrothemal fluids. For example, zircons in the eclogite–jadeitite block in the Syros area, Greece, are thought to have crystallized from hydrothermal fluid (Brocker and Keasling, 2006); zircons which are as big as 3 mm in jadeitite of the Osayama serpentinite, southwestern Japan formed at low temperature and contain mineral inclusions of rutile and jadeite. The Osayama jadeitite is thought to be the product of reaction between alkaline fluids and ultramafic rocks in a subduction zone, and the zircons in the jadeitite are thought to have crystallized during deposition of the jadeitite (Tsujimori et al., 2005; Yui et al., 2010).

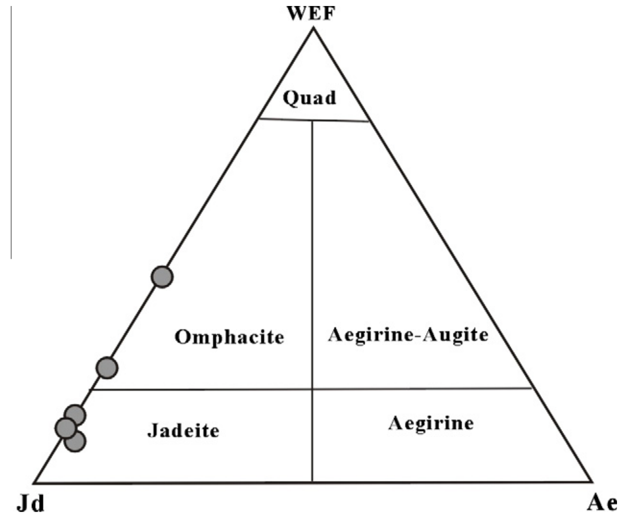

Fig. 6. Jadeite and omphacite compositions plotted on a WEF (Wo, En, Fs)–Jd–Ae ternary diagram. The clinopyroxene classification is after Morimoto et al. (1988).

Cathodoluminescence images (Fig. 7) of short prismatic and long prismatic zircons have similar concentric, oscillating grayish-white and dark gray (or black) zones, suggesting that the zircons grew in a melt or fluid (Corfu et al., 2003).

4.2.2. Dating of the zircons

Results from 13 zircons analyzed with SHRIMP II are given in Table 3. U contents of the zircons range from 27 to 158 ppm and Th contents are low from 1 to 20 ppm. Most of the zircons have very low Th/U ratios below 0.1 (0.03–0.09), compatible with precipitation from an aqueous fluid (Yui et al., 2010); only four grains have Th/U ratios over 0.1(0.1 to 0.21). Eleven concordant analyses yielded a weighted average $^{206}Pb/^{238}U$ age of 404 ± 7 Ma (MSWD = 0.70) (Fig. 8), Two zircons give younger ages of 372 ± 16 Ma and 368 ± 11 Ma (Table 3).

5. Discussion

5.1. Material sources of the jadeitite

Because jadeitite of the Polar Urals (JPU) is composed of only jadeite and lacks other associated minerals, it is difficult to determine the formation temperatures and pressures. However, if its genesis is similar to that of the Levoketchpel jadeitite, which contains both albite and jadeite, the reaction Ab = Jd + Qtz constrains the highest temperature and pressure to be ~450 °C and ~14 kbar when quartz is absent (Harlow and Sorensen, 2005). These temperature and pressure conditions are similar to those estimated for the formation of the blueschist of the Polar Urals (Dobretsov, 1984).

The development of rhythmic growth zones and fluid inclusions in the jadeitite indicate that they grew in fluid. The Levoketchpel jadeite deposit and jadeitites from other areas, such as Myanmar, Guatemala and California also show similar zoning (Harlow and Sorensen, 2005), and fluid inclusions are well developed in those from Myanmar and Guatemala (Shi et al., 2000; Johnson and Harlow, 1999).

The JPU occurs in situ in serpentinite (Fig. 3), produced by alteration of the associated ultramafic rocks (Harlow and Sorensen, 2005). Jadeitite from other areas, such as Myanmar, Guatemala and Japan is also hosted in serpentinite (Harlow and Sorensen, 2005).

Serpentinite of the Syum-Keu complex has $\delta D_{(SMOW)}$ values of −24‰ to −134‰, and $\delta^{18}O/^{16}O$ values of −1.4‰ to −8.64‰, which

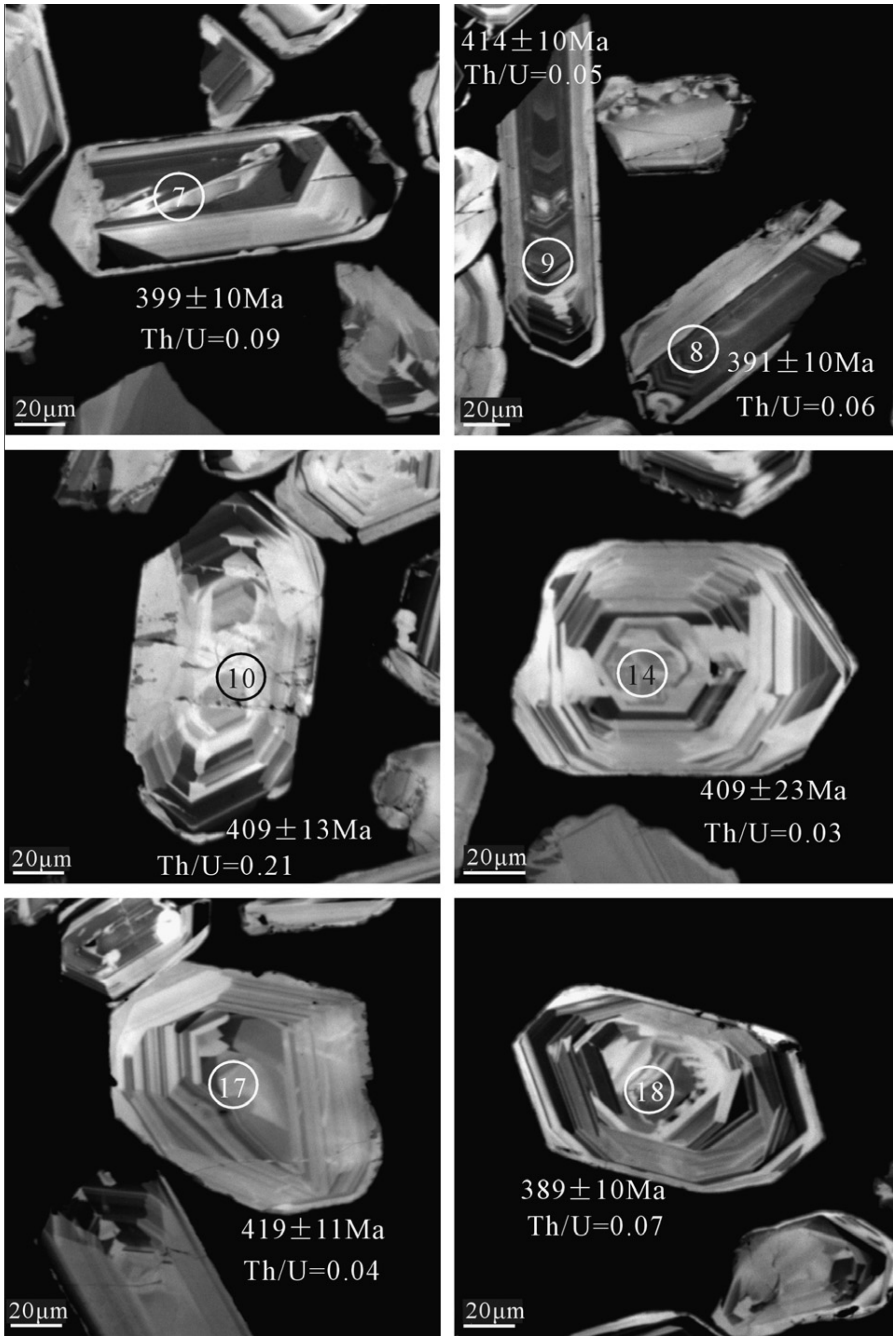

Fig. 7. Representative CL images of the zircon grains from jadeitites Y5-100 (scale bars are 20 μm).

are thought to indicate oceanic water (Braynchaninova et al., 2004). But these H–O isotopic values are very different from those of jadeitite in Guatemala with $\delta D_{(SMOW)} = -12–5‰$ and $\delta^{18}O/^{16}O = 5–6.4‰$ which are also thought to represent oceanic water (Johnson and Harlow, 1999).

Eclogite of the Marun-Keu complex was formed by fluid-rock reaction at eclogitic facies condition. The fluid was enriched in silicon and alkalies with Na_2O contents of 0.5–4.8 wt.% (Molina et al., 2002). Locally in the eclogite, there is a layer enriched in omphacite about 1–2 cm thick. Fluid compositions similar to the above can also be found in the eclogite of Tianshan (Gao and Klemd, 2001). In the Rai-Iz ultramafic bodies (formed in suprasubduction zone), veins centimeters to meters thick are developed with a mineral assemblage of albite + amphibole + chromite + phlogopite + corundum + apatite, which are presumed to have formed in an extensional tectonic setting when the mantle rocks were exhumed to depths of less than 30 km. The mineral assemblage of the veins shows that the fluid was rich in Si, Al, Na and K, all elements released from mafic rocks of the oceanic crust during subduction (Glodny et al., 2003; Gao and Klemd, 2001). By comparison, we suggest that the fluids and elements involved in the formation of the JPU were also derived from subducted oceanic crust. Some trace element data suggest a contribution form the upper sediments of the subducted oceanic crust, for example, high-Ba feldspar occurring in jadeitite of Japan may be related to gypsum on the oceanic floor (Morishita, 2005). Although Na, Al, Si may be

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Table 3
U–Th–Pb SHRIMP zircon data from jadeitites (Y5–100).

Spots	$^{206}Pb_c$ (%)	U (ppm)	Th (ppm)	$^{232}Th/^{238}U$	$^{206}Pb^*$ (ppm)	$^{207}Pb^*/^{206}Pb^*$	±%	$^{207}Pb^*/^{235}U$	±%	$^{206}Pb^*/^{238}U$	±%	Age (Ma)	
												$^{206}Pb/^{238}U$	1σ
1	3.45	76	6	0.08	4.31	0.0700	38	0.620	38	0.0639	3.3	399	±13
3	3.88	37	1	0.04	1.95	0.0540	43	0.440	43	0.0594	4.3	372	±16
7	1.21	131	12	0.09	7.31	0.0470	11	0.414	12	0.0639	2.7	399	±10
8	0.89	130	7	0.06	7.04	0.0553	8	0.477	8	0.0626	2.6	391	±10
9	1.05	147	7	0.05	8.45	0.0516	4	0.471	4	0.0663	2.6	414	±10
10	2.61	27	5	0.21	1.56	0.0727	8	0.656	9	0.0654	3.4	409	±13
12	2.99	158	20	0.13	9.27	0.0372	22	0.340	22	0.0664	2.8	414	±11
13	1.64	110	13	0.12	6.24	0.0543	11	0.484	11	0.0647	2.8	404	±11
14	2.93	54	2	0.03	3.15	0.0456	17	0.412	18	0.0656	5.7	409	±23
15	2.45	118	12	0.10	6.76	0.0467	21	0.419	21	0.0650	3.0	406	±12
17	1.13	100	4	0.04	5.76	0.0491	11	0.449	12	0.0663	2.7	414	±11
18	0.42	93	7	0.07	5.02	0.0546	6	0.468	7	0.0622	2.6	389	±10
19	3.07	48	4	0.09	2.52	0.0480	23	0.391	24	0.0587	3.1	368	±11

Errors are 1-sigma; Pbc and Pb* indicate the common and radiogenic portions, respectively. Common Pb corrected using measured ^{204}Pb.

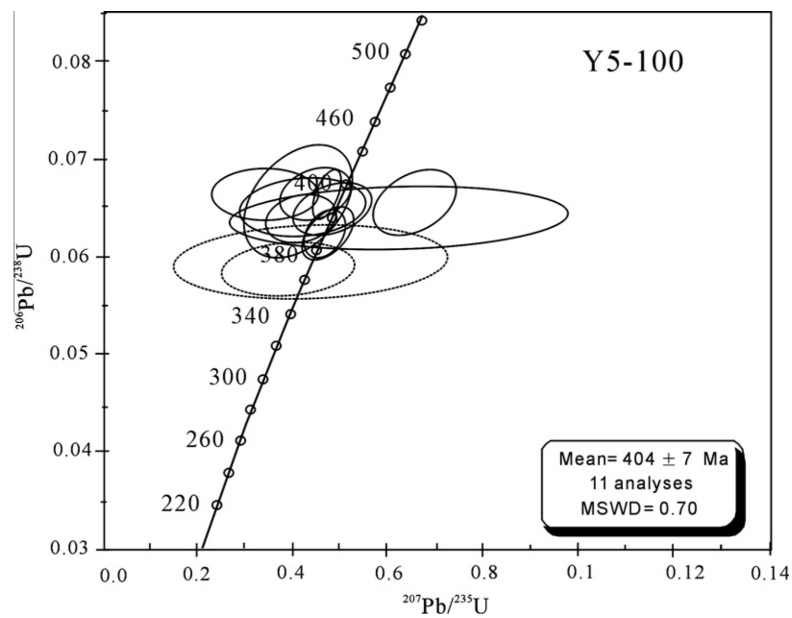

Fig. 8. U–Pb concordia diagram of zircon in jadeitite (sample Y5-100) from the Polar Urals.

derived from plagiogranites or leucogabbros in ultramafic blocks (Dobretsov and Ponomareva, 1965), or from deep mantle melting (Shi et al., 2000), such sources cannot be proved directly.

5.2. Interpretation of SHRIMP U–Pb dating

Eleven concordant analyses yield a weighted average $^{206}Pb/^{238}U$ age of 404 ± 7 Ma (MSWD = 0.70) (Fig. 8 and Table 3), which we interpret to represent the main formation age of the grayish-white jadeitite. Most of the zircons have very low Th/U ratios (<0.1), similar to those of zircons from high-pressure metamorphic veins (Rubatto and Hermann, 2003; Glodny et al., 2004) and zircons from Guatemala jadeitite (Yui et al., 2010). These low Th/U ratios are significantly different from those of zircons from other jadeitites, e.g., the huge zircons in jadeitite of the Osayama serpentinite, southwestern Japan, crystallized from fluids with Th/U ratios over 0.2 (0.2–0.76) (Tsujimori et al., 2005). Zircons from the eclogite–jadeitite block in the Syros area, Greece crystallized from hydrothermal fluid with Th/U ratios of 0.3–1.54 (Brocker and Keasling, 2006) whereas zircons from jadeitite in Myanmar have variable Th/U ratios of 0.04–0.3 (Shi et al., 2008). Therefore, the Th/U ratios of zircons are not a reliable indicator for their genesis (Harley et al., 2007). However, similar fluid inclusions in the zircons and in the jadeites of the Polar Urals indicate that they formed in the same environment.

The two young ages of 368–372 Ma are taken as the formation age of the latest generation of the jadeitite. These ages are similar those (360–355 Ma) of zircons from an eclogite facies vein in the Marun-Keu complex (Glodny et al., 2004) (Table 3).

5.3. Tectonic implications

The three ultramafic blocks Syum-Keu, Rai-Iz, and Voykar-Synisky of the Polar Urals all contain jadeitite which may have a similar genesis (Fig. 1). The Voykar-Synisky ophiolite is thought to have formed at a mid-oceanic ridge at 397 Ma (Edwards and Wasserburg, 1985). The Syum-Keu ultramafic rocks at the north end of the Polar Urals include ophiolite fragments, eclogites and blueschists that presumably mark a former subduction zone (Dobretsov, 1991). The jadeitite veins in the serpentinized peridotites indicate that they are closely related to the subduction zone fluids that caused the serpentinization (Manning, 2004). When the fluids moved into the overlying mantle wedge, they reacted with the peridotites, leading to serpentinization and jadeitite deposition

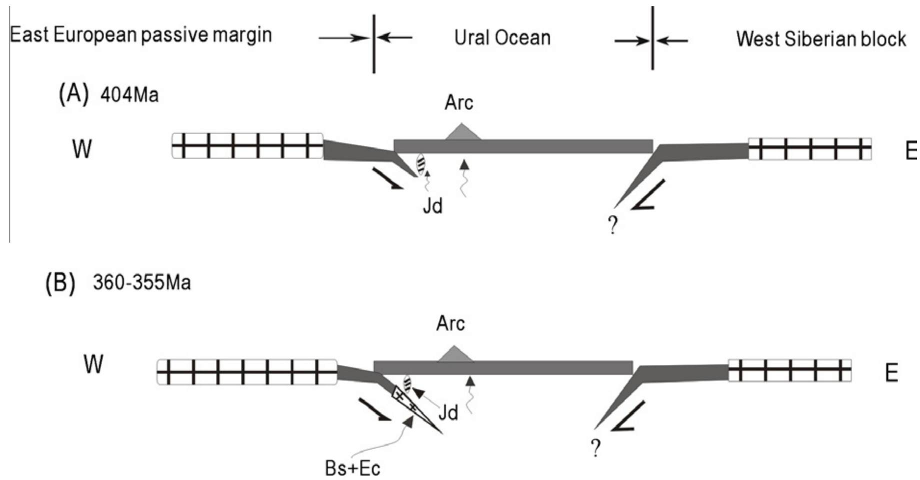

Fig. 9. A model for tectonic evolution of the Polar Urals and formation of jadeitite during Paleozoic.

(Morishita et al., 2007). The process was probably similar to that which formed the jadeitites in Myanmar (Shi et al., 2008).

The appearance of jadeitite in the peridotites suggests that subduction was already underway, thus the date of 404 Ma obtained in this study should represent the minimum age of subduction initiation and the time at which the old Ural ocean basin began to close (Fig. 9A).

Glaucophane eclogite on the west side of the Syum-Keu ultramafic massif has Sm–Nd isochron ages of 366 ± 8.6 Ma, and kyanite eclogite has Sm–Nd isochron ages of 338 ± 40 Ma (Shatsky et al., 2000; Glodny et al., 1999, 2003). Zircons from an eclogite facies vein has U–Pb ages of 360–355 Ma (Glodny et al., 2004). Those ages may represent the timing of eclogite metamorphism during subduction, or the age of collision between the east European plate and island arc systems (Shatsky et al., 2000) (Fig. 9B). The K–Ar ages of amphibole and muscovite of blueschists in the complex are 346 Ma and 347 Ma, respectively (Udovkina, 1985), and these may represent cooling ages of the high pressure schists during exhumation.

The time at which the jadeitite-bearing ultramafic rocks were obducted onto the margin of the East European plate is unclear and needs further detailed research. The paleogeomagnetite data show that the collision between the Laurussian continent and the Siberian plate occurred somewhere between 370 and 245 Ma (Scotese et al., 1979).

The formation of jadeitite in the Polar Urals was closely related to the evolution of the ultramafic rocks. Serpentinization and jadeitite formation occurred simultaneously in the same fluid system. The preservation of jadeitite requires a decrease in fluid or the Na_2O in jadeite will be lost (Li and Zhang, 2004; Li et al., 2004). Only when the rocks are exhumed rapidly can jadeitite can be preserved. The estimated uplift rate of the Marun-Keu complex from eclogite to amphibolite facies conditions is 2 ± 1.3 km/Ma and the rapid uplift probably occurred at ~250 Ma (Glodny et al., 2003). We infer that the Syum-Keu ultramafic rocks underwent a similar evolution.

6. Conclusions

1. Jadeitite of the Syum-Keu ultramafic rocks in the Polar Urals, Russia occurs as veins in serpentinite, where it crystallized from Na, Al, and Si enriched fluids at high pressures and low temperatures.
2. Three generations of jadeitite consisting of jadeite and omphacite are recognized on the basis of their color, texture and structure. The second and third generations are locally of bijouterie quality with high commercial values.
3. The material source of the jadeitite of the Polar Urals was probably subducted oceanic crust.
4. The zircon U–Pb age of the jadeitite of the Polar Urals is 404 ± 7 Ma, which represents both the age of jadeitite formation and the age serpentinization of the hosting peridotite. This age probably also marks the initiation of subduction of the oceanic lithosphere.

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