

REVIEW

Jadeitite (jadeite jade) from Japan: History, characteristics, and perspectives

Tatsuki TSUJIMORI^{*,**} and George E. HARLOW^{***}

^{*}Center for Northeast Asian Studies, Tohoku University, Aoba, Sendai 980-8576, Japan

^{**}Department of Earth Science, Tohoku University, Aoba, Sendai 980-8578, Japan

^{***}Department of Earth and Planetary Sciences, American Museum of Natural History,
Central Park West at 79th Street, New York, NY 10024-5192, USA

Jadeitite, known as ‘*hisui*’ in Japan, has been esteemed as sacred stone in both ancient and modern Japanese cultures. Although it was thought that the source material of Japanese jadeitite was brought from China, the identification of jadeite in 1939 changed this interpretation. Japanese jadeitites and jadeite-rich metasomatic rocks are found in Paleozoic and also Mesozoic geotectonic units. All localities are situated in serpentinite mélangé with high-pressure metamorphic rocks and/or serpentinite lenses within a high-pressure metamorphosed complex. Outcrop exposures of contact between jadeitite and host serpentinite are extremely rare. Normally the jadeitites show lithological heterogeneity in the same locality due to multiple deformation, recrystallization, and metasomatic fluid infiltration. Studies over the last two decades have interpreted jadeitite in worldwide either as the direct aqueous fluid precipitate (P-type) from subduction channel into the overlying mantle wedge, as the metasomatic replacement (R-type) by such fluids of oceanic plagiogranite, graywacke, or metabasite along the channel margin, or a combination of these two processes. Japanese jadeitites are classified into one or the other type. Multiple stable isotope characterization analyses for jadeitite and related metasomatic rocks and serpentinite become increasingly important to decode fluid behaviors in past subduction zone. However, available geochemical data on Japanese jadeitite are very limited in comparison with other studied localities. More systematic research will unlock new insights about fluid flow and its impacts at the bottom of forearc mantle where jadeitites form. Chemical differentiation and transportation of the fluids involved in jadeitite-formation are crucial topics requiring further research. Nevertheless, the designation of jadeite (and jadeitite) as the national stone of Japan by the Japan Association of Mineralogical Sciences in 2016 should bolster education of the public about this revered stone and its role in subduction zone processes.

Keywords: Jadeitite, Jadeite jade, High-pressure metamorphism and metasomatism, National stone of Japan

INTRODUCTION

Jadeitite (‘jadeite’ jade) is a nearly monomineralic rock composed primarily of a dense ($\sim 3.4 \text{ g/cm}^3$), sodium aluminum silicate, jadeite ($\text{NaAlSi}_2\text{O}_6$), typically from ~ 80 to 100 vol%. It is a petrotextonic indicator found only in Neoproterozoic and younger orogenic belts (Stern et al., 2013, 2016). At least 19 jadeitite localities demonstrate that jadeitite-bearing serpentinite-matrix mélangé was exhumed to the Earth’s surface along major transform-type or thrust faults cutting the paleo-forearc or accretionary wedge (Harlow et al., 2015). *P-T* conditions of jadeitites

correlate to forearc mantle wedge and high-pressure metamorphism within a Pacific-type subduction zone at relatively shallow depths ($< \sim 100 \text{ km}$). Jadeitite is a physically tough rock, used by Neolithic cultures as a tool stone, and can sometimes be translucent, intensely colored, and, thus, precious, as in the case of luminous green ‘imperial jade’, ‘*feitsui*’ in China, and ‘*hisui*’ in Japan. In Japanese culture since at least the 8th century, the semi-translucent, white/green, gem-quality jadeitite has been a symbolic stone as attributed with mystic (or talismanic) qualities revered by ancient personages. In addition to the rarity and preciousness of jadeitite, the high density, near-monomineralic constitution and cryptic geological context intoxicated geological scientists before the plate tectonic revolution (e.g., Kunz, 1906; Lacroix, 1930; Yod-

er, 1950; Coleman, 1961) and then, when connected to exhumed subduction contexts, inspired those who have followed (e.g., Dobretsov, 1984; Chihara, 1971; Nishiyama, 1978; Harlow, 1994; Miyajima et al., 1999; Harlow et al., 2004; Tsujimori et al., 2005; Sorensen et al., 2006; García-Casco et al., 2009; Yui et al., 2010; Fu et al., 2010). Extra-terrestrial jadeite found in shocked stony meteorites (e.g., Ohtani et al., 2004) have also attracted high-pressure mineral physicists; see review by Ohtani et al. (2017).

Although the ‘rock-crystal’—transparent colorless variety of quartz—was once suggested as a symbolic gemstone linked to Japan (Kunz, 1913), the Japan Association of Mineralogical Sciences has newly designated jadeitite as the national stone of Japan in 2016 (Tsuchiyama, 2017). This designation would bolster geoscience outreach activities, especially offering an outstanding opportunity to educate how and where jadeitite could form. Moreover, the designation will enhance interdisciplinary scientific cooperation among geoscientists across areas of study and national boundaries, through joint research projects, meetings and workshops.

The current hot topics on jadeitite research in the geosciences reflect their significance regarding subduction zone fluid behaviors and the fluid-mediated processes of oceanic subduction, slab-mantle-fluid interactions, serpentinization, geochemical circulation, and exhumation of high-pressure rocks. Since a comprehensive review by Harlow and Sorensen (2005), several update reviews (Harlow et al., 2007, 2011; Tsujimori and Harlow, 2012; Shi et al., 2012; Flores et al., 2013; Franz et al., 2014; Harlow et al., 2014, 2015, 2016) and one special issue related to jadeitite (Harlow et al., 2012) as well as numerous research papers have been published. Gemological perspectives on Japanese jadeitite were also summarized recently by Abduriyim et al. (2017). Among many new descriptions and data are zircon U-Pb geochronology, trace-element and stable isotope geochemistry; see the recent reviews by Harlow et al. (2015, 2016). Although some of the information was already summarized in the previous reviews, in this article for the special volume relating to the designation of ‘jadeitite’ as a symbolic rock of Japan, we give a broad overview of the Japanese jadeitites, along with comparisons to overseas jadeitite. Specific foci in this review include (1) historical facts before the first identification (Kawano, 1939), and (2) comparisons of specific features and research problems concerning Japanese jadeitite with those of other occurrences. We will also address perspectives on jadeitite research.

In this review, the term ‘jadeitite’ is used for any jadeite-rich metasomatic or metamorphic rocks. Note that the IUGS Subcommittee on the Systematics of Metamorphic Rocks recommends that the suffix added to a

mineral name to generate a rock name requires ≥ 75 vol% of that mineral (Fettes and Desmons, 2007). Before getting to our focus topics, we summarize the scientific consensus on jadeitite formation.

WHERE AND HOW JADEITITES FORM

Over the last decade, geological interpretation of the jadeitite has evolved with the understanding of high-pressure processes in subduction channels, trace elements and isotopic studies, experimental petrology, and geodynamic modeling (Harlow et al., 2015). According to the current knowledge, jadeitites serve as a proxy for the related mass transfer within a subduction zone at relatively shallow depths (<100 km). New interpretations revisited the recognition of two type of jadeitite, i.e., vein-forming fluid-precipitation and metasomatic replacement (Coleman, 1961). Tsujimori and Harlow (2012) classified the two types as precipitated (P-type) and replacive (R-type) jadeitite, respectively, whereas Yui et al. (2012) interpreted a Type-I (R-type) and Type-II (P-type) based on the interpretation of the origin of zircon in jadeitite. The P-type jadeitite does not manifest a protolith and thus shows no evidence of isochemical transformation or pseudomorphic replacement of any precursor rocks. In contrast, the R-type partially preserves textural, mineralogical, or geochemical evidence of a preexisting protolith, such as plagiogranite or metagraywacke-like rock. The occurrence of relict chromite and kosmochlor pseudomorph after chromite in some jadeitites further indicates reaction between jadeitite and host ultramafic rocks.

Globally recognized jadeitite localities are shown in Figure 1. Thus far, up to 20 deposits have been documented in the world (see Harlow et al., 2015). Most jadeitites belong to the P-type and are considered to have precipitated directly from a Na-Al-Si-rich aqueous fluid in some cavity, crack, and fracture in serpentinized peridotite or a high-pressure metamorphic rock (Fig. 2). Jadeitites form under *P-T* conditions that are somewhat hotter than expected for the subduction interface, even compared to hot subduction zones where young crust is subducted, for example beneath Southwest Japan (Fig. 3). This further suggests that jadeitite forms in the warmer mantle wedge, above the subduction interface (Fig. 4).

HISTORICAL TRIVIA OF JAPANESE JADEITITE

From the middle 19th century, a study on jadeitite (‘jadeite’ jade; also known as ‘imperial jade’ or ‘*feitsui*’ in China and ‘*hisui*’ in Japan) has been a topic of multidisciplinary research to identify archaeological ornaments and implements rather than mineralogical research. Since the

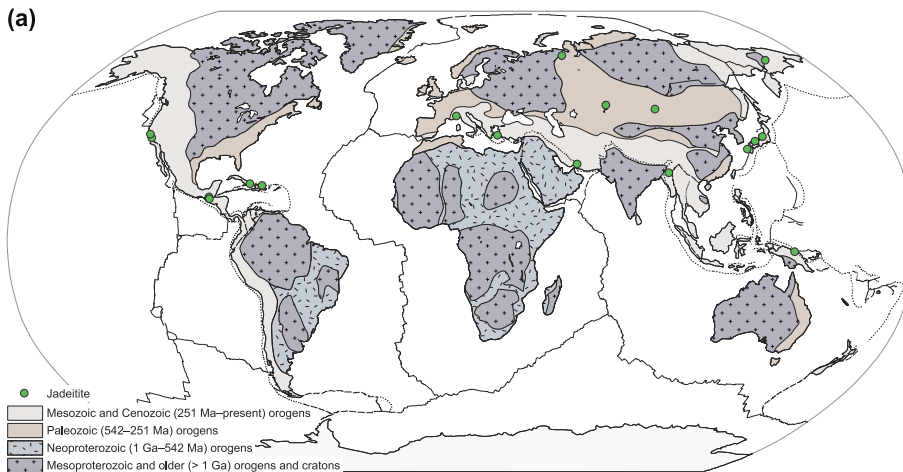


Figure 1. (a) World map of jadeite occurrences and plate boundaries. Continental crust ages are modified after Tsujimori et al. (2006). (b) Geotectonic subdivision of the Japanese Islands (modified after Isozaki et al., 2010), showing localities of jadeites and jadeite-rich metasomatic rocks.

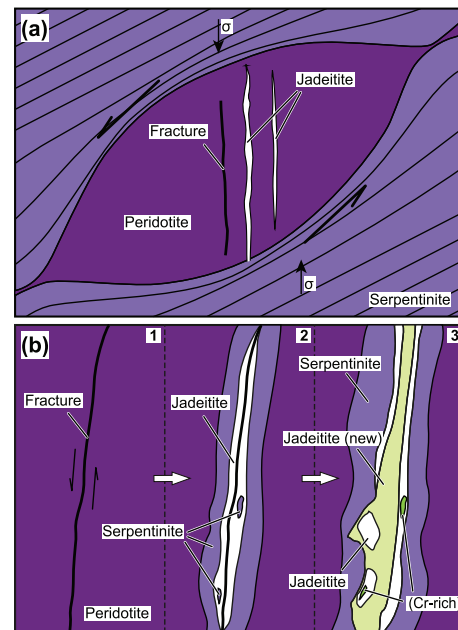
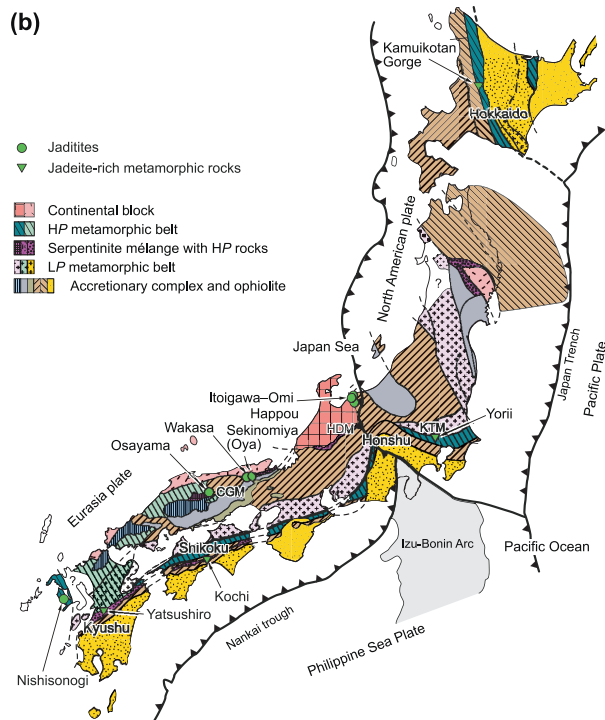


Figure 2. Diagram of model for jadeite formation in veins in peridotite (modified after Harlow et al., 2015). (a) A boudinaged less-serpentinized peridotite with hydrofractures with jadeite precipitation (P-type jadeite). This model is based on Nicolas and Jackson (1982)'s Figure 3 (boudinaged pyroxenite layer with syntectonic gabbroic veins). (b) Step-wise fluid infiltration along the fracture/fault to form multi-generation P-type jadeite (after Harlow and Sorensen 2005). As in Figure 3, the width of these veins and blocks can vary from about 1.5 to 50 m.

first chemical and density analyses of Neolithic 'jadeite' axe by Alexis Damour (1808–1902), a French mineralogist, jadeite ('jadeite' jade) began to be distinguished from 'nephrite' jade (e.g., Damour, 1863, 1866; see Foshag (1957) for the interesting story). Given its beauty and archeological interest, the jadeite objects became a great collection target for archeologists and antiquarians.

In the history of jadeite study, George Frederick Kunz (1856–1932), an American mineralogist, was the first one who tried to summarize knowledge of 'jadeite' jade and 'nephrite' as a book entitled, 'The Bishop Collection. Investigations and Studies in Jade', (Kunz, 1906). In the book, Henry S. Washington's chapter reviewed 'Localities and geological occurrence of jade', and stated

that 'A small number of worked jade objects have also come from Japan, but probably in the course of commerce from China, as we have the explicit statement of Mr. Wada, formerly professor of Mineralogy at the University of Tokio, and ex-Director-General of the Geological Survey of Japan, that jade is not found geologically in that country.' Note that Washington was the first one to have described whole-rock compositions of Japanese blueschists from Sambagawa and Kamuikotan belts in 1901; see

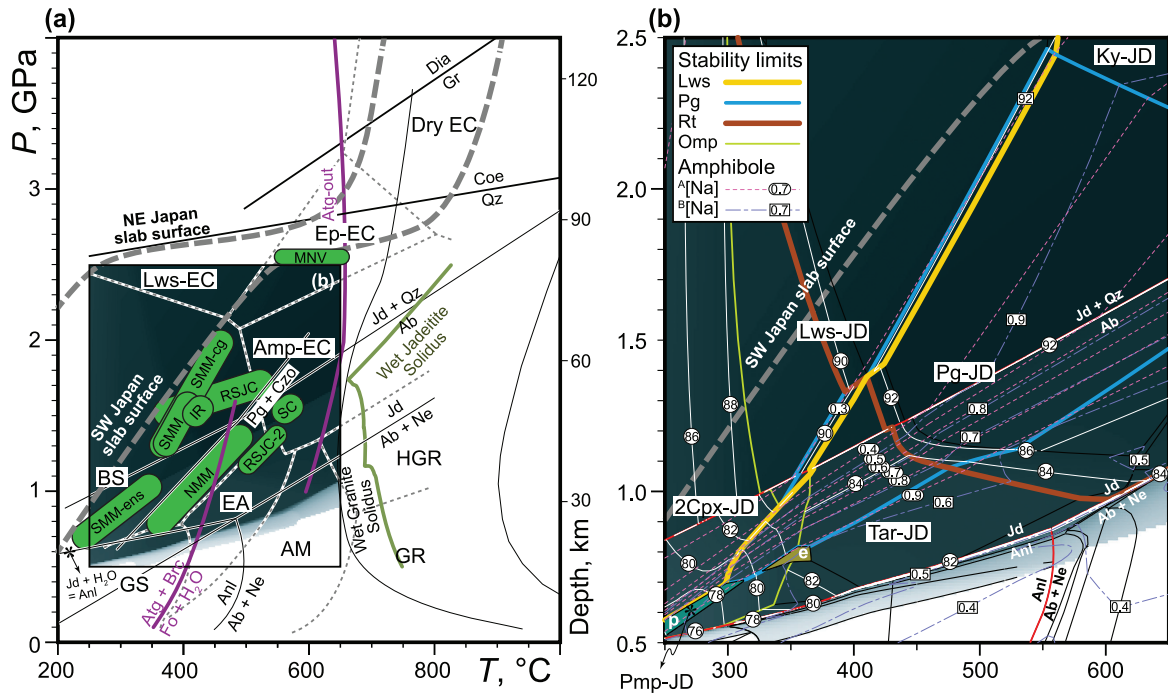


Figure 3. (a) A P - T diagram showing approximate P - T conditions of selected jadeitites from Guatemala, Cuba, Iran, Dominican Republic, and Italian Alps (modified after Tsujimori and Harlow, 2012; Harlow et al., 2014; NMM, Northern Motagua Mélange (Guatemala); SMF, Southern Motagua Mélange (Guatemala); SC, Sierra del Convento (Cuba); IR, Iran; RSJC, Rio San Juan Complex (Dominican Republic); MNV, Monviso (Italy)). Reaction curves limiting jadeitite-bearing mineral equilibria, antigorite, paragonite + clinozoisite assemblage, and modelled wet jadeitite solidus (this study) and P - T paths (model D80 of Syracuse et al., 2010) for slab surfaces, both warm (SW) and cool (NE Japan) subduction zones are also shown. The metamorphic facies boundaries are after Maruyama et al. (1996) and Liou et al. (2004); a boxed P - T space (250–650 °C and 0.5–2.5 GPa) is indicated as P - T pseudosection for panel (b). Metamorphic facies abbreviations: BS, blueschist; AM, amphibolite; Lws-EC, lawsonite eclogite; Ep-EC, epidote eclogite; Amp-EC, amphibole eclogite; Dry-EC, dry eclogite; GS, greenschist; EA, epidote-amphibolite; GR, granulite; HGR, high-pressure granulite. (b) A P - T pseudosection calculated for the average SMM jadeitite composition (see Harlow et al., 2015). The color gradation level represents modal volume of jadeitic clinopyroxene; white thin lines with numbers are contour lines. Contours of amphibole composition (Na in the A - and B -sites) are also shown as pink and blue dotted lines. Jadeitite mineralogical-type abbreviations: Lws-JD, lawsonite jadeitite; Pg-JD, paragonite-jadeitite; Tar-JD, taramite-jadeitite; 2Cpx-JD, two pyroxene (jadeite + omphacite) jadeitite; Ky-JD, kyanite-jadeitite. P and E represent stability of pumpellyite and epidote-group mineral, respectively.

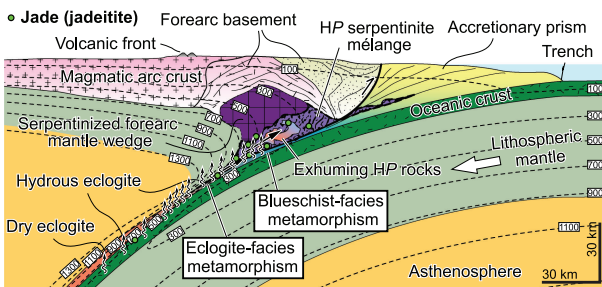


Figure 4. Cross-section showing a Phanerozoic Pacific-type subduction zone where jadeitite forms (modified after Tsujimori and Ernst, 2014). Lithological variations and thermal structures are based on numerical modelling by Gerya (2011). Temperature contours (dotted lines) are in °C. Inferred occurrences of jadeitite in the cross-section are shown by green circles. P-type jadeitite forms in fractures in serpentinizing mantle wedge peridotite (See the details in text).

Washington (1901). Although it was thought that the Japanese jadeitite material was brought from China (Fischer,

1884), this was the first professional note about Japanese jadeitite in an English-written literature. Geological connection between jadeitite and blueschist was already made in the Washington's chapter of Kunz (1906)—‘*These schists are of a peculiar blue color, often running into epidotite and garnetiferous rocks, so as to be usually easily recognizable, and their presence in any region would lead us to hope for the occurrence of jadeite in situ*’.

Prior to the Kunz's book, ‘jadeite’ jade (*‘kōgyoku’*; *‘ying yü’* in China) as a material of archeological objects, such as *‘magatama’*, were translated to ‘nephrite’ rather than ‘jade’; see *‘Notes of Japanese Archeology with Especial Reference to the Stone Age’* (von Siebold, 1879) and *‘Notes on Ancient Stone Implements, & C. of Japan’* (Kanda, 1884). In contrast, Kenji Takahashi (1911) used ‘jade’ instead of ‘nephrite’ to describe *‘kōgyoku’* in his Japanese-written archeology book. In archeology in the late 19th and the early 20th century, however, the ‘jade’

was a synonym of ‘nephrite’. As a member of amphibole supergroup (tremolite or actinolite), it was distinguished from ‘jadeite’ of the pyroxene group (e.g., Kunz, 1906, 1913; Washington, 1922; Forde, 1930).

In the first Japanese ‘modern-style’ mineralogy textbook (Kotō, 1886), an English term ‘jadeite’ was assigned for a variety of alkaline pyroxene, but the Japanese term for the ‘jadeite’ was ‘*nangyoku*’ (‘*ruan yū*’ in China). Instead ‘nephrite’ as a variety of amphibole was used for ‘*kōgyoku*’. This was totally opposite usage of modern terminology. The mis-assignment of ‘jadeite’ for ‘*nangyoku*’ was corrected in Kotō (1897) and also in a next generation textbook (Sato, 1918); in the Sato’s textbook, the ‘Nangyoku’ and ‘nephrite’ were used for fibrous actinolite. A brief note on two different ‘jade’ (‘*kōgyoku*’ and ‘*nangyoku*’) was also presented by Susuki (1910) in the Journal of the Geological Society of Japan; he introduced the English terms ‘jadeite’ for ‘*kōgyoku*’ and ‘nephrite’ for ‘*nangyoku*’. The first mineralogical identification of jadeitite from the Kotaki-gawa River of the Itoigawa area was published in 1939 by Yoshinori Kawano of Tohoku University. He used a term ‘*hisui*’ instead of ‘*kōgyoku*’ to describe ‘jadeite’, because the sample was greenish in color. In the Japanese geoscience community, the ‘*kōgyoku*’ has been used as a scientific term to describe the pyroxene member ‘jadeite’ until the late 1960s (e.g., Banno, 1961; Seki, 1966). In order to avoid misunderstanding among the minerals with the same pronunciation (e.g., ‘*kōgyoku*’ as corundum and ruby), the mineralogical term ‘*kōgyoku*’ was replaced by the new term ‘*hisui kiseki*’ in Japanese-written articles and textbooks (e.g., Miyashiro, 1966).

CHARACTERISTICS: COMPARISON WITH OVERSEA JADEITITES

Occurrences

Occurrences of worldwide jadeitite have been extensively reviewed (c.f. Harlow and Sorensen, 2005; Harlow et al., 2015). Up to twenty localities have been reported in four Phanerozoic orogenic belts (circum-Pacific, Uralides and Central Asia/Altaids, Caribbean, and Alps-Himalayas), excluding xenoliths in kimberlitic pipes (Fig. 1). All localities are situated in serpentinite-dominant geotectonic unit or body, such as blueschist-bearing serpentinite mélange, dismembered ophiolites, high-pressure metamorphosed ophiolites, serpentinite diapir, serpentinite lenses within a high-pressure metamorphosed complex. Most localities lie along major transform-type or thrust faults cutting the paleo-forearc or accretionary wedge. Serpentinite exhumation processes would be important to the

preservation of jadeitite and may also explain the rare occurrence of jadeitite. Occurrence of Japanese jadeitites in the Itoigawa-Omi, Happou, Sekinomiya (Oya), Wakasa, Osayama, and Nishisonogi areas are not exceptional, but the exposure as outcrop is extremely rare.

Coleman (1971) pointed out the tectonic significance of the ophiolite-blueschist belts with jadeitite or eclogite within the ‘exhumed subduction or obduction zones’; he addressed a plate tectonic convergent margin process. As summarized by Tsujimori and Harlow (2012), high-pressure type metamorphic rocks occurs in many of jadeitite localities. The pressure-favored stability of jadeitite and the close association of jadeitite and high-pressure metamorphic rocks naturally indicate jadeitite formation at a paleo subduction zone. In some localities, jadeitite-formation is significantly older than the associated high-pressure metamorphic rocks (e.g., Itoigawa-Omi and Osayama: see Tsujimori, 2017).

Appearance

Worldwide, jadeitite exhibits hues of not only white but also vivid green, green, blue-green, blue, violet (known as ‘lavender’ color), yellow, grey and black (e.g., Hughes et al., 2009; Franz et al., 2014; Harlow et al., 2014). In term of color appearance, Japanese jadeitite covers most variations in worldwide jadeites (See Fig. 5 of Abduriyim et al., 2017). Selected appearance of Japanese jadeitite are shown in Figure 5. The same as with other localities, lithological appearance of Japanese jadeitite is variable. So far, translucent gem varieties are limited to the Itoigawa-Omi area and the Wakasa area; violet-color variations are not limited to the Itoigawa-Omi area (Figs. 5a and 5b). In the marketplace, it is hard to discriminate Japanese jadeitite from Myanmar jadeitite. Blue jadeitite in the Itoigawa-Omi area (Figs. 5d-5f) has a similar appearance to some Guatemalan South Motagua Mélange jadeitite. Coarse-grained jadeitite in Nishisonogi are also indistinguishable in eyes from some Guatemalan North Motagua Mélange jadeitites and some Russian West Sayan jadeitites. Black jadeitite with abundant carbonaceous matter is found in the Itoigawa-Omi area. Carbonaceous matter-bearing tremolite-talc rocks are often associated with the Osayama jadeitite. The carbon-bearing black jadeitites are also found in Guatemala and California. Pyrite-rich variety that was described as ‘Galaxy Jade’ from Guatemala have not yet found in Japanese localities.

Jadeitites are sometimes veined by multiple jadeite crystallization (e.g., New Idria jadeitite: Takahashi et al., 2017). Veined jadeitite are also found in some Japanese localities (Fig. 5c). In the Itoigawa-Omi area, rare pargasitic amphibolite veins crosscut jadeitite (Fig. 5g); very

rare contact relationship jadeitite and amphibolitic rock are also found (Fig. 5h).

Jadeite-rich metasomatic rocks and metasomatic jadeite veins cutting metamorphic rocks have been described from both Paleozoic and Mesozoic metamorphic belts in Japan [e.g., Kochi, Yatsushiro, Yorii, and Kamui-kotan Gorge (Tsuji-mori, 2017; Nishiyama et al., 2017; Hirajima, 2017)]. Such local jadeitite veins and pods are normally associated with lawsonite blueschist localities, like the case in the Dominican Republic (Maresch et al., 2012) and Ward Creek (Banno et al., 2000).

Microtextures

In analogy with appearance of jadeitite, microtextures of jadeitite are highly variable due to grain size diversity, multiple deformation, recrystallization, and metasomatic fluid infiltration. Cathodo-luminescence (CL) petrography is a powerful and effective way of characterizing microtexture of jadeitite (Fig. 6). A variation of CL brightness and color readily provides valuable information on subtle stepwise compositional differences of jadeite crystals in jadeitite (Harlow and Sorensen, 2005; Sorensen et al., 2006; Maresch et al., 2012; Takahashi et al., 2017). In general, CL brightness and color of jadeite are contributed by the existence of luminescence centers, such as impurities and lattice defects (e.g., Takahashi et al., 2017). Sorensen et al. (2006) shows an optical CL image of Kōtaki jadeitite of the Itoigawa-Omi area. The image (Fig. 2a of Sorensen et al. 2006) shows partial resorption and illustrates the relative order of jadeite crystallization; the overgrowths on jadeite grains are characterized by yellow-green luminescence that is also common in Myanmar, Guatemala and Kazakhstan jadeitites. Although CL petrography has not yet been applied for the other Japanese jadeitites, further application will bring new insight in understanding microtextures of Japanese jadeitites.

Mineral assemblages

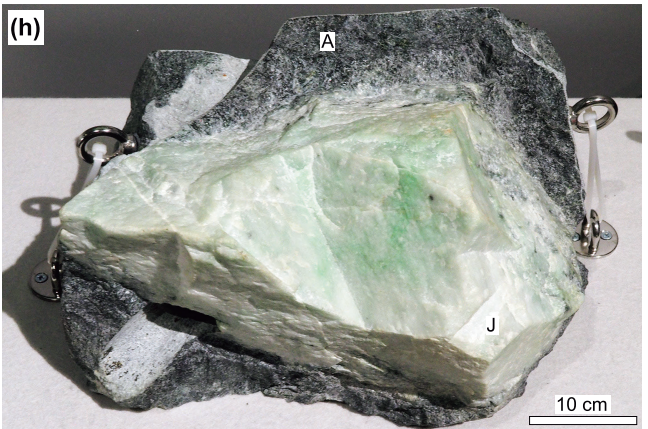
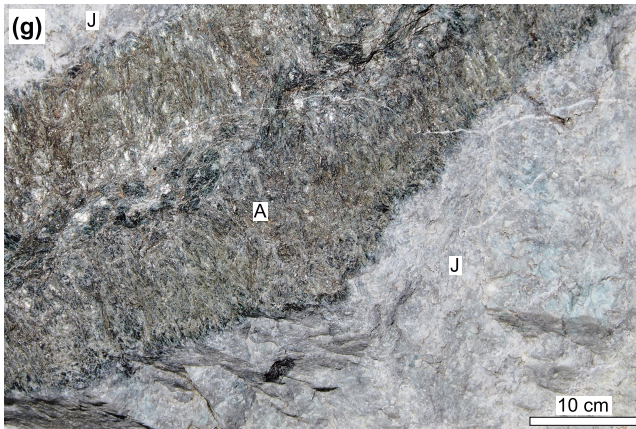
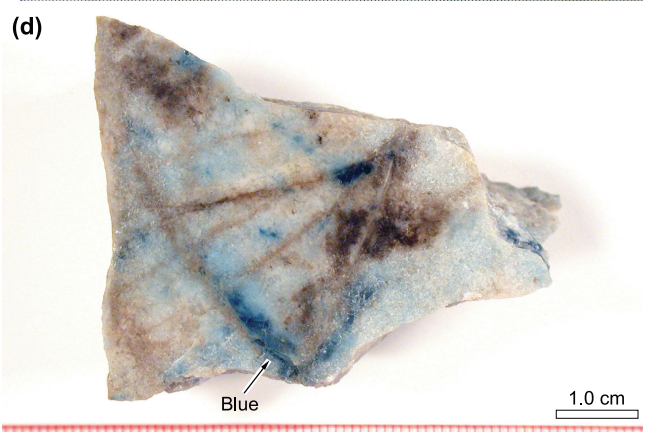
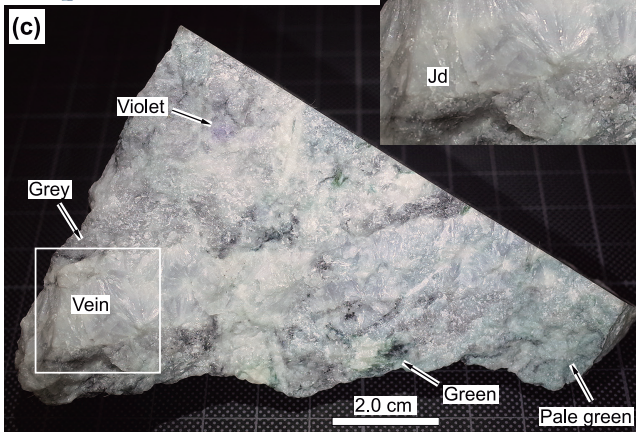
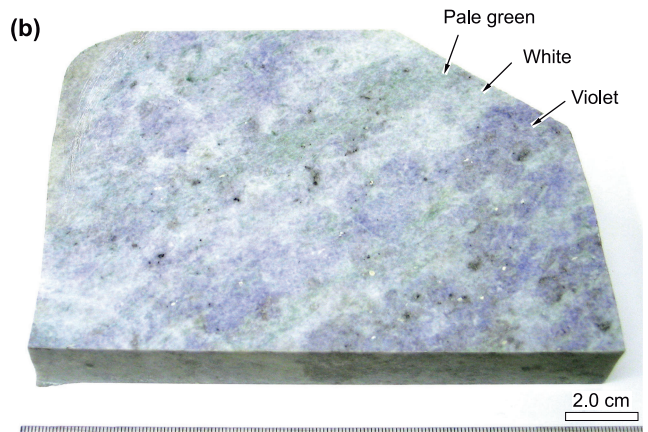
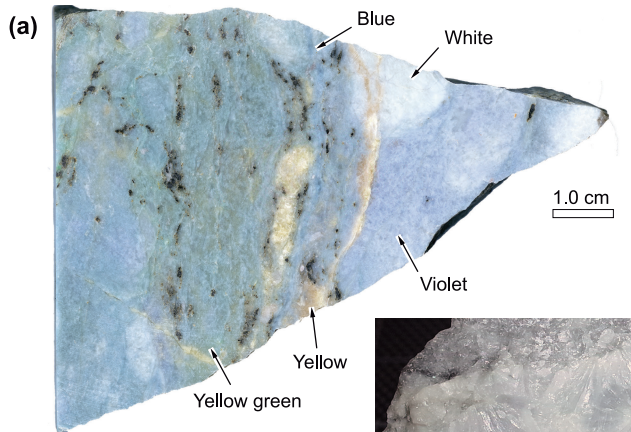
Jadeitites are nearly monomineralic and also lack quartz in the most cases. According to the Gibbs' phase rule, the high-variance mineral assemblages prevent precise estimate of equilibrium condition. However, accessory minerals such as lawsonite, pumpellyite, zoisite, rutile, and titanite can constrain approximate temperature limits. Amphibole members as well as the compositional gap between jadeite and omphacite are another index to assess temperature. Harlow et al. (2015) calculated an equilibrium phase diagram for an average whole-rock composition of Guatemalan South Motagua Mélange jadeitite in the NCFMASHT (NaO-CaO-FeO-MgO-Al₂O₃-SiO₂-

H₂O-TiO₂) system with excess H₂O (Fig. 3). Based on the stability fields of lawsonite, paragonite, Ca-Na amphibole, two coexisting pyroxenes (jadeite + omphacite), and kyanite, they defined five mineralogical types; namely lawsonite jadeitite, paragonite jadeitite, taramite jadeitite, two-pyroxene jadeitite, and kyanite jadeitite. Moreover, the presence of titanite versus rutile in jadeitite indicates different *P-T* conditions or a change when titanite contains a rutile nucleus.

The Itoigawa-Omi-occurrence is unique among jadeitite sources for the late-stage Sr-rich accessory minerals itoigawaite [SrAl₂Si₂O₇(OH)₂·H₂O: Miyajima et al., 1999], renegeite (Sr₄ZrTi₄Si₄O₂₂: Miyajima et al., 2001) and niigataite [CaSrAl₃Si₃O₁₂(OH): Miyajima et al., 2003], and relative rarity in Ba-rich minerals (e.g., cymrite, banalsite, celsian, and hyalophane) found at other jadeitite sources. Otherwise, the mineral assemblages and accessory minerals found in Japanese jadeitites are mostly comparable those of worldwide jadeitite (e.g., Shi et al., 2012). One rare mineral assemblage in Japanese jadeitite is corundum + paragonite + jadeite; corundum replacing paragonite was found in the Sekinomiya (Oya) jadeitite (Tazaki and Ishiuchi, 1976). Corundum-bearing mineral assemblages suggest low-silica activities during jadeite formation (or recrystallization). Glaucophanitic amphiboles and lawsonite are sometime found in jadeitite localities associated with blueschists, such as South Motagua Mélange, Dominican Republic. In Japanese localities, glaucophane is found in jadeitites and jadeite-rich rocks of Nishisonogi, Yorii, Yatsushiro, and Kamui-kotan. However, lawsonite has not confirmed yet, excepting the occurrence of itoigawaite (Sr-analogue of lawsonite) in the Itoigawa-Omi and Wakasa area. Fluid inclusions containing mostly H₂O or CH₄ are ubiquitous in Japanese jadeitites as well as oversea localities.

Geochemical features

Provenance studies of jadeitite composition to identify the geological source has been employed since Kunz's time in both archeology and gemology. Hence, geochemical characterization of whole-rock chemical compositions of jadeitites is the most classical method in the research area, including but not limited to geosciences. Because whole-rock compositions reflect compositions (elemental concentration) and modal volume of constituent-minerals, the characteristics of whole-rock chemistry of jadeitite are highly controlled by accessory minerals (such as phengite, hydrous Ca-Al silicate minerals, titanite, etc.) rather than jadeite. N-MORB-normalized trace-elements patterns of whole-rock jadeitites and jadeite in jadeitites are shown in Figures 7 and 8, respectively. Overall,



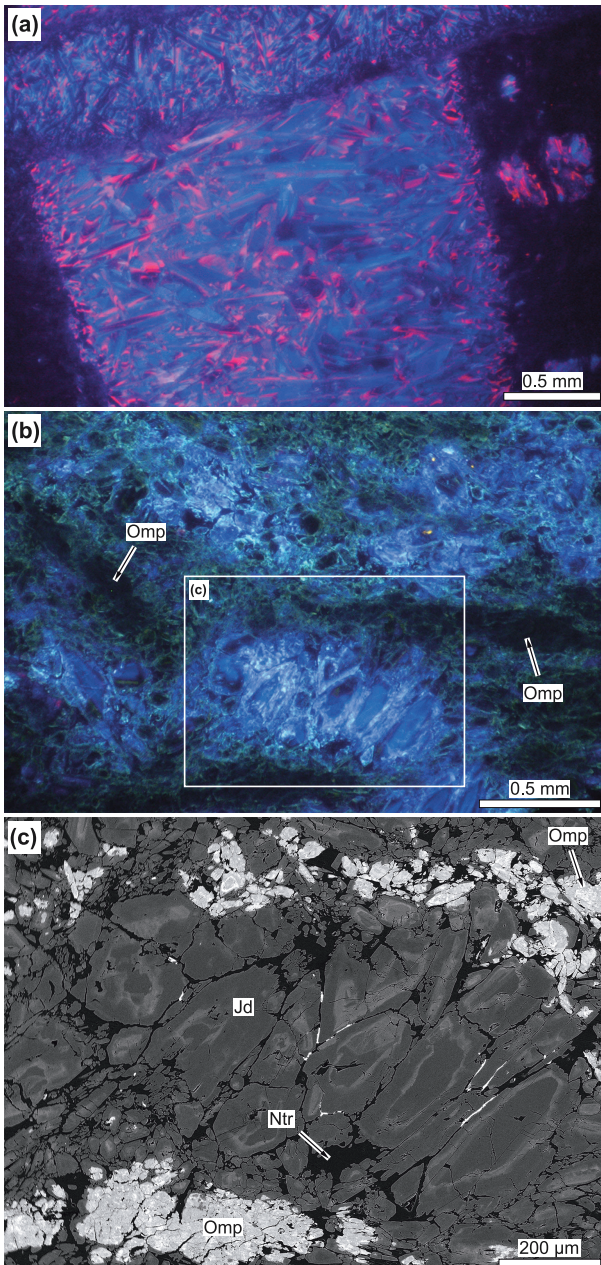


Figure 6. Optical cathodoluminescence (CL) image of jadeitites from (a) New Idria, California (Takahashi et al., 2017) and Chukotka, Russia. For comparison, back-scattered electron image of a part in (b) is shown in (c). Abbreviations: Omp, omphacite; Jd, jadeite; Ntr, natrolite.

Figure 5. Appearance of some Japanese jadeitites. (a) Polished hand specimen of jadeitite from Wakasa area, showing various color. (b) Kotaki-gawa River specimen (AMNH 108657) of mixed white, lavender and blue jadeite with albite, pectolite and stronalsite; American Museum of Natural History sample. (c) Veined jadeitite from the Osayama area. Radial aggregates of coarse-grained jadeite crystals [Jd] were precipitated directly from a Na-Al-Si-rich aqueous fluid in a vein within pre-existing jadeitite. (d) Noguchi, Kotaki specimen (FMM2002-1103-1) of intense blue omphacite and white jadeite with albite, analcime, and K-feldspar; National Science Museum, Tokyo, sample. (e) Kotaki-gawa River specimen (AMNH IJE00-3) with blue omphacite, white jadeite and brown pumpellyite(?) plus albite, analcime and graphite, (f) Kotaki Senoda specimen (AMNH OKJ00-5-1) with blue omphacite and white jadeite. (g) Jadeitite [J] crosscut by a paragenetic amphibolite [A] of the Itoigawa-Omi area. The sample is a collection of the Fossa Magna Museum. Kunugiza et al. (2017) dated zircon from this jadeitite sample. (h) Gem quality jadeitite in contact with amphibolite of the Itoigawa-Omi area. The sample is displayed in the Fossa Magna Museum.

whole-rock jadeites are enriched in large-ion lithophile elements (LILEs)—Cs, Rb, K, Sr, and Ba—, some high field-strength elements (HFSEs)—Zr, Nb, Hf, and Ta—, and some specific elements such as Th, U, and Pb, relative to N-MORB. The trace-element patterns are somewhat similar to that of GLOSS (Global subducting sediments) compositions (Plank and Langmuir, 1998). Some P-type jadeitites show positive Eu anomalies and some R-type jadeitite shows negative Eu anomalies. In available data, the general trend of enrichment of rare-earth elements (REEs) increases in the order of South Motagua Mélange > North Motagua Mélange > Myanmar (Fig. 7a). Comparing with the whole-rock data, in-situ analyses of jadeite are generally depleted in REEs; mostly smaller than primitive mantle (PM) value. Oxygen isotope of Japanese jadeitites are only known from the Kotaki sample of the Itoigawa-Omi area (Sorensen et al., 2006) and the Osayama area (Fu et al., 2010); the $\delta^{18}\text{O}$ values range from +4.5 to +7.1‰ and +7.77 to +9.15‰, respectively. Light carbon isotope value, $\delta^{13}\text{C}$ (−8.6 to −7.9‰) was reported from rhombohedral graphites in a black jadeitite from Omi area (Ogawara and Akai, 2014).

Geochronology

There are no jadeitite occurrences found in pre-Late Neoproterozoic orogenic belts. The oldest occurrences of jadeitite are Early Paleozoic, including Japanese localities. New zircon U-Pb age of ~ 560 Ma of the Itoigawa-Omi jadeitite (Kunugiza et al., 2017) and zircon Hf model age of ~ 570 Ma of the Osayama jadeitite (Fu et al., 2010) are likely the oldest geochronological records in the Japanese jadeitite, while a few Russian localities are also Early Paleozoic (cf. Harlow et al., 2015). It is not easy to say which of these is the oldest, but there is no doubt that the Japanese Paleozoic jadeitites are significantly older than either Myanmar and Guatemalan jadeitites.

As summarized in Tsujimori and Harlow (2012), geochronological data of both jadeitite and associated high-pressure metamorphic rocks show temporal discrepancies among them at some localities. Like Japanese Paleozoic jadeitite localities, the close association between older

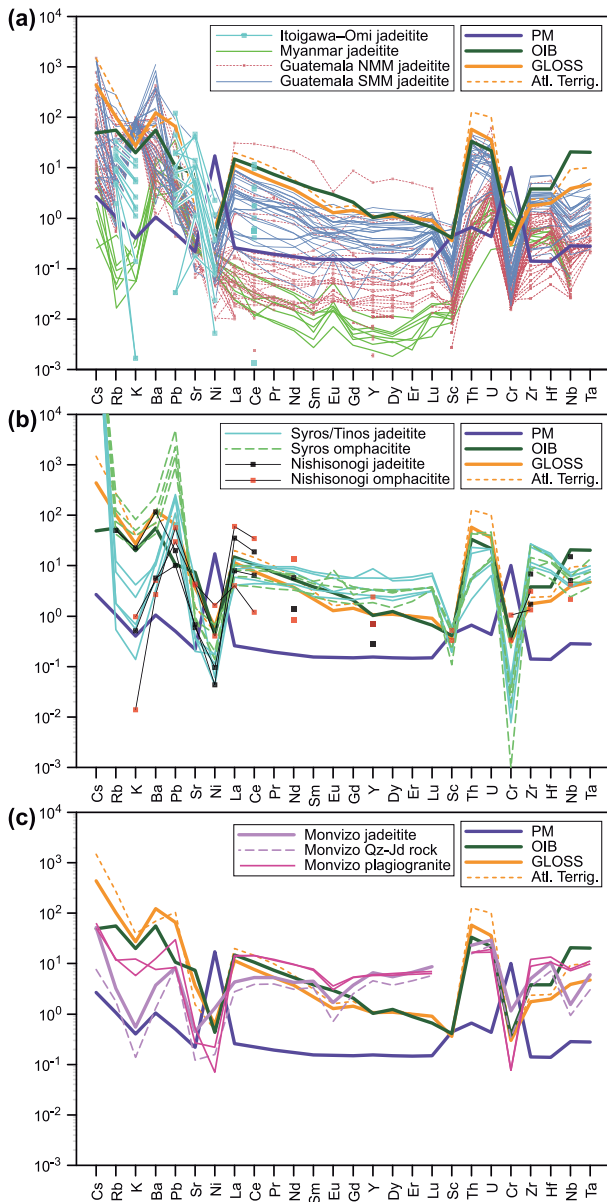


Figure 7. N-MORB-normalized trace element pattern for jadeite from jadeitites. The purple filled circle represents Mn-bearing lavender color jadeite. (a) Itoigawa-Omi, Japan (Sorensen et al., 2006; Morishita et al., 2007; Harlow and Shi, 2011). (b) Myanmar (Sorensen et al., 2006; Harlow and Shi, 2011). (c) Guatemala (Sorensen et al., 2006; Harlow and Shi, 2011). Normalized value and reference values are from Sun and McDonough (1989), McDonough and Sun (1995), Plank and Langmuir (1998); ocean island basalt (OIB), primitive mantle (PM), global subducting sediment (GLOSS), and Antilles terrigenous sediments (Atl. Terrig.). Except for Sorensen et al. (2006)'s SIMS data, data are collected by LA-ICPMS.

jadeitites and younger blueschist (and rare eclogite) in a single mélangé complex implies different histories for the subduction channel and jadeite-bearing mélangé. Available data suggest that the mélangé can stay near the mantle wedge boundary for a considerable time and, as a re-

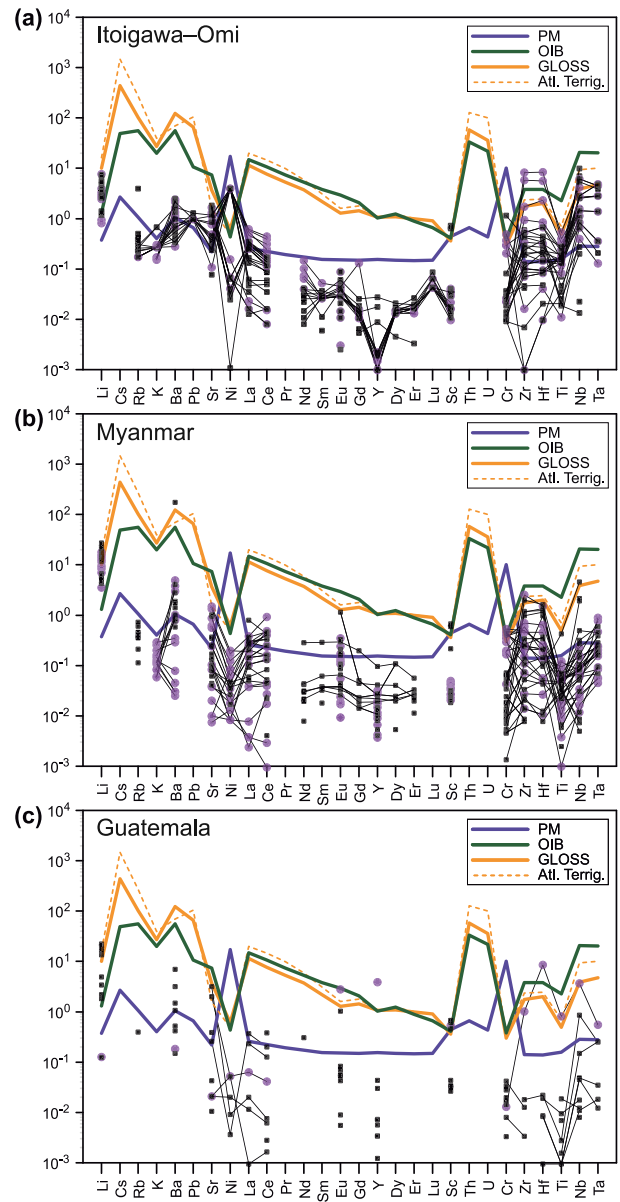


Figure 8. N-MORB-normalized whole-rock minor-trace-element composition spidergrams for jadeitites. (a) Jadeitites from NMM and SMM of Guatemala, Myanmar, and Itoigawa-Omi, Japan (Harlow et al., 2016; Shi et al., 2008; Miyajima, 1999). (b) Jadeitites and omphacitites from Syros and Tinos, Greece and Nishisonogi, Japan (Bröcker and Enders 2001; Shigeno et al. 2012). (c) Jadeitites and associated quartz-jadeite rock and plagiogranite from Monviso, Italy (Compagnoni et al. 2012). Normalized value and reference values are from Sun and McDonough (1989), McDonough and Sun (1995), Plank and Langmuir (1998); ocean island basalt (OIB), primitive mantle (PM), global subducting sediment (GLOSS), and Antilles terrigenous sediments (Atl. Terrig.).

sult, experience multiple fluid-infiltration events. With time, the disrupted mantle wedge containing jadeitites is mixed with younger high-pressure rocks and various fragments of suprasubduction zone lithologies. Consequently,

recrystallization and re-precipitation of jadeite in jadeitite are reactivated along a slab–mantle wedge interface.

Stern et al. (2013) recognized jadeitite as a key petrotectonic indicator for plate tectonics and proposed the term ‘plate tectonic gemstones’ for jadeitite as the subduction zone with a low geotherm. Together with other large-scale tectonic indicators (blueschists, glaucophane-bearing eclogites; coesite- or diamond-bearing ultrahigh-pressure metamorphic rocks; lawsonite-bearing metamorphic rocks) that are mostly found in Neoproterozoic and younger rocks, jadeitite first appeared in Late Neoproterozoic to Early Paleozoic links the secular cooling of the Earth. Subduction zone thermal structures did not evolve toward the necessary low-temperature conditions needed for jadeite formation until that time.

PERSPECTIVES

Research interest in jadeitite has not only included petrotectonics, geochronology, and geochemistry (e.g., Harlow et al., 2004; Brueckner et al., 2009; Fu et al., 2010; Simons et al., 2010; Sorensen et al., 2010; Yui et al., 2012; Flores et al., 2013; Harlow et al., 2015, 2016), but current attention also reflects their significance with respect to the geochemical components of arc magmas (e.g., Marschall and Schumacher, 2012). Studies over the last two decades have interpreted jadeitite either as the direct aqueous fluid precipitate from subduction channel into the overlying mantle wedge or as the metasomatic replacement by such fluids of oceanic plagiogranite, graywacke, or metabasite along the channel margin (cf. Harlow et al., 2015). Most jadeitites are principally fluid precipitates (P-type), but some jadeitite are a metasomatic replacement (R-type) preserving relict minerals and textures of protolith also occur (Tsuji-mori and Harlow, 2012). The new jadeitite classification (P- and R-types) based on formation process has been widely accepted in the geoscience community.

The jadeite-forming aqueous fluids transfer various elements from subduction slab into the transitional mélange and overlying mantle wedge (e.g., Flores et al., 2013; Harlow et al., 2016). The fluids promote mass circulation within a subduction channel and a mantle wedge. Ascending aqueous fluids, possibly jadeite-forming fluids, in a mantle wedge is also supported by a vertical wall-like low- V zones in the forearc region visualized by a high-resolution seismic tomography of NE Japan (‘Water Wall’: Zhao et al., 2015).

Open questions include what are the full range of depths from which jadeitite formation and the associated fluids occur and whether subarc fluid is involved in the jadeitite-forming at fore-arc depths. As we have reviewed in this article, however, available geochemical data on

Japanese jadeitite are very limited compared with those from studied overseas localities. Hence, much remains to be done for a more systematic understanding of Japanese jadeitite.

Multiple stable isotope (Li–B–Mg–O–H) characterization for jadeitite and related metasomatic rocks and serpentinite becomes increasingly important to decode fluid behaviors in past subduction zones. However, the analyses must be done systematically because jadeitites are very heterogeneous even within a single locality. Moreover, experimental determinations of trace-element partition coefficients and also isotopic fractionation factors between jadeite and fluids are crucial tasks requiring further research. So far, geochemical estimation of trace-element property of fluids from jadeitite are based on experimental data of diopsidic clinopyroxene instead of jadeitic pyroxene. A large amount of data via quick and precise in-situ analytical techniques (e.g., Martin et al., 2015; Kimura et al., 2016) and new experimental data will allow to a statistical-mechanical study to decipher fluid evolution in subduction zone system.

Another scientific topic involving Japanese jadeitite is archeology. As a tool, jade was employed during the Paleolithic (before 35000 BCE) but was raised to high symbolic stature as a gemstone in proto-Chinese Hongshan and Liangzhu cultures by 3500 BCE, in the Jōmon culture of Japan by 3000 BCE, and in Central America by the Olmec of the Early Formative period by at least 1500 BCE, and later in the Mayan civilization. In Japan, jadeite artifacts have been found at numerous tumuli from the middle Jōmon period (~ 5000–3500 BCE) up to the Kofun period (~ 250–400 CE). All the archeological sites with jadeite artifacts are younger than the youngest ash of the Kikai-Akahoya tephra of 7.3 cal ka BP (Kitagawa et al., 1995). However, the chronology of the archeological sites with jadeite artifacts is based on so-called ‘seriation’, which is a relative dating method using style and assemblage of artifacts from numerous sites in same culture. Precise age determination of the archeological sites has the potential to tie interdisciplinary studies among genetic origin of modern Japanese, large-scale interaction between immigrants and the original population, and geosciences. To improve this understanding, therefore, the chronology should be investigated further by radio-carbon dating.

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APPENDIX

English to Japanese translations for specific Japanese terms in text.

jadeitite	<i>hisui</i> —ひすい or 翡翠 (' <i>feitsui</i> ' in Chinese)
jadeite	<i>kōgyoku</i> —硬玉 (' <i>ying yü</i> ' in Chinese)
nephrite	' <i>hisui kiseki</i> '—ひすい輝石
corundum	<i>nangyoku</i> —軟玉 (' <i>ruan yü</i> ' in Chinese)
ruby	<i>kōgyoku</i> —鋼玉
	<i>kōgyoku</i> —紅玉