Spherules with pure iron cores from Myanmar jadeitite: Type-I deep-sea spherules?

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Abstract

Here we report spherules in Myanmar jadeitite, a rock forming from jadeitic fluids within mantle-derived serpentinitized rocks in subduction zones under high-pressure conditions (>1.0 GPa) and rather low temperatures of about 250–370 °C. The spherules have off-centre iron nuclei and dendritic wüstite cortexes, with tiny wüstite crystals perpendicular to the surface of iron core. Within the spherules are vesicles occupied by calcite, jadeite, albite? or mixtures of these phases, and the cortexes contain about 10 wt.% SiO₂ + Al₂O₃ + Na₂O filling materials within wüstite. The spherules are in direct contact with jadeite crystals. Contrasting patterns of some individual spherules are obvious between a front area with a crowd of hill-like prominences and a rear zone with one or more rings on the surface. Such surface features and internal textures suggest that they experienced movement at high temperature and then rapid cooling. Chemical compositions of the nuclei are homogenous and consist of nearly pure iron with minor Cr (<0.05 wt.%), Mn (<0.80 wt.%), and Ni (0.142–0.23 wt.%), and a trend of Ni decreasing and Cr increasing from core to cortex. Mn in the cortex (up to about 2.00 wt.%) is far more enriched than the nucleus. The bulk ratios (average) of δ⁵⁶Fe and δ⁵⁷Fe in the core and cortex are 0.51 and 0.78, respectively. Such features suggest that there is a very low possibility of origin associated with volcanic explosive eruption, impact ejecta, chemical reduction or oxidation of iron on seafloor. Since biological reduction processes are not significant under high P/T condition in subduction zones, this origin is excluded. Considering their low Ni contents, it is more likely that they belong to the minor type-I deep-sea cosmic spherules/dusts of low isotope fractionation. This discovery shows that such spherules could remain stable under low-temperature and high-pressure conditions during recycling processes, and therefore could be found in rocks related to slab-derived sediments within subduction zones. This also suggests that subducted oceanic slab sediments contribute to the formation of jadeitite, coupled with dehydration of sediments and altered oceanic crust.

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1. INTRODUCTION

Jadeite, a rock made up almost entirely of jadeitic pyroxene, always occurs in serpentinites, and is associated with eclogite or blueschist within subduction zones (Harlow, 1994; Harlow et al., 2007; Shi et al., 2008, 2009a; Garcia-Casco et al., 2009). Though jadeite is found in only about 15 locations worldwide (e.g., Coleman, 1961; Essene and Fyfe, 1967; Bender, 1983; Harlow et al., 2007), its petrogenesis represents an important geological process, which can give us a better understanding of jadeitites and associated rocks, of their relationship to eclogites and/or blueschists, and host serpentinitized peridotite, of fluids that form jadeitites, and possibly of sodium metasomatism during subduction processes. Of all jadeite locations, the

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largest and most important jadeite (jade) deposit is the Hpak-an–Tawmaw serpentinite, Kachin State, northwestern Myanmar (Burma). Mineralogical studies on the Myanmar jadeite have identified six amphiboles, terrestrial kosmochlor and omphacite of metasomatic origin (Harlow and Olds, 1987; Shi et al., 2003, 2005a; Yi et al., 2006). Methane (CH₄) bearing fluid inclusions found in jadeites from the Myanmar jadeite confirm a fluid-related origin and suggest a reduced environment (Shi et al., 2005b; Sorensen et al., 2006). Studies on zircons in jadeite from Myanmar and elsewhere suggest that their derivation can be from rapid reworking of juvenile oceanic crust, which was hydrated during its formation as revealed from highly positive depleted-mantle εHf(t) values (Qiu et al., 2008; Shi et al., 2009a), although aqueous solutions possibly related to serpentinization are suggested by low Th/U and fluid inclusions (Yui et al., 2010), and zircons in jadeite can have multiple origins (Fu et al., 2010).

Recently spherules with nearly pure iron nuclei were found from the Myanmar jadeite, that are very similar to the type-I cosmic spherules in structure/texture. The term "cosmic dust or spherule" refers to extraterrestrial spherical and/or rounded particles that have been totally or partially melted by atmospheric entry (e.g., Blanchard et al., 1980; Brownlee, 1985; Kosakevitch and Disnar, 1997; Herzog et al., 1999). However, spherules in jadeite are different in chemical composition from the major type-I ones. In this paper we report structures/textures, chemical and iron isotope compositions of the spherules from Myanmar jadeite, and discuss their origins and potential implications.

2. GEOLOGICAL SETTING

The jadeite samples containing the iron spherules were collected in the Myanmar jadeite area (Fig. 1), located in the western part of the Sagaing Strike-Slip Fault belt in Parkhan (also called Hpak-an or Pharkan) area, Myanmar (N 25°36.9’, E 96°18.6’). The Myanmar jadeite belongs to the Indo-Burma (Myanmar) Range which represents the eastern part of subduction zone of oceanic crust of the Indian plate under an overriding the Burmese platelet. The Sagaing Fault is a major strike-slip right-lateral continental fault that extends over 1200 km and connects to the Andaman spreading center at its southern end, and has been interpreted as a plate boundary between India and Indochina by some authors (e.g., LeDain et al., 1984; Guzmán-Speziale and Ni, 1996). However, other authors have pointed out that a significant displacement between the two plates could be accommodated by other tectonic structures in the Myanmar Central Basin (MCB) and the Shan plateau scarps (Hla Maung, 1987; Holt et al., 1991; Bertrand et al., 1999; Bertrand and Rangin, 2003). The Indo-Burma Range covers the area of Myanmar between the MCB and the western border, and its eastern boundary is generally defined by a discontinuous line of ophiolite and ophiolite-derived blocks. The rocks in the Indo-Burma Range are progressively younger from east to west. Recently, the formation age of the Myanmar jadeite was determined at ca. 147 Ma (Group-II) and the host serpen-
tinite at ca. 163 Ma (Group-I) by SHRIMP zircon U-Pb dating (Shi et al., 2008). Our average age (including all Group-I and II) of 157.4 ± 3.8 Ma is almost the same as another ungrouped U-Pb age of 158 ± 2 Ma on zircons in jadeite from the same locality using LA–MC–ICPMS techniques by Qiu et al. (2008) and Mitchell et al. (2004, 2007).

Primary jadeite deposits occur as veins (called "dike" by Chhibber, 1934) cutting serpentitized peridotite that belongs to the Tawmaw–Hpak-an ultramafic body (Fig. 1b) or cutting serpentinite-matrix mélangé (Shi et al., 2001). The jadeite veins are almost vertical, strike N–S, are 1.5–5 m wide, and 5–100 m long. Between the serpentinized peridotite body and the jadeite vein, there exists 1–50 cm wide amphibole boundary (Fig. 2) consisting of six species of sodic to sodic-calcareous amphiboles (eckermannite, magnesiokatophorite, nbyöbite, glaucophane, richterite, winchite) (Shi et al., 2003). Due to several stages of later deformation, fragments of the boundary zone can also be found intermingled with blocks of jadeite that often have a preferred orientation. Within or along the amphibole boundaries, kosmochlor, Cr-bearing jadeite and some Cr-bearing omphacite commonly occur as corona aggregates or small blocks (Shi et al., 2005a). Omphacites are also found here (Yi et al., 2006). The jadeite veins are cut occasionally by fine veins of late-stage albite, which are commonly less than 5 mm wide. Outside the ultramafic bodies, high-pressure rocks such as phengite-bearing glaucophane schists, stilpnomelane-bearing quartzites and eclogite facies rocks, together with high amphibolite facies rocks (garnet-bearing amphibolites, diopside-bearing marbles) occur as tectonic intercalations (Shi et al., 2001; Goffé et al., 2000, 2002). In contrast to some other jadeite localities where eclogite occurs (see review by Harlow and Sorensen, 2005), eclogite has not been found in the Myanmar jadeite area. However, it was found recently from the Naga Hills within the Indo-Burma range (Chatterjee and Ghose, 2009).

The jadeites of the present study are monomineralic, mostly fine-grained, deformed jadeites, whereas a few are coarse-grained, undeformed jadeites with large euhedral to subhedral crystals. Rhythmic zoning patterns of the coarse-grained jadeite crystals are easily observed both by cathodoluminescence and backscattered electron (BSE) images (Shi et al., 2005b), similar to the observations of the Guatemala jadeites (Harlow, 1994; Sorensen et al., 2006); details of the textures has been described elsewhere (Shi et al., 2009b). Jadeites in pure jadeites are very pure, with jadeite (Xsd) contents of more than 90 mol.% (Shi et al., 2003, 2005b). The iron spherules were selected from the pure jadeites.

3. TEXTURES AND COMPOSITIONS OF THE SPHERULES

The iron spherules were detected first under microscope during hand-picking of zircons from manually crushed jadeite (~5.8 kg, white to pale grey) sands sieved by 40–200 meshes following the normal separation procedure (crushing, sieving, gravity separation, electric-magnetic separation and then by microscopic selection) at the Langfang lab, Hebei Geology and Resource Bureau (e.g., Shi et al.,
2008). Being aware of their geological and potential cosmic implications if these spherules were not contamination, the first author then attempted to select spherules from another three jadeitite samples from Myanmar with the same separation procedure. This time an ultrasonic cleaner was additionally used to wash samples, and the crusher was cleaned several times more than the normal to avoid any possible contamination. Spherules with the same appearance were picked out from one jadeitite sample (~2.4 kg, white to slightly grayish). In total, 58 spherule grains from the two samples (together ~8.2 kg) were retrieved. The spherules were separated into two groups. One group of about 28
grains was mounted on epoxy resin, then abraded and polished for microscopic observations, electronic microscope analyses (EMPA) and backscattered electronic imaging. One abraded grain was then taken out for X-ray diffraction, mainly focusing on determining the phase of the cortex. The other group of 30 grains was first placed on graphite-adhesive plaster for scanning electron microscope (SEM) observations. After that, those grains were then used to obtain their iron isotope compositions.

The SEM images (Fig. 2) and spectra were obtained with LEO-21450VP system using an accelerating voltage of 15 kV. The EMPA data and BSE images (Fig. 3) were acquired with a CAMECA CAMEBAX SX51 system under the analytical condition of 15 kV and 20 nA beam current at the Institute of Geology and Geophysics, Chinese Academy of Sciences. EMPA standards include natural and synthesized minerals: andradite for Si and Ca, rutile for Ti, corundum for Al, hematite for Fe, eskolaite for Cr, rhodonite for Mn, Bunsenite for Ni, periclase for Mg, albite for Na, K-feldspar for K. Mineral formulae of jadeites and albites were recalculated using the software MINPET 2.0. For jadeite, a method based on “charge balance iron” was chosen, while for albite, all cations were recalculated as original data entered. After that, one of the abraded spherules (Fig. 3c) was taken out under binocular microscope and then analyzed using a single-crystal repeat-rotation X-ray diffraction method with a Bruker SMART APEX CCD area-detector diffractometer and using graphite-monochromatized Mo Kα radiation (λ = 0.7109 Å) at China University of Geosciences (Beijing), with a tube voltage of 50 kV and a tube current of 30 mA (Li et al., 2009). The powder pattern was obtained using

Fig. 1 (continued)
GADDS software (Häming, 2000) and the X-ray powder-diffraction pattern together with a pattern of wüstite standard is given in Fig. 4.

The spherules have off-centre iron nuclei and oxidized cortexes (since our spherules are similar to the texture of cosmic spherules from French Polynesia (see Kosakevitch and Disnar, 1997), we hereby adopt terms of nucleus and cortex henceforward). Their chemical compositions were also determined by energy spectra attached to the LEO-21450VP system (see Fig. 2a, b, a-1 and 2). The spherules are black and magnetic, and are about 50–300 \( \mu \text{m} \) in diameter. Their shapes are roughly round, with a long tail (Fig. 2a and d), a nearly flat edge or truncation (Fig. 2b, e and f), or completely round (Fig. 2c). SEM images of the spherules show
that most of their surface is smooth under low magnification, similar to the type-I spherules classified by Schmidt et al. (1963), while under high magnification some fine features can be observed. Around the dragging or flat rear, there are one or more rings on the surface, parallel to the outline of the flat rear (Fig. 2f), similar to shrinking features caused by rapid cooling. On the other side of the dragging or flat rear, there are abundant hill-like prominences tightly covering about one quarter to one half of the front area of the spherule (Fig. 2b, d, e and f). Each prominence has radial fine lines on its surface. Between the heads and dragging or flat rears the surfaces are somewhat smooth with fine vertical schlieren stripe patterns (Fig. 2b, d, e and f), similar to patterns caused by movement at high temperature. The completely round spherule is characterized by a rough surface with dendritic pattern partially covering its surface (Fig. 2c).

One spherule was smashed possibly during the crushing process, and its off-central nucleus is partly unveiled (Fig. 2a). The nucleus is round and closer to its front. The surface of the nucleus is round but not very smooth, strikingly similar to molten-like characteristics, i.e., the nucleus may have been at least partially melted before ultimately solidification.

The textures of cortex of spherules (Fig. 3c and d) are comprised of dendritic iron-oxide crystals. The iron-oxide crystal is identified as wüstit by X-ray diffraction (the analyzed spherule is the one shown in Fig. 3c), without detections of magnetite or hematite (Fig. 4). Radial needle-like wüstit in the inner cortex can be observed perpendicular to the surface of its pure-iron nucleus (Fig. 3c). The thickness of the cortex varies greatly, from as thin as 1 μm to more than 100 μm. There are some bubble-like vesicles, now filled with calcite, jadeite, albite or a mixture of these phases within the cortex (Fig. 3a and c).

Some spherules with flat rear are observed to contact jadeite crystals, the main constituent of the host jadeitite (Table 1). The lack of a gap on the border between jadeite and spherule (see Fig. 2b, e, a-1 and 2) show that they are tightly attached, suggesting that these spherules are not from contamination during the mineral separation process. Photomicrographs and backscatter electron (BSE) images on polished thin sections of the spherules (Fig. 3a and b) show that the spherules rear has shrinkage features and the jadeite crystal grew along its outline, suggesting that the spherules formed earlier than the attached jadeite crystals.
Chemical compositions of the nuclei are homogenous and consist of iron (>96.00 wt.%), with minor Cr (<1.50 wt.%), Mn (<0.80 wt.%), and Ni (0.142–0.23 wt.%), except for some bubble-like vesicles, now filled with calcite or Na–Al silicates suspected to be jadeite or albite (?). For the cortex, because of small sizes and dendritic shape of the wüstite, no accurate chemical composition has been obtained. The rough data show that 73.75–87.20 wt.% FeO is detected in the dendritic wüstite aggregates (Table 2). Other oxides detected include SiO₂ (5.43–8.24 wt.%), Al₂O₃ (1.68–3.73 wt.%), and Na₂O (0.41–1.80 wt.%). Within the spherules, there are a few tiny ball-shaped materials composed of SiO₂, Al₂O₃ and Na₂O (Fig. 3), compositionally resembling albite or jadeite (Table 1, not accurate due to small sizes or multiple phases). The cortex contains up to about 2.00 wt.% MnO, far more enriched than in the nucleus, whereas NiO content of the cortex (0.00–0.08 wt.%) is less than that in the nucleus.

The jadeite crystal in contact with the spherule is very pure with ~95% Jd. It is compositionally homogeneous except for slight changes of Fe, Mg and Ca. The analyses show that there is more Fe in the Jd grain adjacent to the spherule as opposed to the core of the Jd crystal, but Mg and Ca show the opposite trend. This zonation is consistent with the suggestion that the spherules formed earlier than the attached jadeite crystals.

4. FE ISOTOPE COMPOSITION OF THE SPHERULES

About 10 spherule grains were handpicked and cleaned ultrasonically in purified Milli-Q H₂O (18.2 MΩ) before digestion. The spherules were then digested as one sample using ultrapure 6M HCl on hot-plate at ca. 120 °C in class 100 fume cupboard. Sample solutions were evaporated to dryness after complete dissolution, and then converted to chloride form. In order to eliminate the matrix effects, samples were purified using anion exchange chromatography as described before (Zhu et al., 2002). The purified sample was measured for Fe isotopes on a Nu Instruments multiple collector plasma source mass spectrometer at high-resolution mode using a standard-sample bracketing approach; details of the mass spectrometry have been described elsewhere (Zhu et al., 2008). Briefly, solutions of standard and samples were introduced into the mass spectrometer through a DSN-100 desolvating nebulizer at 5 ppm
Fe in 0.1 M HNO₃ medium, and concentrations of sample and standard are matched to be within 10%. Runs of sample and standard were separated by washes using 2 M and 0.1 M HNO₃ for 3 and 2 min, respectively. Signals of ⁵⁴Fe, ⁵⁶Fe, ⁵⁷Fe were collected simultaneously together with ⁵³Cr, which was used to monitor the interference of ⁵⁴Cr on ⁵⁴Fe. In all cases ⁵³Cr signals were <10⁻⁴, and no ⁵⁴Cr correction was needed. Data were acquired in blocks of 10 ratios with 10-s integration times, and background measurements were taken prior to each data block. The Fe isotope results are expressed as deviations of a Fe isotope ratio of a sample from that of the reference material IRMM-14:

\[
\delta^{56}\text{Fe}_{\text{IRMM-014}}(\%o) = \left(\frac{\text{Fe}_{\text{sample}}}{\text{Fe}_{\text{IRMM-014}}} - 1\right) \times 1000
\]

\[
\delta^{57}\text{Fe}_{\text{IRMM-014}}(\%o) = \left(\frac{\text{Fe}_{\text{sample}}}{\text{Fe}_{\text{IRMM-014}}} - 1\right) \times 1000
\]

The sample was measured in triplicate, and the average \(\delta^{57}\text{Fe}\) is 0.78 (Table 3).

### 5. DISCUSSION AND CONCLUSIONS

#### 5.1. Origins of the spherules

Native iron and spherules can have either an extraterrestrial origin, i.e., cosmic spherules, or a terrestrial origin from volcanic explosive eruptions, impact ejecta, xenoliths, etc.
in basalt, in serpentine rocks or by biological reduction process. The structures, textures, chemical compositions and Fe isotope compositions of the spherules from the Myanmar jadeite, however, suggest that these are type-I deep-sea cosmic spherules. Their textural features of off-central iron nucleus and oxide cortex are similar to type-I cosmic spherule patterns described by Kosakevitch and Disnar (1997). It has been reported that there are three types of cosmic spherules: the stony- or type-S which are chondritic, the type-G (dendritic magnetite in glass) and the type-I or iron (nonchondritic), among which type-I is characterized by a metallic core and oxidized cortex (Blanchard et al., 1980; Brownlee, 1985; Kosakevitch and Disnar, 1997; Herzog et al., 1999). Apart from this iron core and iron-oxide cortex, other features of the spherules in the Myanmar jadeites suggest that they have undergone oxidization and subsequent rapid cooling at very high temperature.

The pattern of radial iron-oxide needles perpendicular to the iron nucleus shows that the iron-oxide cortex formed at the expense of the iron core. Cosmic spherules having structures and textures similar to ours (dendritic wüstites perpendicular to iron core) have not been reported before. This pattern, geometrically, looks like the typical replacement texture such as coronal kosmochole on chondrites (Shi et al., 2005a). Dendritic wüstite crystals in the cortex (Fig. 3) are inferred to crystallize quickly from a melt of the iron core at very high temperature, and the shrinkage features on the surface of the iron core (Fig. 2) also suggest that the core had once experienced a period at temperature above the melting point of iron (1535°C at room pressure). Wüstite, Fe<sub>1-x</sub>O, rarely occurs naturally in near-surface rocks, since FeO is highly reactive with SiO<sub>2</sub>, leading to preferred incorporation of Fe into silicate minerals, thus its preferential occurrences are in metallurgic slags, meteorites and as inclusions within diamonds (Waychunas, 1991). It normally forms under conditions of very low oxygen fugacity, temperatures above 570°C, and SiO<sub>2</sub>-undersaturation (Lindsley, 1991; Seifert et al., 2010). Contrasting characteristics between the front and the rear of an individual spherule (Fig. 2) show the effects of varying temperatures; the front having abundant prominences had experienced higher temperature than the rear. This difference can be explained by movement through the atmosphere (oxidization medium), and a reasonable explanation for such high temperatures and gradients is that the spherules are type-I spherules.

In comparison to the most commonly reported typical type-I spherules (e.g., Brownlee, 1985; Kosakevitch and Disnar, 1997; Herzog et al., 1999), the spherules in the present investigation have the same structure with off-central nucleus and cortex, showing a compositional trend of decreasing Ni and increasing Cr from core to cortex (Table 2), as well as cooling structure/textures. The Myanmar spherules have low Ni concentrations of less than 1.0 wt.% lower than most type-I cosmic spherules (Herzog et al., 1999; Basu et al., 2003; Gounelle et al., 2003; Taylor et al., 2005), but similar to some minor type-I cosmic spherules containing iron cores with very low nickel contents. The Ni-poor spherules could be from pre-existing metal and sulfide, or produced by the reduction of low-Ni sulfide or silicates in the interior of the decelerating object, in such cases the droplet begins to cool before appreciable Rayleigh fractionation takes place (e.g., Xue et al., 1995; Herzog et al., 1999). Other supportive evidence includes the existence of pure iron nuggets from chondritic meteorites that lack obvious fractionation and enrichment process (Miono et al., 1999).

The Fe isotope compositions of the spherules (Table 3) are lighter than most type-I spherules (Davis et al., 1991; Davis and Brownlee, 1993; Herzog et al., 1999; Engrand et al., 2005). The data of Engrand et al. (2005) fall on the terrestrial fractionation line with δ<sup>56</sup>Fe values ranging from 50.3 ± 0.2 to 50.2 ± 1.0 (average δ<sup>56</sup>Fe = 40.3 ± 7.3‰) and δ<sup>56</sup>Fe values from 20.8 ± 3.0 to 26.2 ± 1.0 (average δ<sup>56</sup>Fe = 29.3 ± 5.2‰), whereas our values are 0.51 and 0.78 for δ<sup>56</sup>Fe and δ<sup>57</sup>Fe, respectively. On the other hand, our values are significantly heavier than the bulk silicate Earth: they are higher than terrestrial basalts (δ<sup>56</sup>Fe = 0.76 ± 0.02‰), high Ti basalt (δ<sup>56</sup>Fe ≈ 0.2‰), Weyer et al., 2005), four international granitoid standards (δ<sup>56</sup>Fe/δ<sup>56</sup>Fe ≈ 0.118–0.132‰), gabbros and tonalites (δ<sup>56</sup>Fe ≈ 0.03–0.09‰) to granodiorites and silicate dykes (δ<sup>56</sup>Fe ≈ 0.14–0.23‰) (Schoenberg and von Blanckenburg, 2006). They are also higher than the spinel from fore-arc and continental margins (δ<sup>57</sup>Fe = –0.50 ± +0.36‰, Williams et al., 2004). Williams et al. (2004) also report two higher δ<sup>57</sup>Fe values (0.96‰ and 1.20‰) of spinels, but their spinels come from continental (intraplate) zone, and the geological setting is totally different from the intra-oceanic subduction zone of the Myanmar jadeite revealed by mantle-depleted Hf isotope signatures (Shi et al., 2009a,b), thus they cannot be compared. Hence we interpret the spherules from the Myanmar jadeite as type-I spherules lacking significant fractionation of iron isotopes.

Spherules can also be produced by means of impact ejecta. Lowe and Byerly (1986) identified layers containing sand-sized spherical particles spherules, which they interpreted to represent quenched liquid silicate droplets in the Barberton Greenstone Belt, South Africa and Eastern Pilbara Block, Western Australia. These droplets formed as a result of large Archean meteorite or comet impacts (Lowe and Byerly, 1986; Kyte et al., 2003). On the Nunsvaqu peninsula, Western Greenland, glass spherules were also found in sedimentary deposits (Jones et al., 2005). These are round iron-rich silicate glass grains with a very characteristic signature of meteorite impact ejecta, but as yet, no iron core spherules have been found. This is in agreement with the theoretical work by Ebel and Grossman (2005), which have shown that condensate from astrobomes on Earth do not yield metal because of reaction with Earth’s atmosphere, and the high-T condensate phases are oxides, particularly spinels.

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Bioconcentration processes (e.g., Propp and Propp, 2004) are expected to be insignificant under the high-P low-T conditions in subduction zones and are thus excluded. Irons could conceivably have formed from reduction by bacteria or by serpentinization and rodingitization (e.g., Palandri and Reed, 2004; Propp and Propp, 2004) and then experienced oxidation on the seafloor, but the resulting occurrence should not have the same wüstite cortex and off-central structure as the present spherules.

We conclude that the spherules from the Myanmar jadeite are type-I cosmic dust/spherules, chemically similar to the minor type-I cosmic dust/spherules with iron nucleus. Cosmic dust can be used to investigate properties of the interplanetary medium (Blanchard et al., 1980; Brownlee, 1985), reactions with Earth’s atmosphere during its entry (Kosakevitch and Disnar, 1997), terrestrial environments (Raukas, 2000), and geodynamic process (in this investigation). Cosmic dust is recovered or collected from four main sources: (1) historical deposits in deep-sea sediments (e.g., Brownlee, 1985; Herzog et al., 1999), (2) Greenland lake deposits (Maurette et al., 1991), (3) Antarctic ice (Taylor et al., 1998; Genge et al., 1997), and (4) the stratosphere (Brownlee, 1985). Other sources for cosmic spherules such as magmatic rocks, have been occasionally reported (e.g., Wang et al., 1995), but not widely acknowledged because of no convincing observations. Type-I spherules are rare among those recovered from Antarctic ice deposits: for instance, 1588 cosmic spherules collected from the bottom of the South Pole Water Well by Taylor et al. (2000) include only 2% type-I spherules. They are relatively common, however, among cosmic spherules found in deep-sea sediments (Maurette et al., 1991; Taylor et al., 1998), where they are simply more readily found among materials that fall into the deep-sea ooze (e.g., Herzog et al., 1999).

5.2. Preservation of the spherules

Because the Myanmar jadeites have been considered to form from fluids related to dehydration of seawater-altered oceanic crust or serpentinite minerals under high pressure and low temperatures in a subduction zone (Harlow, 1994; Essene and Fyfe, 1967; Shi et al., 2005b, 2009a; Sorensen et al., 2006; Harlow et al., 2007), the spherules from the jadeite are likely to have experienced a series of events including: entry through the atmosphere, landing on seafloor, transport with the oceanic slab into a subduction zone, high P/T metasomatism/metamorphism along with entrainment by jadeite, and ultimate exhumation. These processes can be traced back to Late Jurassic when the jadeite formed (Shi et al., 2008). However, these spherules are well-preserved, their shapes and chemical compositions are not obviously altered. This may be attributed to: their small sizes, SO₂-Al₂O₃-Na₂O filling materials within the cortex, relative low temperature of formation of the Myanmar jadeite, and its texture.

The approximately 10 wt.% of SO₂ + Al₂O₃ + Na₂O material present within the cortex (Table 2) possibly formed from the jadeite forming fluids, and could have made the spherules stronger and more resistant to high P/T metasomatism/metamorphism, and deformation during/after formation of the Myanmar jadeite. A reduced environment, revealed by primary methane (CH₄)-bearing fluid inclusions found in the jadeite (Shi et al., 2005b) may have a positive effect in keeping the spherules from oxidized alteration, and iron and wüstite could be stable under the rather lower formation temperatures of about 250–370 °C (Shi et al., 2003) of the jadeite relative to the high temperatures at which the spherules formed. In addition, the small-size and spherical shape of the spherule with filling materials might survive and remain stable even in a heavily sheared environment (Sorensen et al., 2006). The textural juxtaposition (Fig. 3a) and texture of the jadeite (see Shi et al., 2009b for detail) suggest that the Jd grain could be a barrier to prevent alteration of small round spherules included within the jadeite.

The discovery of type-I spherules in high P/T rocks indicates that iron spherules landing on the deep-sea floor can be preserved during recycling of the oceanic slab in a paleo-subduction zone. Cosmic spherules have fallen on the earth’s surface since its formation, but most collected have young falling ages because of weathering. This discovery, therefore, provides us a clue that there is another source for collecting iron spherules, i.e., from HP rocks associated with subducted slabs possibly at any geological time, even in Archean ages (e.g., Schmitz et al., 2004).

5.3. Implications for petrogenesis of the jadeite

Discovery of the spherules in the Myanmar jadeite provides evidence for petrogenesis of jadeite: subducted oceanic slab sediments play an important role in the formation of the jadeite. Though previous genetic models for the origin of pure jadeite include metasomatism and metamorphism (Coleman, 1961; McBurney et al., 1967), pressure solution and re-deposition in fractures (Harlow, 1994), and recent observations increasingly indicate a metasomatic origin (Shi et al., 2003; Harlow and Sorensen, 2005; Sorensen et al., 2006), as the presence of a hydrous fluid during formation of jadeite is documented by primary fluid inclusions in jadeite from the jadeite (Johnson and Harlow, 1999; Shi et al., 2005b). The source for the required aqueous solution rich in Na, Al, and Si but poor in K is still not fully understood, however. By far the most revealing evidence, the finding of Ba minerals in the Guatemala,
Japanese and Myanmar jadeites (Harlow, 1995; Morishita, 2005; Shi et al., 2010), suggests that jadeite-forming materials might have been derived from subducted oceanic crust. However those Ba minerals have undergone multiple chemical reactions, thus the evidences are indirect. In addition, there are jadeites that contain inclusions of other metamorphic rocks associated with the subduction channel or mélangé (Shigeno et al., 2005; Harlow et al., in press). For instance, Shigeno et al. (2005) suggested that the jadeite core was produced by an isochemical breakdown of albite under increasing P/T conditions. Albite is petrogenetically closely related to jadeite, however, the origin of albite in subduction zones is even more poorly understood than that of jadeite. Combined with findings of a low-salinity, seawater-like fluid in jadeite (Johnson and Harlow, 1999; Shi et al., 2005b), the finding of type-I like spherules in the Myanmar jadeite allow us to suggest that the jadeite-forming materials were derived from, or at least partially from oceanic sediments on subducted altered oceanic crust, coupled with dehydration of the sediments and the altered oceanic crust (e.g., Shi et al., 2009a; Simons et al., 2010; Harlow et al., in press).

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