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**Jadeitite:
new occurrences, new data,
new interpretations**

Petrogenetic relationships between jadeitite and associated high-pressure and low-temperature metamorphic rocks in worldwide jadeitite localities: a review

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Abstract: Jadeitite-bearing serpentinite-matrix mélange is distributed in the Caribbean (Guatemala, Cuba, and Dominican Republic), circum-Pacific (Japan, Western USA, and Papua New Guinea), Alpine-Himalayan (Italy, Iran, Greece, and Myanmar), and Caledonian (Russia and Kazakhstan) orogenic belts, and always contains high-pressure, low-temperature (H*P*-L*T*) metamorphic rocks. There are also jadeitite xenoliths in kimberlitic pipes in the Colorado Plateau (USA). The oldest occurrences of jadeitite are Early Paleozoic in Japan, Russia, and Kazakhstan, suggesting subduction-zone thermal structures evolved the necessary high pressure/temperature conditions for jadeitite formation since Early Paleozoic; the youngest occurrence is a xenolith from the Colorado Plateau. Major occurrences consist principally of fluid precipitates (P-type) that infiltrated the mantle wedge; fewer occurrences document metasomatic replacement (R-type) of plagiogranite, metagabbro and eclogite, and both types may be possible in the same occurrence or system. The *P-T* conditions for jadeitite formation can be extended beyond the previously argued limits of blueschist-facies conditions. Some jadeitite formed at epidote amphibolite and others at eclogite facies conditions. Available geochronological data of both jadeitite and associated H*P*-L*T* rock show temporal discrepancies between jadeitite formation and H*P*-L*T* metamorphism at some localities. The close association between older jadeitite and younger H*P*-L*T* rock in a single mélange complex implies different histories for the subduction channel and jadeitite-bearing mélange. Jadeitite-bearing serpentinite mélange can stay at the mantle wedge for a considerable time and, as a result, experience multiple fluid-infiltration events. The subduction channel can occasionally incorporate overlying serpentinized mantle wedge material due to tectonic erosion. With time, the disrupted mantle wedge containing jadeitite veins is mixed with younger blueschists, exhumed eclogites and various fragments of suprasubduction-zone lithologies. Consequently, recrystallization and re-precipitation of jadeitite are reactivated along a slab–mantle wedge interface. All these possible scenarios and their combinations yield a complicated petrological record in jadeitite. With further investigation, the rock association of jadeitite–H*P*-L*T* metamorphic rocks–serpentinite has the potential to yield a greater understanding of subduction channels and overlying mantle wedge.

Key-words: jadeitite, blueschist, eclogite, H*P*-L*T* metamorphism, serpentinite mélange, fluid precipitation, metasomatic replacement.

1. Introduction

Jadeitite is an uncommon, nearly monomineralic rock that has been interpreted to have crystallized directly from subduction-zone Na-Al-Si-rich hydrous fluids or formed through almost complete metasomatic replacement of precursor-rocks by subduction-zone fluid–serpentinite interaction (*cf.* Harlow & Sorensen, 2005; Sorensen *et al.*, 2006; Harlow *et al.*, 2007). In either formation process, fluid that can be saturated with jadeite (Manning, 1998, 2004) is an essential component in the subduction zones. Since the polymerized Na-Al-Si-rich hydrous fluids at H*P*-L*T* conditions can behave as an agent of mass transfer, the petrological record within the jadeitites offers a proxy for the fluid-related mass transfer within a subduction zone. Moreover, fluids released from subducting slabs enhance serpentinization of mantle wedge peridotites and, consequently, control a variety of processes relating to the subduction channel as an interface between the subducting plate and an overlying serpentinizing mantle wedge. So far, the subduction-related origin of jadeitite has been documented in various localities in close spatial association with high-pressure and low-temperature (H*P*-L*T*) metamorphic rocks, such as blueschist and eclogite. In particular, a jadeitite-bearing H*P*-L*T* complex with a large quantity of ultramafic rocks (typically a mélange) can be regarded as a fossil serpentinite-dominant subduction channel, in which a buoyancy-driven return flow necessary to exhume deeply subducted materials is established (*e.g.*, Cowan & Silling, 1978; Cloos, 1982; Guillot *et al.*, 2001; Gerya *et al.*, 2002; Tsujimori *et al.*, 2006a;

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Federico *et al.*, 2007; Krebs *et al.*, 2008, 2011; Blanco-Quintero *et al.*, 2011).

The slab-derived fluids in a subduction channel can hydrate less-serpentinized peridotite and consequently the serpentinized peridotite can exhume eclogites; hydration of eclogites is evidenced by retrograde recrystallization as well as infiltration with fluid crystallization products such as phengite. Likewise, the slab-derived fluids also can crystallize jadeitite in openings (fractures) and/or promote metasomatic replacement of pre-existing rocks. The occurrence of relict chromian spinel or its pseudomorphs (aggregates of kosmochlor/Cr-jadeite) in many jadeitites (*e.g.*, Ou Yang, 1984; Harlow & Olds, 1987; Shi *et al.*, 2005) also suggests an inevitable petrogenetic relationship between jadeitite and host ultramafic rocks. The stability of jadeitic clinopyroxene in metamorphic environments is most consistent with low geothermal gradients and relatively low temperatures (∼200–400 °C) for the formation of jadeitite. Thus, the close association of jadeitite and H*P*-L*T* metamorphic rocks naturally should indicate nearly simultaneous jadeitite formation and metamorphic recrystallization/metasomatism of associated H*P* rocks. However, this concept is still controversial, because, in particular, recent data do not necessarily show simultaneous formation of jadeitite and associated H*P*-L*T* rocks in the same mélange (*e.g.*, Tsujimori *et al.*, 2005a). To resolve this dilemma, several main interrelated questions need to be examined: for any (or all) occurrence(s), what are the petrogenetic relationships between jadeitite and associated H*P*-L*T* rocks? Is jadeitite-formation coeval with the metamorphism recorded in the associated H*P*-L*T* rocks? What are the *P*-*T* conditions of jadeitite formation? What is the geotectonic significance of the close association of jadeitite and H*P*-L*T* metamorphic rock in a jadeitite-bearing serpentinite mélange? Multiple approaches to study jadeitite and associated lithologies can result in new insights into subduction-zone geodynamics.

This article summarizes the petrogenetic and geochronological relationships between worldwide jadeitite and associated high-pressure metamorphic rocks from the literature along with specific illustrations. Our new and updated petrographical data from the Japan, California, and Guatemala are also included for the review.

2. H*P*-L*T* metamorphic rocks in worldwide jadeitite localities

Occurrences of jadeitite have been extensively reviewed (*cf.* Harlow & Sorensen, 2005; Harlow *et al.*, 2007). So far, nineteen ‘‘jadeitite’’ localities have been reported in four Phanerozoic orogenic belts (Caribbean, circum-Pacific, Alps-Himalayan, and Caledonian), excluding xenoliths in kimberlitic pipes (Fig. 1; Table 1). Most localities lie within serpentinite mélange, with fragments of oceanic crust and H*P*-L*T* metamorphic rocks, along major transform-type or thrust faults cutting the paleo-forearc or accretionary wedge. Considering these worldwide occurrences, it is clear that serpentinite exhumation and mélange formation may be important for the preservation of jadeitite. These exhumation processes may also explain the rare occurrence of jadeitite.

Based on possible formation models of jadeitite, here we propose to classify two types: fluid precipitates (P-type) and metasomatic replacement (R-type). Precipitated jadeitite does not manifest a protolith and, thus, shows no

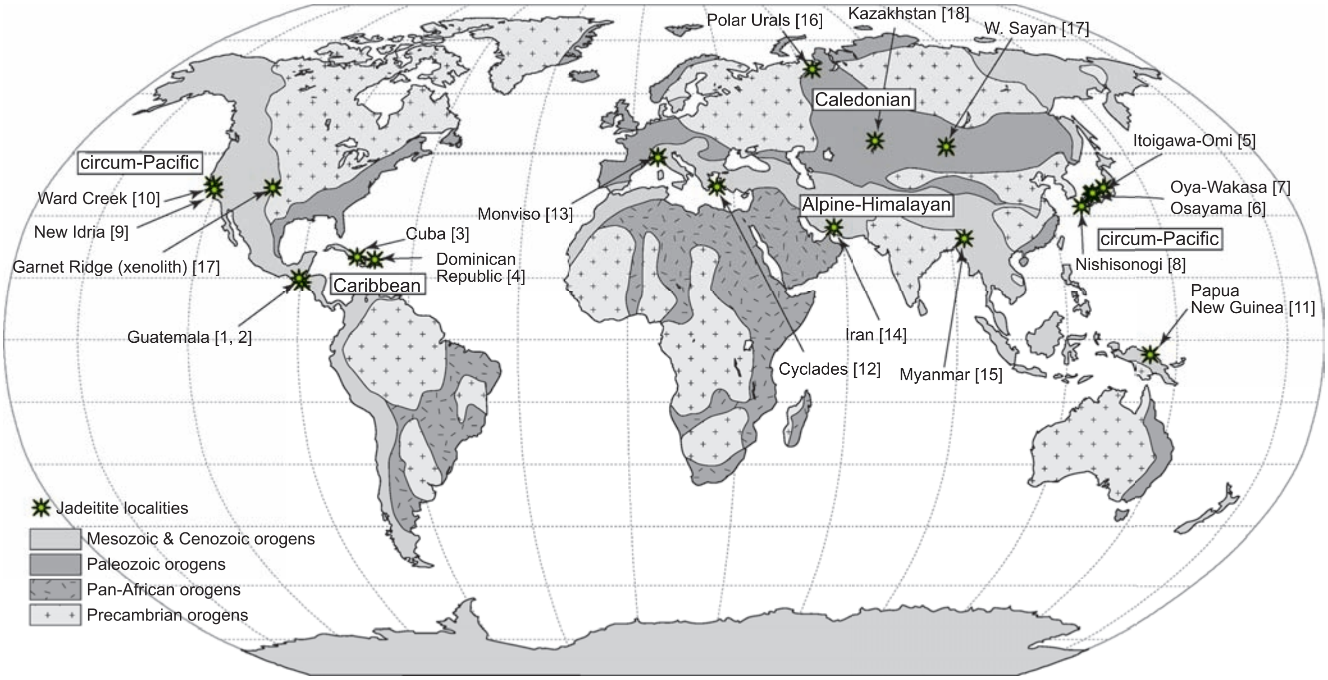

Fig. 1. Distribution of jadeitite in the world. The base world map is after Tsujimori *et al.* (2006b).

Table 1. Summary of jadeitites (types and ages) and associated mafic H*P*-L*T* metamorphic rocks (lithologic variations and ages) of the world.

	Jadeitite				H*P*-L*T* metamorphic rocks		
Locality	Type	Protolith age	Jadeitite formation	Recrystallization or cooling	Variation of mafic rocks	Metamorphic age	Temporal relations
Caribbean							
1. North of Motagua fault, Guatemala	P	N/A	Zrn 98–95 Ma	Phe 77–65 Ma	Ep-Gln eclogite [EC]w/ [BS, AM], Grt amphibolite [EA-AM]	Sm-Nd 159–126 Ma [EC]	[EC]>JAD> [EA-AM]
2. South of Motagua fault, Guatemala	P, R	Zrn 154 Ma?	Zrn 154 Ma?	Phe 125–113 Ma	Lws eclogites [EC] w/ [BS], Jd-eclogite[EC], Lws blueschst [BS]	Sm-Nd 144–132 Ma [EC]	JAD>[EC]> [BS]
3. Sierra del Convento, Cuba	P	N/A	Zrn 107–108 Ma	N/A	Ep-Grt amphibolite [EA-AM], trondhjemitic Ep gneiss [EA-AM] w/ [BS], bluechist [BS]	Zrn 113 Ma [EA-AM]	JAD≈[EA-AMP]>[BS]
4. Rio San Juan Complex, Dominican Republic	P P, R?	Zrn 139 Ma N/A	Zrn 115 Ma	Zrn 93 Ma	Eclogite [EC] Lws and Grt-Om blueschist [BS]	Lu-Hf 104 Ma [EC] Rb-Sr 80 Ma, 62 Ma [BS]	JAD≈[EC] [BS]≤JAD
Circum-Pacific							
5. Itoigawa-Omi, Japan	P, R	N/A	Zrn 520 Ma	Phe 340–320 Ma	Ep-Gln eclogite [EC] w/ [BS], Ep blueschist [BS], Ep-Grt amphibolite [EA-AM]	Phe 340–320 Ma [BS]	JAD≈ [EA-AM]≫ [EC], [BS]
6. Osayama, Japan	P, R	Zrn 523–488 Ma	Zrn 521–451 Ma	N/A	Lws-Pmp blueschist [BS], Ep blueschist [BS], Ep-Gln eclogite [EC] w/ [BS]	Phe 320 Ma [BS]	JAD>[BS], [EC]
7. Oya-Wakasa, Japan	P	N/A	Early Paleozoic?	N/A	Lws-Pmp blueschist [BS], Ep blueschist [BS], amphibolite/metagabbro [EA-AM]	Phe 290–280 Ma [BS], Hbl 470–440 Ma [EA-AM]	
8. Nishisonogi, Kyushu, Japan	R	Zrn 142–131 Ma	Zrn 82 Ma	N/A	Ep blueschist [BS]	Phe 90–75 Ma [BS]	JAD≈[BS]
9. New Idria, Franciscan Complex	P	N/A	Cretaceous?	N/A	Lws blueschist [BS], Ep eclogite [EC] w/ [BS], Grt-Cpx amphibolite w/ [EA]	Hbl 110 Ma [EA-AM]	[BS]≤JAD
10. Ward Creek, Franciscan Complex	P	N/A	Cretaceous?	N/A	Lws blueschist [BS], Pmp-Ep blueschist [BS], eclogite [EC] w/ [BS]	N/A	JAD≈[BS]
11. Cyclops Mountain, Papua, New Guinea		N/A	N/A	N/A	N/A	N/A	
Alpine-Himalayan							
12. Syros and Tinos, Cyclades, Greece	P, R	In debate: Zrn 80 Ma	In debate: Zrn 80 Ma	N/A	Ep-Gln eclogite [EC] w/ [BS]	Zrn 52 Ma [EC-BS], Phe 52–43 Ma [EC-BS]	JAD≈[EC]
13. Monviso, Western Alps	R	Zrn 163 Ma	Eocne?	N/A	Lws eclogite [EC]	Zrn 163 Ma (protolith), 45 Ma [EC]	
14. Sorkhan, Iran	P	N/A	Cretaceous?	N/A	Lws blueschist [EC]	Phe 90–80 Ma [EC]	

Table 1. Continued

Locality	Jadeitite				HP-LT metamorphic rocks		Temporal relations
	Type	Protolith age	Jadeitite formation	Recrystallization or cooling	Variation of mafic rocks	Metamorphic age	
15. Jade Mines area, Myanmar	P, R	Zrn U-Pb 163 Ma	Zrn 158, 147, 122 Ma	N/A	blueschist [BS], eclogite [EC]	Phe 80 Ma [EC], 30 Ma [BS]	JAD>>[BS]
Caledonian							
16. Voikar-Syninsky, Polar Urals, Russia	P	Early Paleozoic?	Zrn 404 Ma	Zrn 378, 368 Ma	Ep-amphibolite (metagabbro) [EA-AM], eclogite [EC]	Zrn 500 Ma [EA-AM], 360–355 Ma [EC]	JAD>[EC], JAD≈[EC]
17. Borus Range, West Sayan Russia	P, R	N/A	Early Paleozoic?	N/A	eclogite [EC], blueschist [BS]	N/A	
18. Kenterlau-Itmurunda-Arkharsu, East Kazakhstan	P	N/A	Zrn 450 Ma	N/A	Grt amphibolite [EA-AM], blueschist [BS]	N/A	
Xenolith							
19. "Jadeitite" xenolith from the Colorado Plateau	P	N/A	N/A	N/A	UHP Lws eclogite [EC], Jd eclogite [EC]	Zrn 81–33 Ma [EC]	

Abbreviations: Zrn—zircon U-Pb age, Phe—phengite K-Ar (or ^{40}Ar/^{39}Ar) age, Hbl—hornblende K-Ar age, Sm-Nd, Lu-Hf, Rb-Sr—isochron age, [BS]—blueschist facies, [EC]—eclogite facies, [EA]—epidote amphibolite facies, [AM]—amphibolite facies

evidence of isochemical transformation or pseudomorphic replacement of any precursor rocks. Most jadeitites belong to this P-type, and they 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 HP-LT metamorphic rock. In contrast, replacive jadeitite partially preserves textural, mineralogical or geochemical evidence of a pre-existing protolith, such as plagiogranite.

In the following section, petrogenetic relationships between jadeitite and HP-LT metamorphic rocks in selected localities are described.

2.1. North of Motagua fault, Guatemala

Along the Motagua fault in central and eastern Guatemala, jadeitite-bearing serpentinite mélange is exposed stretching ~200 km north of the Motagua fault (but south of the Polochic fault). The jadeitite occurrence north of the Motagua fault has been described in detail (Harlow, 1994; Johnson & Harlow, 1999; Sorensen *et al.*, 2006; Harlow *et al.*, 2011) and has been shown to be distinctly different in age, P-T record, and mineralogy from occurrences south of the fault (see below) as described in Harlow *et al.* (2011). Clinozoisite- and paragonite-bearing mineral parageneses of jadeitite suggest an approximate P-T condition of jadeite formation at $T = 300$–400 °C and $P = 0.6$–1.2 GPa (Harlow *et al.*, 2011). The rhythmic zoning pattern of jadeite crystals and abundant fluid inclusions imply that the jadeitites are essentially P-type (Harlow, 1994; Sorensen *et al.*, 2006). Texture and relict minerals of primary peridotite of the mélange indicate spinel-peridotite (mostly harzburgite but also lherzolite) protolith (Bertrand & Vuagnat, 1977, 1980; Harlow *et al.*, 2010). The north serpentinite mélange contains a variety of rocks indicative of HP-LT conditions, including garnet amphibolite, omphacite-taramite-zoisite rock, albitite, phengitic-muscovite rock, epidote-paragonite-glaucophane eclogite and rare blueschist. Eclogite recorded prograde epidote-eclogite facies metamorphism in a relatively low-T glaucophane stability field, and the rock then experienced higher-T amphibolite-facies hydration and subsequent blueschist-facies overprinting. Zoned garnets preserve rare clinozoisite-paragonite pseudomorphs after lawsonite, recording the increase in temperature. The eclogitic mineral parageneses give a maximum P-T condition at $T = 600$–650 °C and $P = 2.0$–2.3 GPa (Tsujimori *et al.*, 2004). Garnet amphibolite, which is found ~100 km east of the eclogite, shows a clearly lower P-T trajectory with garnets containing both omphacite and clinozoisite and interpreted P-T of 550–600 °C at ~1.5 GPa (Harlow *et al.* 2008). The P-T condition of blueschist-facies overprinting is likely consistent with that of jadeite formation. However, the blueschist-facies mineral assemblage in eclogite does not have jadeitic pyroxene. Moreover, jadeitites are variably retrograded at amphibolite- and greenschist-facies conditions; for instance, jadeite crystals were replaced by a symplectitic intergrowth of albite + analcime ± nepheline (Fig. 2).

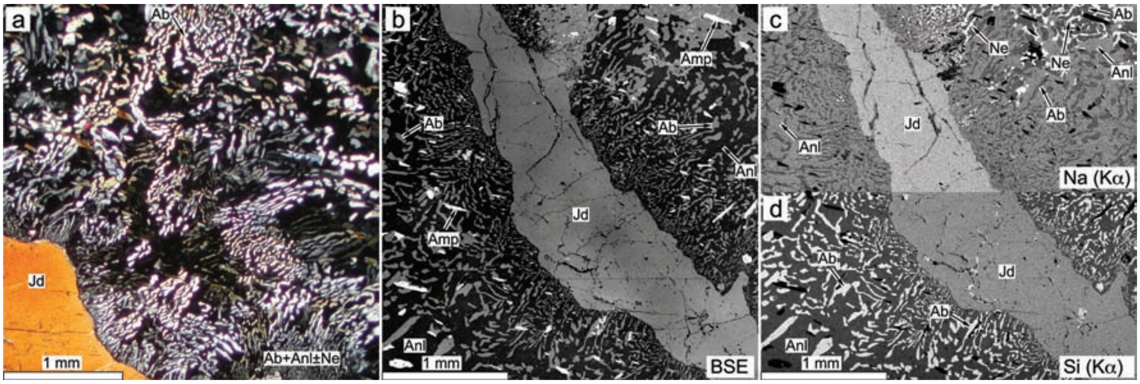

Fig. 2. Retrograde breakdown texture of jadeitite from north of the Motagua fault zone. (a) Cross-polarized light view of albite-analcime–nepheline (Ab-Anl-Ne) symplectite around jadeite (Jd). Same textural relations have been known in jadeitite from the northern MFZ (Fig. 5a of Harlow, 1994). (b) Back-scattered electron (BSE) image showing a typical breakdown texture. The size and spacing of symplectite-forming minerals becomes smaller toward jadeite. Minor amount of well-oriented taramitic amphibole (Amp) is involved within the vermicular networks of the symplectite. (c-d) X-ray (Na and Si) images of the upper and lower halves of (b). Nepheline is locally intergrown with other phases in symplectite. Vermicular albite grains are roughly perpendicularly orientated to the reacting interfaces.

Oscillatory-zoned hydrothermal zircon in jadeitite yielded ion-microprobe U-Pb ages of 98–95 Ma (Yui *et al.*, 2010, 2012). Phengite in jadeitite yielded ^{40}Ar/^{39}Ar ages of 77–65 Ma (Harlow *et al.*, 2004). These ages are younger than Sm-Nd mineral isochron ages of eclogite-facies metamorphism at 159–125 Ma (Brueckner *et al.*, 2009).

2.2. South of Motagua fault, Guatemala

Tectonic blocks of lawsonite-bearing jadeitite, pumpellyite-bearing jadeitite, lawsonite eclogite, omphacite-glaucophane rocks, and lawsonite blueschist have been described in the south serpentinite mélange of Guatemala (Harlow *et al.*, 2004; Tsujimori *et al.*, 2006b; Harlow *et al.*, 2011). Some jadeitite contains variable amounts of quartz and the inferred *P*-*T* range for the formation of jadeitite is $P =$ 1.0–2.0 GPa at $T =$ 300–400 °C (Harlow *et al.*, 2011). Protoliths of antigorite serpentinite are mainly spinel harzburgite, lherzolite, dunite and rare chromitite. In the south mélange, jadeitic pyroxene occurs not only in jadeitite but also in lawsonite eclogite (Tsujimori *et al.,* 2005a, 2006a). In particular, zoned garnets of lawsonite eclogites with basaltic bulk compositions have abundant mineral inclusion of jadeite, whereas all matrix pyroxenes are omphacitic; oscillatory zoning of Mn, Ca and Mg is common in the rims (Fig. 3a–c). Moreover, some eclogites contain oscillatory-zoned coarse-grained jadeite crystals (Fig. 3d–f). This eclogite-facies jadeite is always associated with rutile rather than titanite. On the other hand, the Ti-bearing phase in retrograded eclogite, omphacitite, and jadeitite is commonly titanite; in some cases, titanite includes relict rutile or zircon in the core. These indicate that rutile is consistent with peak metamorphism or higher *T* and that replacement occurs during retrogression or metasomatism.

Laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) yields a zircon U-Pb age of 154 Ma (Fu *et al.*, 2010); based on the oxygen-isotope composition, the zircon was interpreted as an igneous relic, suggesting R-type. However, our own observations indicate inclusions of jadeite, mica, and fluids in zircon, so the interpretation of the origin of zircons is still under debate. Sm-Nd mineral isochron ages from eclogite are 144–132 Ma (Brueckner *et al.*, 2009) and phengite ^{40}Ar/^{39}Ar ages from both eclogite and jadeitite are 125–113 Ma (Harlow *et al.*, 2004).

2.3. Sierra del Convento, Cuba

Recently, a new jadeitite locality has been reported from eastern Cuba (García-Casco *et al.*, 2009; Cárdenas-Párraga *et al.*, 2010, 2012). The jadeitite occurs as tectonic blocks in a serpentinite mélange. The mélange contains two contrasting tectonic block types: (1) H*P*-L*T* lawsonite-blueschist facies rocks and (2) higher-*T* garnet amphibolite with tonalitic-trondhjemitic gneiss. The garnet amphibolite of the Sierra del Convento mélange yields a peak *P*-*T* condition of 1.5–1.8 GPa at 750–800 °C and also records a blueschist-facies overprint (García-Casco *et al.*, 2006). The blocky jadeite crystals in jadeitite exhibit oscillatory zoning (García-Casco *et al.*, 2009), which is the most common feature of type-P jadeitite. Zircon from tonalitic-trondhjemitic rock yielded ion-microprobe U-Pb age of 112.8 ± 1.1 Ma (Lázaro *et al.*, 2009). Zircon from jadeitite yielded ion-microprobe U-Pb age of 107.4 ± 0.5 Ma and 107.8 ± 1.1 Ma, indicating jadeitite formation during the earliest stages of subduction in the region (Cárdenas-Párraga *et al.,* 2012), consistent with a higher *T* interpretation for jadeitite crystallization of $T = 550$–560 °C and $P = 1.5$ GPa (García-Casco *et al.*, 2009).

2.4. Rio San Juan Complex, Dominican Republic

Another recently discovered source of jadeitite and jadeite-bearing rocks is in northeastern Dominican Republic, Hispaniola (Schertl *et al.*, 2007a,b, 2012; Krebs *et al.*, 2011), now making three occurrences along the North American–Caribbean plate boundary. Jadeitite and jadeite-rich rocks have so far been found in serpentinite

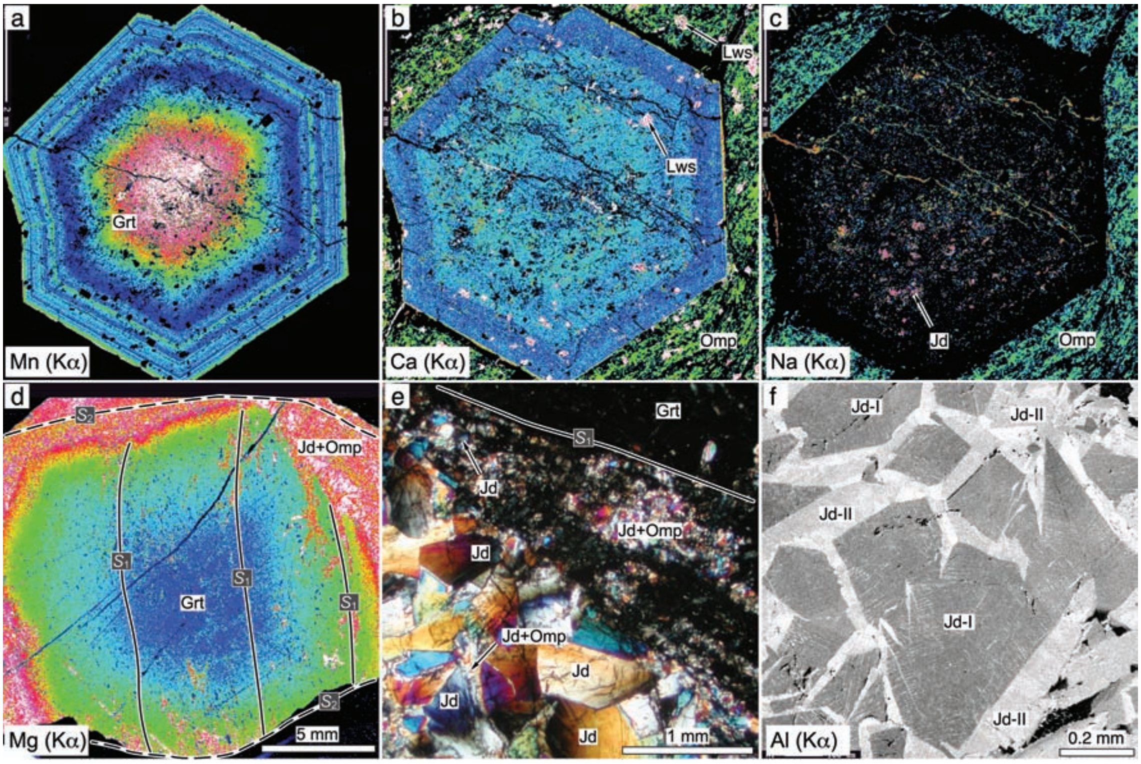

Fig. 3. Occurrences of jadeite in eclogites from south of the Motagua fault zone. (a)-(c) X-ray images (Mn, Ca, and Na) of prograde zoned garnet with abundant inclusions of jadeite in lawsonite eclogite (Type-I eclogite of Tsujimori *et al.,* 2006). (d) Mg X-ray image of prograde zoned garnet in coarse-grained jadeite-lawsonite eclogite (Tsujimori *et al.*, 2005b; Tsujimori *et al.,* 2006a). (e) Crossed-polarized light optical image of coarse-grained jadeitites in jadeite-lawsonite eclogite. (f) Al X-ray image of two generations of jadeititic pyroxenes in jadeite-lawsonite eclogite. Oscillatory growth bands parallel to growth faces are developed in the 1st generation impure jadeite (Jd-I, up to 75 mol% jadeite). The retrograde jadeites (Jd-II, up to 87 mol% jadeite) fill fractures of fragmented Jd-I (Tsujimori *et al.*, 2005b).

mélanges as allochthonous blocks in lag deposits, as river-bed boulders, and as veins and layers in blueschist blocks of the mélanges. The serpentinite mélanges of the Rio San Juan Complex also contain various tectonic blocks of lawsonite blueschist, jadeite (or omphacite) blueschist, garnet blueschist, eclogitic blueschist, glaucophane-epidote eclogite, glaucophane-free eclogite, and granitic orthogneiss (Krebs *et al.*, 2008, 2011). Lu-Hf data yield 104 Ma for peak eclogite-facies metamorphism during early intra-oceanic subduction ($T = 750$ °C, $P = 2.3$ GPa), and Rb-Sr and $^{40}Ar/^{39}Ar$ geochronology give 80Ma down to 62 Ma for later blueschist-facies metamorphism ($T = 340$–550 °C, $P = 1.2$–1.8 GPa) (Krebs *et al.*, 2008) as the subduction zone evolved and cooled.

Two types of jadeitite or jadeite-rich rock occurrences are found in the Rio San Juan (Schertl *et al.*, 2012). The first type is jadeitite (generally quartz-free) containing >90 vol% jadeite. This type of jadeitite has so far only been found as loose blocks. Cathodoluminescence studies show oscillatory zoning of jadeite as well as zircon and apatite, supporting crystallization from an aqueous fluid, *i.e.*, P-type. Zircon from this type of jadeitite has been dated by ion microprobe, yielding core ages of 114.9 ± 2.9 Ma, essentially contemporaneous with initiation of subduction of the complex. The inferred *P*-*T* conditions are similar to those of eastern Cuba (*i.e.*, high-*T* jadeitite). In contrast, a second type of quartz-bearing jadeitite, grading into jadeite and jadeite-lawsonite quartzite, is found as concordant layers and discordant veins in lawsonite and garnet-omphacite blueschists of the mélange. The inferred *P*-*T* conditions are very similar to those of lawsonite-bearing jadeitites in the south of the Motagua Fault and Iran. Although no geochronological data are available for these lawsonite-bearing jadeite-rich rocks, their formation is likely to be coeval with the timing of blueschist-facies metamorphism (80–60 Ma), close to the end of subduction activity and cooler conditions.

2.5. Itoigawa-Omi, Japan

In the Hida Mountains, an eastern portion of Southwestern Japan, Late Paleozoic H*P*-L*T* schists occur as tectonic slices and blocks within antigorite serpentinite as a matrix (*e.g.*, Tsujimori, 2002). Since Kawano (1939) first identified jadeitite as boulders in the Kotaki-gawa River, numerous jadeitite boulders have been found and mined from several different creeks of the area (*e.g.*, Chihara, 1971, 1989; Miyajima *et al.*, 1999; Morishita *et al.*, 2007). Most jadeitites are P-type and quartz-free, but rare R-type jadeitite preserving relict hornblende and gabbroic textures occur (Kunugiza & Goto, 2010). Although rutile is stable in massive coarse-grained jadeitite, it is replaced by titanite in recrystallized jadeitite that underwent grain-size reduction by recrystallization during deformation. The protolith of the antigorite serpentinite was mainly dunite or harzburgite and rarely chromitite; chromian spinel in chromitite contains abundant igneous pargasite, suggesting a mantle-wedge peridotite origin (Tsujimori, 2004). The H*P*-L*T* schists in the serpentinite mélange, termed the Renge metamorphic rocks, record primarily greenschist–epidote-amphibolite-facies metamorphism and locally preserve epidote-blueschist–eclogite-facies assemblages. Although no outcrops of jadeitite have been confirmed, the boulders of jadeitite and albitite occur together with those of epidote-blueschist–eclogite-facies rocks. The transition from blueschist to eclogite facies is preserved as mineral inclusions in prograde-zoned eclogitic garnet and blueschist-facies overprinting in the rock's matrix (Tsujimori, 2002). Conditions of the peak eclogite-facies metamorphism were estimated as $P = 1.8$–2.1 GPa and $T = 550$–600 °C (Tsujimori & Matsumoto, 2006). Phengitic white micas of pelitic schists of either greenschist–epidote-amphibolite facies or epidote-blueschist–eclogite facies units yield K-Ar, ^{40}Ar/^{39}Ar, and Rb-Sr ages of 340–320 Ma (*cf.* Tsujimori, 2010). In contrast, zircons in jadeitites interpreted as fluid precipitates on the basis of their rhythmic zoning, inclusions suites and rare-earth elements (REE) patterns, yield ion-microprobe U-Pb ages of 519 ± 17 and 512 ± 7 Ma (Kunugiza & Goto, 2010). Albitite in this area that can be interpreted to represent retrograded equivalents of jadeitite yield phengite K-Ar and ^{40}Ar/^{39}Ar ages of approximately 340–320 Ma.

In the H*P*-L*T* schists, rare examples of post-metamorphic Na- and Ca-metasomatism and mineralization in mm- to cm-scale veins and rinds are found. These features include albitization, crystallization of pectolite and K-rich richterite, and formation of tremolite-rich rinds surrounding tectonic blocks. Phlogopite from a tremolite-rich rock yielded an ^{40}Ar/^{39}Ar age of 339 ± 7 Ma. The serpentinite matrix also underwent regional metamorphism (Tsujimori, 2004), but there is no age constraint for this recrystallization.

2.6. Osayama, Japan

In the central Chugoku Mountains, Southwestern Japan, the Osayama serpentinite mélange contains tectonic blocks of Late Paleozoic Renge H*P*-L*T* schists (Tsujimori & Itaya, 1999; Tsujimori & Liou, 2005), and occurrences of jadeitite, omphacitite and omphacite-bearing tremolite rock have been described (*e.g.*, Kobayashi *et al.*, 1987; Tsujimori, 1997; Tsujimori *et al.*, 2004a). Relict minerals in serpentinite indicate that the protoliths were mainly harzburgite and minor dunite. Chrysotile/lizardite is the dominant serpentine mineral, and rare winchitic to tremolitic amphiboles and diopside occur as metasomatic minerals in the serpentinite. The Osayama jadeitites are P-type and quartz-free, and jadeitite crystals often show oscillatory zoning; rutile and zircon area common accessory minerals (Fig. 4). Omphacite, pectolite, analcime and titanite are common secondary minerals. In some jadeitites,

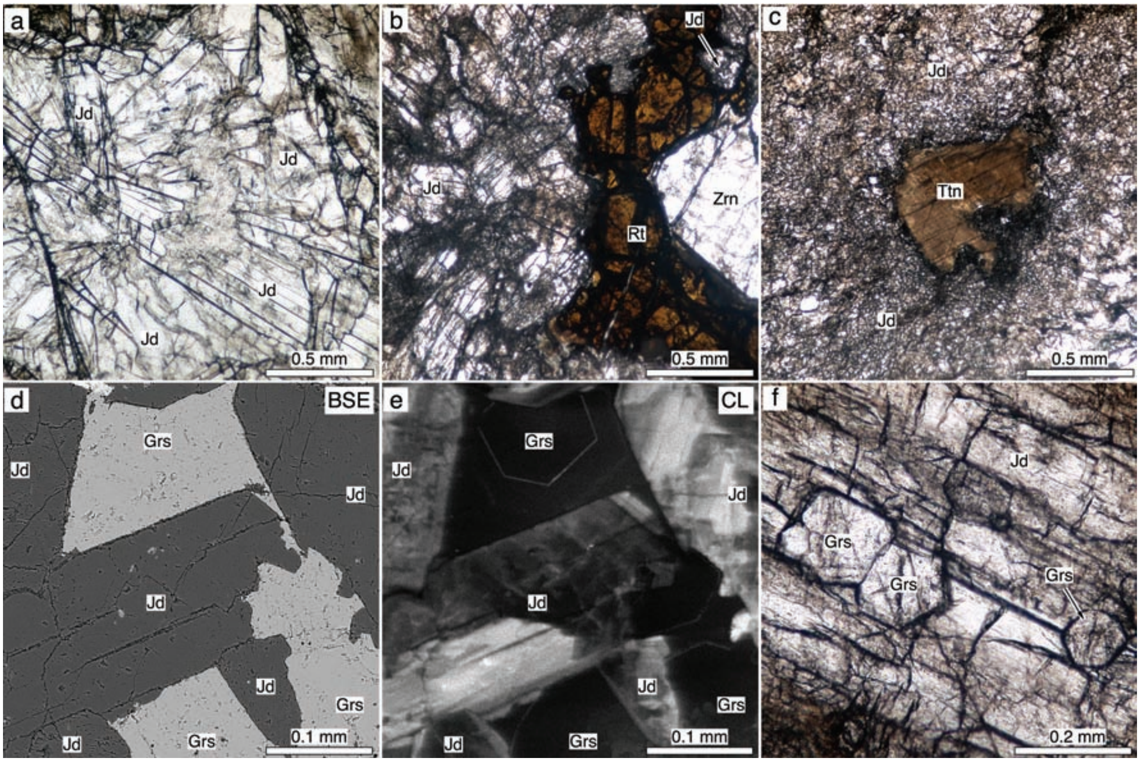

Fig. 4. Microtextures of jadeitite from Osayama. (a) Plane-polarized light (PPL) view of radial aggregate of coarse-grained jadeite crystal. (b) PPL view of irregular rutile (Rt) vein and coarse-grained zircon (Zrn) in jadeitite. (c) PPL view of titanite (Ttn) pseudomorph after rutile in a recrystallized fine-grained neoblastic jadeite matrix. (d) BSE image of subhedral jadeites with interstitial grossular. (e) CL image of (d). (f) PPL view of jadeitite with inclusions of euhedral grossular.

randomly oriented euhedral to subhedral jadeite crystals are enclosed by grossular; grossular also occurs as inclusions in jadeite (Fig. 4d–f).

Albitite appears to be the retrograded equivalent of jadeitite and contains minor amounts of aegirine-augite. The blueschist-facies blocks have been subdivided into lawsonite-pumpellyite and epidote grades, based on mineral assemblages. Gabbro and dolerite blocks within the mélange also contain blueschist-facies assemblages of lawsonite-pumpellyite grade. Omphacitite and omphacite-bearing tremolite rock also contain pumpellyite as an accessory mineral. The highest-grade block is a garnet-glaucophane schist with relict eclogite-facies mineral inclusions. The mineral parageneses of low-grade blueschists give approximate metamorphic conditions of $P =$ 0.7–1.0 GPa and $T =$ 250–300 °C, and the relict eclogite-facies mineral assemblage in high-grade blueschist gives a minimum P of 1.1–1.3 GPa at T of ~480–550 °C (Tsujimori & Liou, 2005). Phengitic white micas of the H*P*-L*T* schists yield K-Ar ages of around 320 Ma, regardless of metamorphic grade (Tsujimori & Itaya, 1999). In contrast, oscillatory-zoned rutile- and jadeite-bearing zircons in jadeitite yielded ion-microprobe U-Pb ages scattering from 521 to 451 Ma (weighted mean age 472 ± 8.5 Ma). Inherited igneous cores of zoned zircons suggest possible protoliths of gabbro, norite or plagiogranite and therefore an oceanic crustal origin (Fu *et al.*, 2010); these yielded an age range from 523 to 488 Ma (Tsujimori *et al.*, 2005a). Oxygen isotope compositions of zircon formed during jadeitite-formation is lighter ($\delta^{18}O = 3.6 \pm 0.6$ ‰) than that of the inherited igneous core formed in equilibrium with mantle compositions ($\delta^{18}O = 5.0 \pm 0.4$ ‰) (Fu *et al.*, 2010). It is noteworthy that the age of jadeitite formation is significantly older than the blueschist-facies metamorphism of the H*P*-L*T* schists in the same mélange.

2.7. Oya-Wakasa, Japan

In the eastern portion of the Chugoku Mountains, about 180 km to the east of the Osayama occurrence, essentially EW-trending serpentinized peridotite bodies of the Early Paleozoic Oeyama ophiolite are exposed, and beneath this massive serpentinized peridotite is an antigorite serpentinite mélange with enclaves of Late Paleozoic Renge H*P*-L*T* schist. Two jadeitite localities are known in the Oya and Wakasa areas.

In the Oya area, lawsonite-glaucophane schists, albitite, and rare albitized jadeitite occur as tectonic blocks in the mélange (Hashimoto & Igi, 1970; Tazaki & Ishiuchi, 1976; Tsujimori & Liou, 2007). This jadeitite is P-type, without quartz, and contains radial aggregates of coarse-grained jadeitite crystals; paragonite and rare corundum also occur. Lawsonite-blueschist facies metabasalt contains abundant aegirine-augite. The rock is characterized by an aegirine-augite–lawsonite–chlorite assemblage, suggesting equilibrium *P-T* conditions of $T <$ 280 °C and $P =$ 0.6–0.7 GPa (Tsujimori & Liou, 2007). Although the *P-T* conditions appear to be close to those of jadeitite formation in general (Harlow, 1994), there is no direct contact between blueschist and jadeitite. Antigorite serpentinite contains relict minerals of spinel-harzburgite protoliths.

In the Wakasa area, up to thirty jadeitite blocks have been mined as river float (Masutomi, 1966; Chihara, 1989; Shimobayashi, 2004); some jadeitite contains itoigawaite (Sr equivalent of lawsonite) and pumpellyite. The serpentinite mélange contains tectonic slices of the Late Paleozoic Renge H*P* schists – pelitic schist with layers of epidote-glaucophane (rare barroisite) and pumpellyite-glaucophane schist – with phengite K-Ar and Rb-Sr ages of about 290–280 Ma (Shibata & Nishimura, 1989), and blocks of gneissose epidote-amphibolite with hornblende K-Ar ages of about 470–440 Ma (Nishimura & Shibata, 1989). Similar gneissose epidote-amphibolites with kyanite, paragonite, staurolite and rutile occur in serpentinites of the Oeyama area, about 20 km to the east of the Oya-Wakasa area (Tsujimori *et al.*, 2004b). The Oya-Wakasa jadeitites have not yet been dated, but on the basis of petrotectonic continuity (Ishiwatari & Tsujimori, 2003) we expect that jadeitite formation is likely to be coeval with the Early Paleozoic metamorphism rather than the Late Paleozoic H*P* metamorphism.

2.8. Nishisonogi, Kyushu, Japan

Jadeitite-bearing serpentinite layers (less than 350 m thick) are intercalated in a H*P* pelitic-psammitic schist unit of the Nishisonogi metamorphic rocks, Nagasaki Peninsula (Nishiyama, 1978; Shigeno *et al.*, 2005, 2012). The serpentinites also contain taramite-zoisite rock, omphacitite, albitite and rare garnet-blueschist (Nishiyama *et al.*, 1986; Nishiyama, 1990); metasomatic reaction rinds developed at contacts between blocks and serpentinite. The H*P* schist unit is considered to be a western extension of the Sambagawa H*P* belt (Itaya *et al.*, 2011), and the mafic schist layers have an epidote-blueschist facies mineral assemblage, giving *P-T* conditions of $P =$ 0.8 GPa and $T =$ 440 °C (Mori *et al.*, 2007). In contrast, some jadeitites in the serpentinite contain quartz inclusions in the cores of jadeite grains. The presence of quartz and the clinozoisite + paragonite mineral assemblage suggest higher-pressure conditions of $P >$ 1.3 GPa at $T >$ 400 °C (Shigeno *et al.*, 2005). Jadeitites contain relict detrital zircon having metamorphic rims with jadeite inclusion; ion-microprobe U-Pb geochronology yields 142–131 Ma for the detrital cores and 82 Ma for the overgrowths (Mori *et al.*, 2011; Yui *et al.*, 2012). Consequently, the jadeitites are interpreted as primarily of the R-type. The timing of the rim growth is within the range of phengite K-Ar and $^{40}Ar/^{39}Ar$ ages (90–75 Ma) of the host pelitic schists and jadeitite (Faure *et al.*, 1988; Mori *et al.*, 2006).

2.9. New Idria, Franciscan Complex

The jadeitite-bearing New Idria serpentinite body (23 × 8 km) forms the core of an antiform structure along the crest of the Diablo Range between the San Andreas Fault on the west and the San Joaquin Valley of the California Coast

Range. The serpentinite body is in contact with the Franciscan Complex by high-angle faults, and contains numerous tectonic blocks of lawsonite-blueschist facies metagraywacke and rare high-grade blocks (eclogite and augite-garnet amphibolite) (Coleman, 1961, 1980; Tsujimori *et al.*, 2007). The protoliths of serpentinite are spinel harzburgite, dunite and rare chromitite.

Jadeitite occurs as discrete lenses (several meters in length) in antigorite serpentinite and veins (mm- to several cm-wide) cross-cutting host blueschist (Fig. 5a–c) (Coleman, 1961). The crack-seal character of the veins indicates that the jadeitite precipitated after the syn-metamorphic recrystallization (P-type) of the host metagraywacke. Some more massive varieties of jadeitized carbonaceous metasediments contain jadeite, omphacite, graphite, Ce-rich clinozoisite, cymrite, titanite, apatite, pectolite and zircon (Fig. 5d–e). Moreover, post-peak-metamorphic Na-metasomatism of blocks of eclogite and garnet amphibolite led to crystallization of jadeite that partially replaces omphacite and augite (Fig. 5f). This form of retrograde jadeitite in high-grade blocks was probably synchronous, or nearly so, with the precipitation of jadeitite veins (Tsujimori *et al.*, 2007).

2.10. Ward Creek, Franciscan Complex

Continuous exposures of low-grade blueschist and serpentinite mélange with high-grade blocks (eclogite) of the Cazadero area show a metamorphic zonal structure from lawsonite, pumpellyite to epidote zone in ascending order (Coleman & Lee, 1963; Maruyama & Liou, 1988). In this classic Franciscan locality, nearly monomineralic jadeitite was described from the pumpellyite zone (Banno *et al.*, 2000); jadeite crystals in the jadeitite exhibit sector zoning that suggests rapid crystal growth. The Ward Creek blueschist itself contains jadeitic pyroxene (Maruyama & Liou, 1987, 1988). There is no detailed description of the host rock, but the unusual monomineralic nature suggests that the Ward Creek jadeitite was precipitated in a local cavity of massive blueschist sequence or tectonic block. Such monomineralic pyroxene veins have been known in Franciscan blueschist (*e.g.*, Carpenter, 1980a). Although these local cavity/veins are different from other jadeitite sources, the large amount of serpentinite associated with the Franciscan blueschist might have played a role in forming such local ‘‘type-P jadeitite’’ veins from fluid.

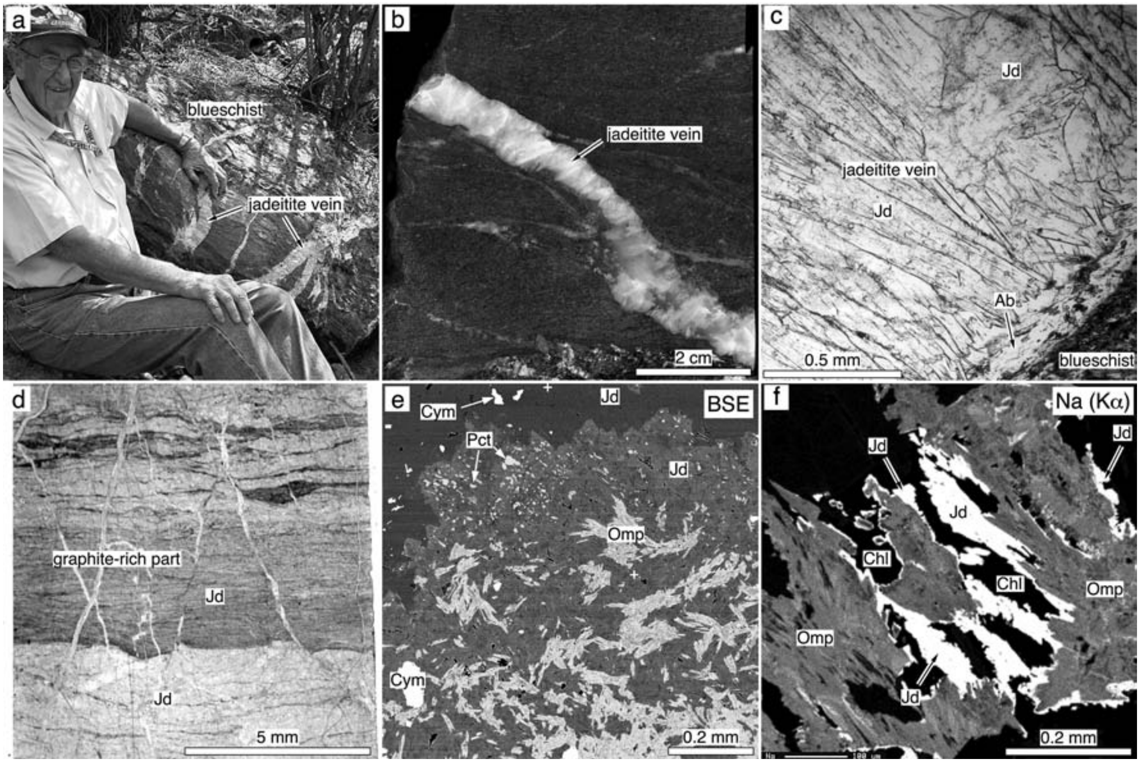

Fig. 5. Occurrences and microtextures of jadeitite in New Idria. (a) Jadeitite veins cross-cutting a blueschist block described by Coleman (1961). (b) Polished hand specimen of blueschist with a jadeitite vein. (c) PPL view of a jadeitite vein. Jadeite crystal grows perpendicular to the vein wall. (d) Scanned thin-section image of jadeitized schist. (e) BSE image showing coexisting jadeite and omphacite in green-colored jadeitite. (f) X-ray (Na) image of retrograde jadeite crystals replacing omphacite in eclogite block (jadeite-bearing eclogite of Tsujimori *et al.*, 2007).

2.11. Cyclops Mountain, Papua, New Guinea

A new and as yet not well-documented occurrence of a unique jadeitite is described in this issue from the northern coast of New Guinea (Harlow *et al.*, 2012). Identified from the historical but only recently (posthumously) published work of C.E.A. Wichmann (Visser, 2004), in a search for the source of a jade artifact retrieved from Emirau Island, Papua New Guinea, the jadeitite is defined by pyroxene with compositions along the jadeite-aegirine join together with Nb-rich titanite and another Nb+Y-rich phase. The area, which is inadequately described, consists of metamorphic basement with a variably interpreted *P*-*T* history from H*P*-H*T* to H*P*-L*T* (*e.g.*, van der Wegen, 1971) conditions of Cretaceous to Eocene age, overthrust by an ophiolite assemblage of Miocene age in the Pliocene (Monnier *et al.*, 1999). Further study on 100-year old samples from Wichmann's collection at Utrecht are underway.

2.12. Syros and Tinos, Cyclades, Greece

The Kampos mélange of Syros and Tinos Islands of the Cycladic blueschist belt in the central Aegean Sea contains numerous tectonic blocks of eclogite, blueschist (glaucophanite), and felsic gneiss and jadeitite; metasomatic reaction rinds of omphacitite, glaucophanite and chlorite-actinolite rock developed at contacts between blocks and serpentinite (Dixon & Ridley, 1987; Bröcker & Enders, 1999; Bröcker & Keasling, 2006; Bulle *et al.*, 2010). Both P-type and R-type jadeitite occur, and the R-type jadeitite has a protolith of plagiogranite or felsic melt within metagabbro. Some eclogites show spectacular network veins of jadeitite filling fractured eclogite in the interiors of blocks (Fig. 3e of Bröcker & Keasling, 2006). Syros jadeitites were formed at $T = 270$–$500\ ^\circ$C and $P = 0.8$–1.8 GPa (Bröcker & Keasling, 2006). These *P*-*T* estimates are well within the conditions of H*P* rocks of Tinos at $T = \sim450$–$550\ ^\circ$C and $P = \sim1.2$–2.0 GPa (Bröcker *et al.*, 1993).

Zircon from jadeitite and all other reaction-zone rocks exhibits regular oscillatory zoning and contains H*P* mineral inclusions such as glaucophane. Consistent U-Pb zircon ages from jadeitite, omphacitite, glaucophanite, and chlorite-actinolite rock clustering around 80 Ma were interpreted as dating the hydrothermal or metasomatic processes in a subduction zone environment (Bröcker & Keasling, 2006). Nevertheless, oxygen-isotope compositions of 80 Ma zircon determined by ion-microprobe suggest that these are relict igneous crystals inherited from metasomatically altered precursor rocks (Fu *et al.*, 2010; 2012). On Syros, phengite from H*P* rocks yielded an ^{40}Ar/^{39}Ar age of 52–43 Ma (Tomaschek *et al.*, 2003; Putlitz *et al.*, 2005). Ion-microprobe zircon U-Pb geochronology of eclogite has confirmed a H*P* metamorphic event at 52 Ma (Tomaschek *et al.*, 2003).

2.13. Monviso, Western Alps

R-type jadeitite occurs in the Monviso metamorphic ophiolite and mélange sequence of the Piemonte Zone (Compagnoni *et al.*, 2007, 2012). An association of plagiogranite with FeTi-oxide gabbro in serpentinite underwent lawsonite-eclogite facies metamorphism, and plagiogranite was metasomatically recrystallized into fine-grained jadeite-rich rock. Adjacent gabbro was partially replaced with jadeitite (Castelli *et al.*, 2002; Groppo & Castelli, 2010; Angiboust *et al.*, 2011, 2012). *P*-*T* pseudosection modeling of lawsonite eclogite suggests peak metamorphic conditions of $P = 2.5$–2.6 GPa at $T \geq 550\ ^\circ$C (Groppo & Castelli, 2010) or $P = 2.2$–2.4 GPa at $T = \sim480$–$500\ ^\circ$C (Angiboust *et al.*, 2012). Eclogite veins have zircons with ion-microprobe U-Pb ages of 45 Ma, whereas relict magmatic zircons in eclogitic metagabbro yield 163 Ma (Rubatto & Hermann, 2003). The recrystallization of plagiogranite during subduction to form ''jadeitite'' is most likely coeval with the timing of eclogite facies metamorphism.

2.14. Sorkhan, Iran

P-type jadeitite occurs as a vein cutting magnesite rock in a metamorphosed Mesozoic ultramafic mélange sequence of southeastern Iran (Oberhänsli *et al.*, 2007). The serpentinized harzburgite unit contains blocks of mafic and sedimentary fragments that underwent lawsonite-blueschist (and greenschist) facies metamorphism. Jadeitite is quartz-free and contains minor lawsonite and katophoritic amphibole. Fluid inclusions are common in jadeite crystals. Phengite from mica schist yielded K-Ar and ^{40}Ar/^{39}Ar ages around 90–80 Ma (Ghasemi *et al.*, 2002; Agard *et al.*, 2006). No geochronological data are available from the jadeitite.

2.15. Jade Mines area, Myanmar

The jadeitite-bearing serpentinite mélange occurs in the ophiolite belt along the Sagaing fault of the Indo-Burma Range of northern Myanmar. The serpentinite mélange and overlying conglomerates/alluvial deposits are recognized as the world's largest and most commercially important jadeitite (jade) deposits (Chhibber, 1934; Shi *et al.*, 2012). Myanmar jadeitite occurs as ''massive veins'' in the serpentinized peridotite (Chhibber, 1934) and commonly has blackwall (metasomatic rind) of various sodic amphiboles in a contact boundary between jadeitite and host serpentinized peridotite (Shi *et al.*, 2003; Harlow *et al.*, 2007).

Ion-microprobe U-Pb dating of zircon in jadeitite by Shi *et al.* (2008) showed clusters at 163 Ma, 147 Ma and 122 Ma. They interpreted the oldest dates as indicating zircon relics of an igneous protolith, indicating the age of formation of oceanic crust, whereas zircons with intermediate dates were thought to have formed during jadeite formation, with the youngest dates indicating modification/overgrowth of pre-existing zircons by a later hydrothermal event. On the other hand, Qiu *et al.* (2009) argued that jadeitite formation occurred at 158 Ma, based on LA-ICMPS zircon U-Pb dating. Although the timing of jadeitite formation is still being debated, the rhythmic zoning pattern of jadeite crystals and abundant fluid inclusions imply that the Myanmar jadeitites are essentially P-type.

However, the presence of relict igneous zircon would also indicate replacement features.

The jadeitite-bearing serpentinite mélange also contains tectonic blocks of blueschist, eclogite, amphibolite and marble (Shi *et al*., 2001; Goffé *et al*., 2002). In the Jade Mines area, eclogites record both epidote-amphibolite facies and lawsonite-blueschist facies overprinting; phengite ^{40}Ar/^{39}Ar geochronology suggests about 80 Ma for eclogite-facies metamorphism and about 30 Ma for blueschist-facies overprinting (Goffé *et al*., 2002). Although neither a locality nor an occurrence of eclogites has so far been documented in the literature, Enami *et al*. (2011) recently described an eclogite boulder from the Kumon range, about 80 km to the east of the Jade Mines area.

2.16. Voikar-Syninsky, Polar Urals, Russia

The Voikar-Syninsky ophiolitic belt of the Polar Ural Mountains is well-known as one of the Russian jadeitite localities (*e.g*., Dobretsov & Sobolev, 1984; Sobolev *et al*., 1986; Efimov & Potapova, 1992). Serpentinite mélange units in ultramafic bodies contain tectonic blocks and slices of various ophiolitic fragments (gabbro, amphibolite, plagiogranite), jadeitite and albitite. The metabasite fragments underwent high-*P* epidote-amphibolite facies metamorphism, and kyanite- and paragonite-bearing amphibolites have been found (Efimov & Potapova, 1995, 1996). The peridotites are predominantly harzburgite and dunite (Belousov *et al*., 2009). The ultramafic bodies with the jadeitite-bearing serpentinite mélange tectonically overlie the blueschist- and eclogite-bearing Marun-Keu H*P*-L*T* belt (*e.g*., Glodny *et al*., 2003). Zircon in gabbronorite associated with the ultramafic bodies yields an ion-microprobe U-Pb concordia age of 578 ± 8 Ma (Remizov & Pease, 2004). Zircon in chromitite from an ultramafic cumulate section gives similar ion-microprobe U-Pb age of 585 ± 6 Ma (Savelieva *et al.,* 2006). In contrast, zoned zircons in metagabbro show 500 Ma for the cores and 350 Ma for the rims (Remizov & Pease, 2004). The core ages overlap with zircon U-Pb ages (360–355 Ma) of eclogite veins (Glodny *et al*., 2003) from the H*P*-L*T* belts beneath the ultramafic unit.

Zircon in jadeitite exhibits a remarkable oscillatory zoning and contains mineral inclusions of pyroxene, rutile, muscovite, feldspar, quartz, and zeolite, as well as water-rich fluid inclusions (Meng *et al*., 2011); these features suggest P-type. Zircon in jadeitite yields ion-microprobe U-Pb age (weighted mean) of 404 ± 7 Ma, excluding young (372 and 368 Ma) spot ages (Meng *et al*., 2011); the results have been interpreted as the main formation and the latest generation ages of jadeitite, respectively.

2.17. Borus Range, West Sayan, Russia

The Borus Range jadeitites (also referred to as Yenisey River deposits of Khakassia) are very closely associated with eclogite blocks in an Early Paleozoic serpentinite mélange of the West Sayan terrane (Fig. 2 of Sobolev *et al*., 1986; Sklyarov *et al*., 1994; Buslov, 2011); eclogite blocks are surrounded by diopside-jadeite rock and jadeitite, suggesting that jadeitite was formed by Na-metasomatism of eclogite (Dobretsov & Tatarinov, 1983; Dobretsov & Sobolev, 1984; Dobretsov & Buslov, 2004). Whether the rocks are overgrowths (P-type) or metasomatic replacements (R-type) is not fully clear. Both types are clearly possible, and P-type jadeitite is described in other locations within the area. Jadeitite also accompanies glaucophane-bearing rocks. The *P*-*T* conditions of these H*P*-L*T* rocks were estimated as $T = 600$–700 °C and $P =$ 1.0–1.6 GPa). The age of the H*P*-L*T* metamorphism is 540–520 Ma (Dobretsov & Buslov, 2004; Volkova & Sklyarov, 2007), but no ages specifically from jadeitite have been published.

2.18. Kenterlau-Itmurunda-Arkharsu, East Kazakhstan

Jadeitites are known from the serpentinite mélange of the Kenterlau, Itmurunda, and Arkharsu ultramafic bodies, near Lake Balkhash, of the Itmurunda (Itmurundy) zone (*e.g*., Fig. 1 and 2 of Kovalenko *et al.,* 1994). The ultramafic bodies of the Itmurunda zone are tectonically underlain by jadeitite- and blueschist-bearing serpentinite mélange, and are in contact with Early-Middle Ordovician pelagic sediments (Zhylkaidarov, 1998). The serpentinite mélange is developed along the northern part of an ophiolite exposure and includes blocks of serpentinized harzburgite, gabbro/dolerite, plagiogranite, altered basalt, pelagic sediments, garnet amphibolite, garnet-bearing mica schist, blueschist, jadeitite, albitite, and rare corundum rock (Yermolov & Kotelnikov, 1991; Kovalenko *et al.,* 1994). Jadeitite occurs as blocks in serpentinite mélange and underwent various degrees of albitization; the jadeitite blocks have blackwall rinds (chlorite-actinolite rock) in the contact boundary between jadeitite and host antigorite serpentinite. The CL images of jadeite crystals exhibit multiple growth patterns, indicating that P-type jadeitite is most likely (Sorensen *et al*., 2006). Zircon in jadeitite yields a U-Pb age of 450 Ma (Yermolov & Kotelnikov, 1991). *P*-*T* constraints are not available for either jadeitite or associated H*P* rocks.

2.19. "Jadeitite" xenolith from the Colorado Plateau

Various xenoliths of "jadeitite," omphacitite, zoisite-eclogite, kyanite-eclogite and lawsonite-eclogite have been found in kimberlitic pipes at Garnet Ridge in the Colorado Plateau (Watson & Morton, 1969; Smith & Zientek, 1979; Helmstaedt & Schulze, 1988; Usui *et al*., 2006). A single coesite inclusion was found in garnet of a lawsonite eclogite. The peak eclogite-facies metamorphism was estimated as $T =$ 560–760 °C at $P = 3$–5 GPa. Jadeitite xenoliths ("jadeite-clinopyroxenite") contain up to ~70 vol% of jadeite, and trace amounts of garnet and zoisite (Usui *et al*., 2006). Jadeite crystals exhibit a remarkable oscillatory zoning (Smith & Zientek, 1979), resembling jadeite crystal zonation in P-type jadeitite. The Sr-Nd-Pb isotopic compositions suggested that the jadeitite had a MORB-like protolith and metasomatized in the subduction zone (Usui *et al.*, 2006). Ion-microprobe U-Pb ages for zircon in eclogite xenoliths range from 81 to 33 Ma and reveal that the eclogitic xenolith had been residing in a slab–-mantle wedge interface for 50 Ma (Usui *et al.*, 2003). Considering this residence time of up to 50 Ma, these differences might be viewed either as a single event or a cycle.

3. Discussion

3.1. Reassessment of petrogenetic relationships between jadeitite and associated HP-LT metamorphic rocks

To estimate the *P-T* conditions of jadeitite formation is always a difficult task (*e.g.*, Harlow, 1994). Most jadeitites lack quartz and contain high-variance mineral assemblages (few phases containing many components). However, the presence of lawsonite or glaucophane in some jadeitites (*e.g.*, South of the Motagua Fault in Guatemala, Iran, Nishisonogi, and Dominican Republic) is direct evidence of jadeitite formation at blueschist-facies conditions. For instance, the presence of lawsonite in jadeitite suggests formation at *T* below the reaction lawsonite + jadeite = zoisite + paragonite + quartz + H_2O (Heinrich & Althaus, 1988). The close association of eclogite overprinted in the blueschist facies with adjacent jadeitite to the south of the Motagua Fault, the presence of sodic-amphibole rocks associated with jadeitite (Shi *et al.*, 2003), and the unusual jadeitite-bearing retrograde mineral assemblage in eclogite of New Idria (Tsujimori *et al.*, 2007) give good petrological evidence for jadeitite formation at blueschist-facies conditions. The compositional gap between jadeite and omphacite is another index to assess temperature (Carpenter, 1980b; Tsujimori *et al.*, 2005b; Oberhänsli *et al.*, 2007; Green *et al.*, 2007; García-Casco *et al.*, 2009), although much omphacite growth in jadeitite post-dates jadeite crystallization (*e.g.*, Harlow, 1994). The apparent jadeite–omphacite compositional gaps in some jadeitite are comparable to those of blueschist-facies two-pyroxene pairs (*e.g.*, Carpenter, 1980b). Moreover, the *P-T* conditions of jadeitite formation in the blueschist facies can be further subdivided according to the presence of the assemblage clinozoisite (or epidote) + paragonite (*e.g.*, North of Motagua Fault) (Fig. 6).

Lawsonite-eclogite-facies jadeitite formation is evident from the occurrence of jadeitite forming from lawsonite-eclogite-facies meta-plagiogranite at Monviso (Compagnoni *et al.*, 2007; Groppo & Castelli, 2010; Angiboust *et al.*, 2011, 2012). The jadeite-bearing lawsonite eclogite from south of the Motagua Fault also suggests possible jadeitite formation during prograde lawsonite-eclogite facies metamorphism. Although the occurrence is quite different, the presence of suites of lawsonite eclogite and jadeitite xenoliths in the Colorado Plateau (Smith & Zientek, 1979; Usui *et al.*, 2006) is another example of jadeitite formation at lawsonite-eclogite facies conditions. In a cold subduction zone, subduction channels might provide the perfect environment not only to transform oceanic crust fragments into blueschist and lawsonite eclogite but also to crystallize jadeitite by episodic infiltration of slab-derived fluid and to replace plagiogranite with jadeitite.

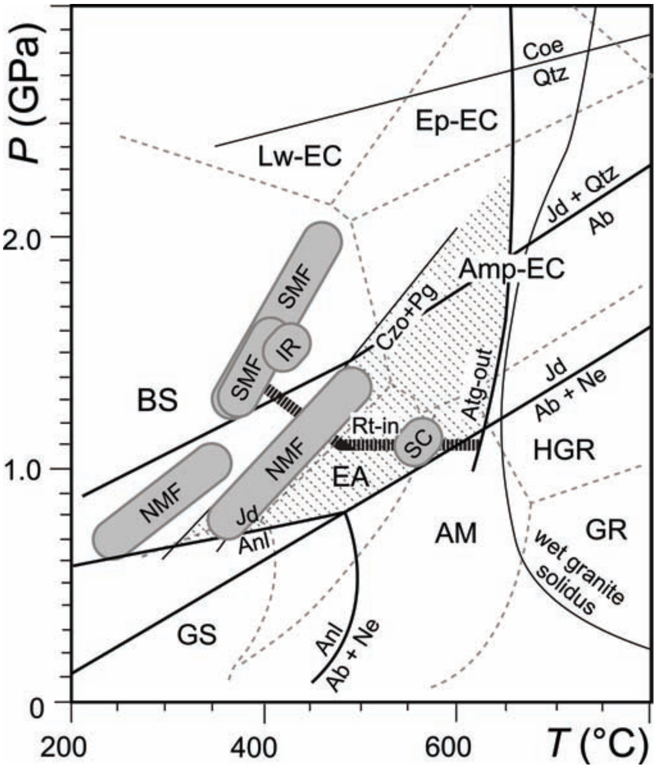

Fig. 6. *P-T* diagram showing approximate *P-T* conditions of selected jadeitites from Guatemala (Harlow *et al.*, 2011), Cuba (García-Casco *et al.*, 2009) and Iran (Oberhänsli *et al.*, 2007); NMF—North of Motagua fault (Guatemala), SMF—South of Motagua fault (Guatemala), SC—Sierra del Convento (Cuba), and IR—Iran. Hatched area represents the jadeite (Jd) + clinozoisite (Czo) + paragonite (Pg) assemblage in the antigorite stability field; the reactions involving jadeite and those defining jadeite stability are after Harlow *et al.* (2011). Thick striped Rt-in line represents lower-*P* and –*T* limits of the jadeite (Jd[$jd_{90}di_{10}$]) + rutile + clinozoisite assemblage obtained with the THERMOCALC software and database of Holland & Powell (1998). The metamorphic facies and their abbreviations are after Liou *et al.* (2004).

On the other hand, higher-*T* (>550 °C) jadeitite formation was recently proposed by García-Casco *et al.* (2009) for eastern Cuba, based on the jadeite–omphacite miscibility gap. Schertl *et al.* (2012) suggest jadeitite formation occurred at similar conditions in the Dominican Republic as well. García-Casco *et al.* (2009) considered that jadeitite-forming fluids in the Sierra del Convento mélange originally evolved from partial melts in the subduction environment at high *T*. In general, jadeitites commonly contain accessory minerals enriched in high field strength elements (HFSE) – *e.g.*, titanite, zircon and rutile –. These minerals indicate HFSE mobility in fluids during jadeitite formation. Thermodynamic calculations for rutile-bearing mineral equilibria suggest that the rutile-bearing jadeitite formed at higher *T* and *P* than blueschist-facies jadeitite (Fig. 6). In fact, the precipitation of rutile crystals has been often reported in eclogite veins (*e.g.*, Rubatto & Hermann, 2003; Gao *et al.*, 2007). Considering these new insights, the *P-T* conditions for jadeite formation can be extended beyond the previously argued limits of blueschist-facies conditions. In other words, jadeitite can form not only in cold subduction zones, but also in hotter ones, if enough slab-derived fluid is available to interact with ultramafic rocks.

As described above, a few jadeitite occurrences indicate that they formed later than the associated H*P* rocks. Jadeitite surrounding the eclogite blocks of Borus (Sobolev *et al.*, 1986) and net-veins of jadeitite in the interior of an eclogite block in Syros (Bröcker & Keasling, 2006) are evidence that the jadeitite formed subsequent to eclogite formation; they have most likely formed during the blueschist-facies overprint of pre-existing eclogite. In contrast, jadeitite veins cross-cutting host blueschist in New Idria and the Dominican Republic record fluid infiltration after blueschist formation. Such local jadeitite veins might be common in other lawsonite blueschist localities as well (*e.g.*, Seki *et al.*, 1960; Imaizumi & Kanehira, 1980; Maresch *et al.*, 2012). In order to solve these time differences, more geochronological constraints are required.

3.2. Geochronological conundrum

Over the last several years, zircon in jadeitite has been dated using the ion microprobe (Tsujimori *et al.*, 2005a; Bröcker & Keasling, 2006; Shi *et al.*, 2008; Yui *et al.*, 2010, 2012; Mori *et al.*, 2011; Schertl *et al.*, 2012). Some of these results can constrain the timing of zircon growth in jadeitite (*i.e.*, timing of jadeitite formation). Zircon growth during jadeitite formation is generally supported by the presence of H*P*-L*T* mineral inclusions. However, without such information, it is not always easy to discriminate whether the zircons are igneous or hydrothermal in origin. Recent O-isotope measurements attempted to address the origin of zircons in jadeitite (Fu *et al.*, 2010). In the several cases examined, zircons in jadeitite show isotope composition similar to mantle peridotite or MORB. Hf-isotope compositions also suggest an igneous source (*e.g.*, Shi *et al.*, 2009). Stable-isotope characterization of such zircons has just begun, but O–Hf isotope systematics – fractionation, partitioning, etc – particularly in fluid-related processes, are not well understood. Thus, the correct interpretation of the timing of zircon crystallization in jadeitite requires a comprehensive approach to focus on *in situ* geochemical and isotopic analyses of zircon, as well as on other indicators such as inclusions in zircon compared to the mineral assemblages found in the jadeitites and associated H*P*-L*T* rocks.

Available ages from both jadeitite and associated H*P*-L*T* rocks from selected localities are summarized in Fig. 7. Temporal discrepancies between jadeitite formation and H*P*-L*T* metamorphism have been documented for some localities. North of the Motagua Fault of Guatemala, zircon U-Pb ages of jadeitite are more than 30 Ma younger than Sm-Nd mineral isochron ages of eclogite-facies metamorphism (Yui *et al.*, 2010). This result is consistent with an interpretation that the jadeitite formed during blueschist-facies overprinting subsequent to the eclogite-facies metamorphism. However, this area experienced two H*P*-L*T* events, not one, so the second event must be considered (Fig. 8). This event is distinctively documented by eclogite remnants in the Chuacús complex in which the mélange is sandwiched; Sm-Nd mineral isochrons yield an age of ~70 Ma (Martens *et al.*, 2007a, b), roughly equivalent to the ^{40}Ar/^{39}Ar ages of 65–75 Ma of both the Chuacús schists as well as the jadeitites, albitites, and mica rocks. In this context, the U-Pb zircon dates from jadeitite, now confirmed by our own measurements on jadeitite and albite-mica rock samples (85–95 Ma), are 15–25 Ma older than this H*P*-L*T* event. South of the Motagua fault, Fu *et al.* (2010) reported a U-Pb zircon age of ~154 Ma from a jadeitite, compared to the Sm-Nd mineral isochron from eclogite of 132–144 Ma and ^{40}Ar/^{39}Ar mica ages of 116–125 Ma. Whereas Fu *et al.* (2010) argued for an inherited zircon origin, we have observed clinozoisite, omphacite and fluid inclusions in these zircons and made new U-Pb measurements that yielded 149 Ma, 5–22 Ma older than the eclogite. Zircons from Japanese Paleozoic jadeitites are more than 100 Ma older than the associated Late Paleozoic H*P*-L*T* schists (Tsujimori *et al.*, 2005a; Kunugiza & Goto, 2010). The jadeitite formation may be linked to Early Paleozoic high-pressure amphibolite-facies metamorphism of ophiolitic fragments (Tsujimori *et al.*, 2005b); the common occurrence of rutile, suggesting jadeitite formation at higher *T*, supports this hypothesis.

3.3. Recrystallization/re-precipitation of jadeitite

Several examples (Fig. 8) suggest that the timing of original jadeitite formation is not necessarily directly correlated with the blueschist/eclogite-facies metamorphism documented in the associated metabasic blocks. We suggest that, while the latter are associated with the main subduction channel, some jadeitite-bearing mélanges may document processes in the overlying mantle wedge. Despite the present close association between older jadeitite and younger H*P*-L*T* rock in a single mélange complex, different or evolving histories for the subduction channel and mélange are implied. The subduction channel behaves like a conveyor belt – with time the eclogites can be delivered deep into the mantle where they may not be exhumed, whereas the jadeitites are implanted in the mantle wedge, where they can be. In other words, jadeitite can stay at the edge of the mantle wedge for a considerable time. As jadeitites are emplaced into the mantle wedge rather than the mélange, they are more robust in retaining shallower position compared with the channel, which largely flows with the slab. Therefore, the blueschists seen in a mélange

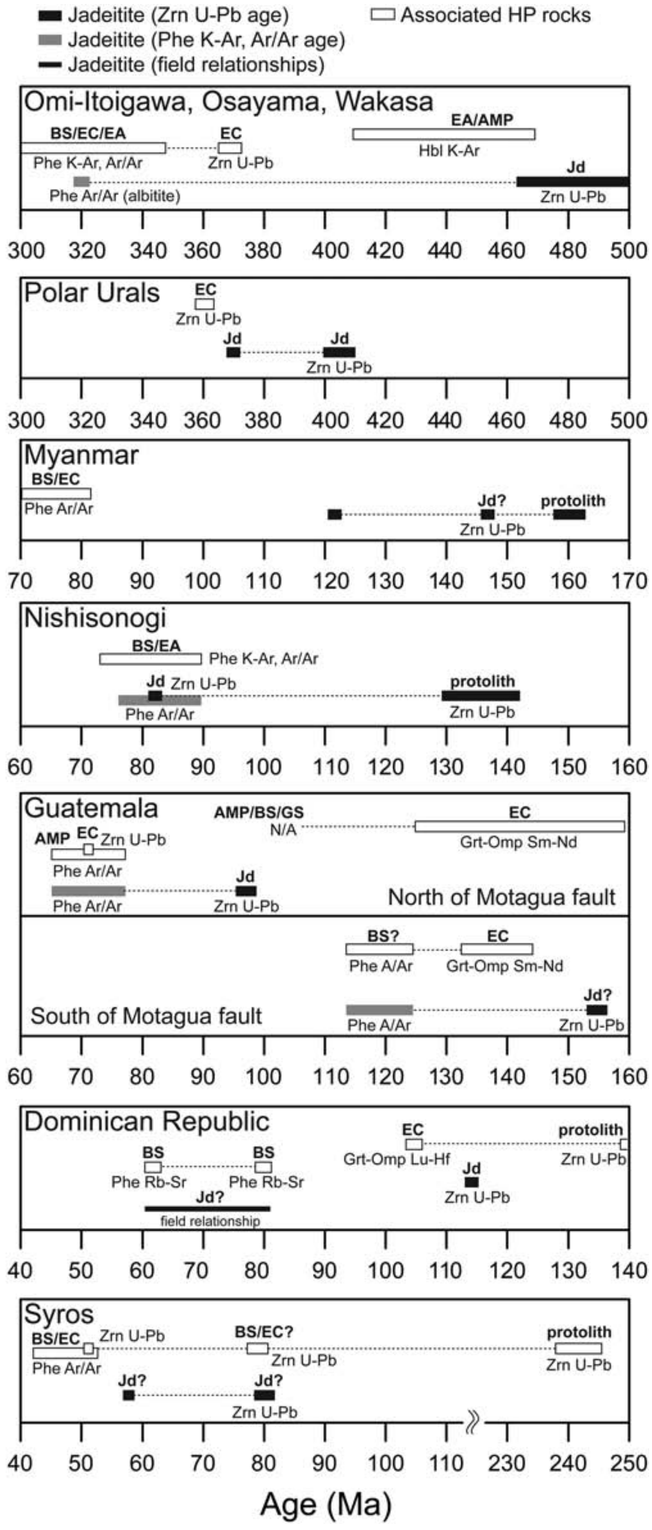

Fig. 7. Summary of geochronological data for jadeitite and associated HP-LT metamorphic rocks from selected localities (see references in text). Abbreviations: Jd—jadeitite, protolith—protolith age, Zrn—zircon, Phe—phengite, Hbl—hornblende, Grt—garnet, omphacite—omphacite, GS—greenschist facies, BS—blueschist facies, EC—eclogite facies, EA—epidote amphibolite facies, AM—amphibolite facies.

are returned without further descent down the channel. Eclogites that return are either sampled contemporaneously from the channel or returned in the developing mélange as a numerical simulation by Gerya *et al*. (2002) might suggest. Various localities, particularly Cuba, support this aspect. In addition, multiple fluid-infiltration events can affect the jadeitite during this long residence time. Multiple cycles of recrystallization and/or re-precipitation likely erase the initial accessory minerals except for zircon. The textural relationship between rutile and titanite in the Osayama jadeitite is a good example that rutile as an initial jadeitite mineral assemblage was replaced by titanite during secondary recrystallization (Fig. 3b–c). Moreover, the long residence time can also lead to the complete breakdown of jadeititic mineral assemblages at a shallower depth. For instance, the symplectitic breakdown texture of jadeitite north of the Motagua Fault records an incipient disappearance process of jadeitite (Fig. 2).

In another aspect of the convergent margin, the subduction channel can occasionally consume parts of the overlying serpentinized mantle wedge due to tectonic erosion. With time the disrupted mantle wedge with jadeitite veins is mixed with younger blueschists, exhumed eclogites and various fragments of suprasubduction zone lithologies. Consequently recrystallization and re-precipitation of jadeitite are reactivated along the slab – mantle wedge interface. All these possible scenarios and their combinations result in a complicated petrological record in jadeitite. With further investigation, however, the rock association of jadeitite – HP-LT metamorphic rocks – serpentinite has the potential to yield a greater understanding of subduction channels and the overlying mantle wedge.

4. Conclusions

Jadeitites are products of fluid-mediated crystallization and/or metasomatism largely restricted to subduction channels and the overlying mantle wedge. Major occurrences consist principally of primary fluid precipitates (P-type) that infiltrated the mantle wedge, whereas fewer occurrences document metasomatic replacement (R-type) of plagiogranite, metagabbro or eclogite, and both types may be possible in the same occurrence or system. P-T conditions of crystallization are difficult to constrain because of high-variance assemblages. Evidence for close association with blueschists is abundant, but less so for coexistence with eclogites; however, without adequate phase-assemblage constraints, jadeitite formation at eclogite conditions cannot be ruled out. Finally, developing evidence suggests that rather than preserving a record of subduction termination through collision or some other process that initiates exhumation of the HP-LT complex, jadeitite formation may record a longer process and predate early exhumation by many millions of years. This

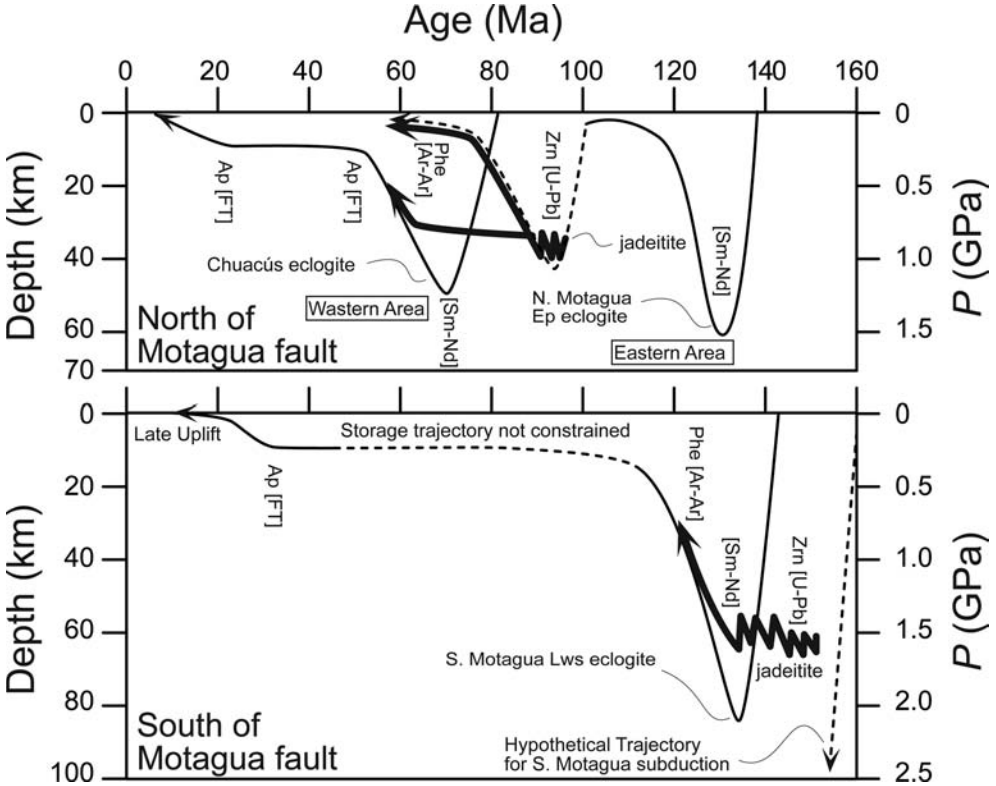

Fig. 8. Pressure–age diagrams showing burial evolution for subduction/collision-related rocks from Guatemala (see details in text). The arrows represents trajectory of jadeitite (bold lines) and H*P*-L*T* rocks (regular lines). The trajectories were delineated based on our interpretation of geochronological data (zircon U-Pb, phengite ^{40}Ar/^{39}Ar, apatite fission track [FT], and Sm-Nd isochrons). The zig-zag pattern during the time of jadeitite formation is to suggest the cycling of temperature recorded by Jd-Omp pairs (Harlow *et al.*, 2011), and inferred to reflect pressure as well; its use in the figure is only diagrammatic. The trajectories in dashed lines are not yet constrained.

should be considered reasonable, if, as argued, most jadeitites reside in the brittle domain of the mantle wedge which is not subducted, but remain in the upper lithosphere and are susceptible to exhumation. Much remains to be learned about these relatively rare samples of the subduction – mantle hydration process: what controls their distribution – is it something particular about subduction, exhumation, or perhaps both; what particular signatures of their subduction origin do they document; what is their potential for preservation in the lithosphere (*e.g.*, Colorado Plateau samples)?

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