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Very-low-temperature record of the subduction process: A review of worldwide lawsonite eclogites

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Abstract

Lawsonite eclogites preserve a record of very-low-temperature conditions in subduction zones. All occur at active margin settings, typically characterized by accretionary complexes lithologies and as tectonic blocks within serpentinite-matrix mélange. Peak lawsonite-eclogite facies mineral assemblages (garnet+omphacite+lawsonite+rutile) typically occur in prograde-zoned garnet porphyroblasts. Their matrix is commonly overprinted by higher-temperature epidote-bearing assemblages; greenschist- or amphibolite-facies conditions erase former lawsonite-eclogite relics. Various pseudomorphs after lawsonite occur, particularly in some blueschist/eclogite transitional facies rocks. Coesite-bearing lawsonite-eclogite sare known. Using inclusion assemblages in garnet, lawsonite eclogites can be classified into two types: L-type, such as those from Guatemala and British Columbia, contain garnet porphyroblasts that grew only within the lawsonite stability field and E-type, such as from the Dominican Republic, record maximum temperature in the epidote-stability field.

Formation and preservation of lawsonite eclogites requires cold subduction to mantle depths and rapid exhumation. The earliest occurrences of lawsonite-eclogite facies mineral assemblages are Early Paleozoic in Spitsbergen and the New England fold belt of Australia; this suggests that since the Phanerozoic, secular cooling of Earth and subduction-zone thermal structures evolved the necessary high pressure/temperature conditions. Buoyancy of serpentinite and oblique convergence with a major strike-slip component may facilitate the exhumation of lawsonite eclogites from mantle depths. © 2006 Elsevier B.V. All rights reserved.

Keywords: Cold subduction; HP-UHP metamorphism; Lawsonite; Eclogite; P-T trajectory

1. Introduction

The discovery of supracrustal rocks metamorphosed at ultrahigh-pressure (UHP) and/or ultrahigh-tempera-

ture (UHT) conditions is a revolution in our under-

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standing of crustal-scale processes in the lithosphere (e.g., Liou et al., 1994; Coleman and Wang, 1995; Maruyama et al., 1996; Liou et al., 1997; Hacker and Liou, 1998; Harley, 1998; Pattison et al., 2003; Carswell and Compagnoni, 2003; Rumble et al., 2003; Liou et al., 2004). These extreme high-*P* or high-*T* metamorphic processes have played a crucial role in the evolution of

the continental crust. On the other hand, another extreme occurs at the high-P but extremely low-Tconditions produced in subducting slabs recorded by the lawsonite-eclogite facies (e.g., Pawley, 1994; Schmidt and Poli, 1998; Okamoto and Maruvama, 1999). Lawsonite, CaAl₂Si₂O₇(OH)₂·H₂O, accommodates up to 11.5 wt.% H₂O, has favorable sites for REE, Sr, Pb, Th and U in its structure, and is stable in subducting slab to at least 300 km depth within cold subduction zones (e.g., Schmidt, 1995; Pawley et al., 1996; Comodi and Zanazzi, 1996; Schmidt and Poli, 1998; Okamoto and Maruyama, 1999; Spandler et al., 2003). Consequently, dehydration of lawsonite-bearing slabs may play an important role in arc magmatism, subduction zone seismicity, and the recycling of volatiles and selective trace elements into the mantle (Peacock and Wang, 1999; Kerrick and Connolly, 2001; Connolly and Kerrick, 2002; Hacker et al., 2003a,b; Liou et al., 2003; Rüpke et al., 2004; Ohtani, 2005).

The occurrence of lawsonite eclogites in many orogens demonstrates that some crustal rocks were subducted and experienced HP–UHP metamorphic conditions at what was previously thought to be forbidden-zone P-T regions (cf. Liou et al., 2000). Moreover, P-T constrains on lawsonite eclogites create important anchor points for thermal models of modern subduction zones. Understanding the extent of eclogitization within the lawsonite stability field on a regional scale and the mechanisms whereby these deep-seated low-T rocks have been exhumed to the surface are crucial scientific challenges for Earth scientists. This article summarizes the results of recent petrochemical studies of natural lawsonite eclogites from both our own data and the literature.

In this paper, we use the term "eclogite" for any metabasite in which garnet and omphacite are present as an equilibrium assemblage, regardless of their abundance. Throughout this paper mineral abbreviations are after Kretz (1983) excepting phengite (Phe).

2. Worldwide distribution of lawsonite eclogites

Ten lawsonite-eclogite localities (Fig. 1) have been documented in Phanerozoic orogenic belts, excluding xenoliths in kimberlitic pipes. Many are formed at active margins that are characterized by accretionary complexes with 'Pacific-type' lithologies (Maruyama et al., 1996; Ernst, 2005) that include ophiolitic serpentinites, greenstones, seamount fragments, bedded cherts and trench turbidites (Zack et al., 2004). Most occurrences of lawsonite eclogites are tectonic blocks within serpentinite and are not associated with granitic gneiss and marble. Peak lawsonite-eclogite facies mineral assemblages are preserved primarily in garnet porphyroblasts that have prograde chemical zoning. Higher-T epidote-bearing assemblages overprint the matrix of some of these eclogites. What follows are descriptions of the lithological and petrochemical characteristics of lawsonite eclogites from different localities. Mineral assemblages, P-T conditions and radiometric ages are summarized in Table 1.

2.1. Southern Motagua fault zone, Guatemala

McBirney et al. (1967) first described eclogites from south of the Motagua fault zone (MFZ). The MFZ, a left-lateral strike-slip fault, is the present-day boundary between the North American and the Caribbean plates; it juxtaposes the Maya and Chortís continental blocks. Along the MFZ, serpentinite-matrix mélange is exposed on both sides of the Río Motagua (e.g., Harlow, 1994; Harlow et al., 2003, 2004). Lawsonite eclogite occurs as tectonic blocks within antigorite serpentinite ~ 15 km south of the Río Motagua (Sisson et al., 2003; Tsujimori et al., 2003; Harlow et al., 2004; Tsujimori et al., 2005, 2006). The eclogite-bearing serpentinite mélange unit contains meter-size and larger blocks of lawsonite eclogite, garnet-bearing lawsonite blueschist, garnetiferous quartz micaschist, jadeite whiteschist, omphacitite and jadeitite (Harlow et al., 2004; Tsujimori et al., 2006). This association of metabasalt and metapelite in serpentinites suggests oceanic protoliths with trench-fill sediments, typical of the 'Pacific-type' intra-plate subduction. Geochemical analysis indicates a MORB protoliths for the metabasalt. Phengite in the lawsonite eclogites yield integrated ³⁹Ar-⁴⁰Ar ages of 116-120 Ma (Harlow et al., 2004). Sisson et al. (2003) and Brueckner et al. (2005) reported Nd-Sm garnetomphacite-whole rock isochron ages of 132 Ma for peak eclogite-facies metamorphism.

Most lawsonite eclogites are characterized by the prograde mineral assemblage Grt+Omp (~52 mol% jd)+ Lws+Rt+Qtz±Chl±Phe (3.5–3.7 Si pfu) (Fig. 2a). This textural evidence indicates synchronous growth of lawsonite and other eclogite-facies minerals (Grt+Omp+ Rt). The modal abundance of Grt+Omp reaches locally up to 80%. The post-eclogite stage blueschist-facies overprint (Gln+Lws+Chl+Ttn+Qtz±Phe) locally replaces earlier mineral assemblages. Garnet porphyroblasts with prograde chemical zoning contain abundant mineral inclusions of lawsonite, omphacite, rutile, chlorite and quartz (Tsujimori et al., 2006) (Fig. 2b and c). Lawsonite inclusions within garnet, in turn, preserve traces of pumpellyite crystals. Omphacite in



Fig. 1. Distribution and peak metamorphic age of lawsonite-eclogite mineral assemblages in the world. Recognized UHP terranes (Liou et al., 2004) are also shown.

Table 1			
Summary of lawsonite	eclogites	of the	world

	-						
	South Motagua fault zone, Guatemala (GT)	Samaná Peninsula, Dominica Republic (DR)	Schistes Lustrés, Corsica (CS)	Central Pontides, Turkey (TK)	Port Macquarie, New England fold belt, Australia (AU)	Pinchi Lake, British Columbia (BC)	Ward Creek, Franciscan complex (WC)
Occurrence	Tectonic block within serpentinite mélange	Tectonic block within serpentinite mélange	Coherent meta-ophiolite unit	Tectonic block within serpentinite mélange	Tectonic block within serpentinite mélange	Tectonic block within serpentinite mélange	Coherent metabasite
Associated rocks	Serpentinite, omphacitite, jadeitite, blueschist, micaschist	Serpentinite, blueschist, micaschist	Metagabbro, metachert, metaquartzite, dolomitic marble	Serpentinite, blueschist	Serpentinite, omphacitite, blueschist	Serpentinite, blueschist, metachert	Blueschist, jadeitite
Age	132 Ma (Nd–Sm), 116–120 Ma (⁴⁰ Ar– ³⁹ Ar Phe)	84 Ma (Sm–Nd), 25–49 Ma (⁴⁰ Ar– ³⁹ Ar Phe)	85 Ma (Sm–Nd), 64Ma (⁴⁰ Ar– ³⁹ Ar Phe)	Cretaceous?	450 Ma (K–Ar Phe)	211–218 Ma (K–Ar Phe)	145 Ma (⁴⁰ Ar- ³⁹ Ar Phe)
Prograde LwEC facies assemblage	$\begin{array}{l} Grt+Omp+Lws+\\ Rt\pm Gln\pm Phe+\\ Qtz,\ Grt+Jd+\\ Lws\pm Gln\pm Chl+\\ Rt+Qtz \end{array}$	Grt+Lws+ Omp+Pg+ $Phe\pm Gln+Qtz$	Grt+Omp+ Gln±Act+ Lws+Phe+ Ttn+Qtz	Grt+Omp+ Lws+Gln+ Rt+Phe+Qtz	Grt+Omp+ Lws+Ttn+ Qtz±Rt±Phe	Grt+Omp+ Lws+Gln+ $Rt+Phe\pm$ Tlc+Qtz	$Grt+Omp+Lws+Gln\pmAct+Rt\pmTtn\pmPhe+Qtz$
Grt–Cpx $K_{\rm D}$ Prograde garnet	100–18 pyr = 2–17%, alm = 54–71%, grs = 18–31%, sps = 0–16%	64-32 pyr=3-7%, alm=47-61%, grs=31-33%, sps=1-17%	77-74 pyr=0-17%, alm=43-68%, grs=21-38%, sps=0-54%	93-50 pyr=1-5%, alm=23-58%, grs=22-36%, sps=4-54%	31–27 pyr=1–11%, alm=56–70%, grs=22–36%, sps=0–18%	49–18 pyr=2–12%, alm=47–67%, grs=18–20%, sps=1–32%	70-34 pyr=2-6%, alm=36-53%, grs=33-34%, sps=10-29%
Prograde clinopyroxne Phengite	jd=30-52%, jd=61-75% Si=3.5-3.7	jd=40-44% Si=3.4	jd=30-40% Si=3.5-3.6	jd=22-44% Si=3.1, BaO=	jd=29-47% Si=3.4-3.7	jd=20-45% Si=3.4-3.8	jd=30-50% Si=3.4-3.5
Grt–Cpx–Phe thermobarometry $P-T$ estimates	P=2.5 GPa, T=470 °C $P=\sim1.8-2.5$ GPa, T=290-470 °C	P=1.6 GPa, T=360 °C P=1.6 GPa, T=360 °C	P=2.0 GPa, T=390 °C P>1.0 GPa, T=ca.	~2.7 wt.% N/A P > 1.4 GPa, T = ca.	P=2.0-2.4 GPa, T=420-570 °C $P=\sim 1.8$ GPa, T<ca. 560 °C	P=2.2 GPa, T=450 °C P>1.3 GPa, T=ca. 565 °C	<i>P</i> =1.8−2.2 GPa, <i>T</i> =420−460 °C <i>P</i> >1.0 GPa, <i>T</i> =360−445 °C
Prograde Ep Retrograde Lws Retrograde Ep Prograde metamorphic	Absent Present Absent LwEC	Present Absent Present LwEC→ EpEC	Absent Present Absent LwEC	Present Absent Absent LwEC \rightarrow EpEC	Absent Absent Present LwEC	Absent Present Absent LwEC	Present Absent ? Absent LwEC→ EpEC (?)
Overprinting Type Representative citations	LwBS Type L McBirney et al. (1967), Harlow et al. (2004), Tsujimori et al. (2005, 2006)	EpBS/GS Type E Zack et al. (2004)	LwBS Type L Caron and Péquignot (1986)	EpBS Type E Altherr et al. (2004)	EpBS/GS Type L Watanabe et al. (1997), Och et al. (2003), Enami et al. (1999)	LwBS Type L Ghent et al. (1993)	LwBS (?) Type E (?) Maruyama and Liou (1998), Oh et al. (1991), Shibakusa and Maekawa (1997)

 $Lws^{\uparrow}{=}inclusions$ in the cores of garnet; 'Coe'=pseudomorph after coesite. a UHP.

Barru complex, Sulawesi, Indonesia (ID)	Pam Peninsula, New Caledonia (NC)	Motalafjella, Spitsbergen (SB)	Garnet Ridge, Colorado Plateau (CO)	Huangzhen- Zhujiachong, Dabie, China (DB)	Qinglongshan, Sulu, China (SL)	Verpeneset, Western Gneiss Region, Norway (VP)
Tectonic block within serpentinite mélange	Coherent metabasite	Mafic layer in coherent schist	Xenolith in kimberlitic pipes	Mafic layer in coherent gneiss	Mafic layer in coherent gneiss	Mafic layer in coherent gneiss
Serpentinite, micaschist	Blueschist	Micaschist, marble	Zoisite-eclogite, kyanite-eclogite, jadeitite, omphacitite	Orthogneiss, paragneiss	Orthogneiss, paragneiss	Orthogneiss, paragneiss
106 Ma (K–Ar Phe)	37 Ma (⁴⁰ Ar- ³⁹ Ar Phe), 44 Ma (U-Pb Zrn)	450–475 Ma (⁴⁰ Ar– ³⁹ Ar Phe)	33–81 Ma (U–Pb Zrn)	242 Ma (U–Pb Zrn), 242–245 Ma (⁴⁰ Ar– ³⁹ Ar Pg)	231 Ma (U–Pb Zrn)	385–390 Ma (⁴⁰ Ar- ³⁹ Ar Phe), 403 Ma (U–Pb Zrn)
Grt+Omp+ Gln+Ep+ Phe+Rt+ Lws+Qtz	Grt+Lws [†] ±Omp	Grt+Omp+Lws [†]	Grt+Omp+Lws+ Rt±Phe+Coe	Grt+Omp+ Lws pseudomorph [Ky+Czo+Qtz]+ $Pg+Zo+Rt\pm$ Tlc+Coe	Grt+Omp+Lws pseudomorph [Ky+Ep+Qtz]+ Ep+Tlc+Rt+Coe	Grt+Omp+Lws pseudomorph [Czo]+Ky±Tlc± Pg±Hbl+Rt+'Coe'
N/A N/A	>35? pyr=12-40%	>35 N/A	16-14 pyr=2-6%	>3 pyr=27-37%	>3-4 pyr=37-47%	N/A pyr=18-44%
1.1/2.1	alm=45%, grs=32%, sps=21%	1.1/2.1	alm=32-63%, grs=311-25%, sps=1-3%	alm=46-52%, grs=8-15%, sps=1-5%	alm=36-46%, grs=15-18%, sps<2%	alm = 36-48%, grs = 17-25%, sps = 0-10%
N/A	?	jd=20-30%	jd = ~43%, jd = ~62%	jd=49-55%	jd=37-47%	jd=34-47%
N/A	?	N/A	$Si = \sim 3.8$	N/A	Si=3.6	Si=3.3-3.4
N/A	N/A	N/A	<i>P</i> =3.5 GPa, <i>T</i> =540 °С	N/A	<i>P</i> =3.4–3.6 GPa, <i>T</i> =650–700 °C	<i>P</i> =2.9 GPa, <i>T</i> =710 °C
$P = \sim 2.1$ GPa,	P = ca.	<i>P</i> >0.8 GPa,	P=3-5 GPa,	P=ca.	<i>P</i> =3.3–3.5 GPa,	P=2.9 GPa,
<i>T</i> =ca. 520 °C	2.0 GPa, <i>T</i> ≥ca. 460 °C	<i>T</i> =350–400 °C	<i>T</i> =ca. 560–700 °C	3.3 GPa, <i>T</i> > a670 °C	<i>T</i> =600–700 °C	<i>T</i> =710 °C
?	Present	Present	Present	Present	Present	Present
?	Absent	Absent	Absent	Absent	Absent	Absent
?	Present	?	Present	Present	Present	Present
?	$EpBS/LwEC \rightarrow$	LwEC→	LwEC ^a	LwEC ^a	$LwEC^{a}(?) \rightarrow$	$LwEC^{a}(?) \rightarrow$
	EpEC	EpEC		$(?) \rightarrow EpEC^{a}$	EpEC ^a	EpEC ^a
?	EpBS	EpBS/GS	EpEC ^a	AM	EA/AM	EA/AM
Type E (?)	Type E	Type E	Type L	Type E	Type E	Type E
Parkinson et al. (1998)	Clarke et al. (1997)	Hırajıma et al. (1988)	Watson and Morton (1969), Helmstaedt and Schulze (1988), Usui et al. (2003, 2006)	Castelli et al. (1998), Li et al. (2004)	Mattinson et al. (2004)	Krogh (1982), Carswell et al. (2003), Root et al. (2004)



Fig. 2. Microtextures of Guatemalan lawsonite eclogite. (a) Photomicrograph showing the coexistence of Grt+Omp+Lws (plane polarized light=PPL). (b) X-ray image of Mn concentration of prograde-zoned garnet porphyroblast; contour of rimward decrease in Mn shows the form of near-euhedral polygons. (c) Photomicrograph showing inclusion-rich garnet (PPL); inclusions are mainly lawsonite and omphacite. (d) X-ray image of Ca concentration of matrix omphacite contains mineral inclusions of lawsonite and rutile. (f) Photomicrograph showing omphacite crystal with abundant fluid inclusions (PPL). (g) Photomicrograph showing eclogite-stage matrix lawsonites coexist with rutile (PPL).

the matrix contains mineral inclusions of lawsonite and rutile (Fig. 2d); some matrix omphacites contain sparse to abundant fluid inclusions (Fig. 2e). Although rutile in the matrix is commonly replaced by titanite, matrix rutile does not have a titanite rim in less-retrograded eclogites (Fig. 2f). Some lawsonite eclogites contain impure jadeite (61–75 mol% jd) instead of omphacite (Tsujimori et al., 2005). Grt–Cpx–Phe thermobarometry of Krogh Ravna and Terry (2004) suggest that eclogitization initiated at $T=\sim300$ °C and P>1.1 GPa, and continued to $T=\sim480$ °C and $P=\sim2.6$ GPa (Tsujimori et al., 2006).

2.2. Samaná Peninsula, Hispaniola (Dominican Republic)

Zack et al. (2004) recently described a lawsoniteeclogite pebble from the Samaná Peninsula of Hispaniola. In this region, blueschist-facies metasediment, limestone and serpentinite are distributed along the northern portion of the Septentrional fault zone, an extension of the present-day North American–Caribbean suture. Glaucophane-bearing zoisite-eclogite occurs as blocks within garnetiferous quartz micaschist and serpentinite (Giaramita and Sorensen, 1994; Gonçalves et al., 2000; Catlos and Sorensen, 2003). Garnet porphyroblasts in micaschist with Grt+Gln+Zo/Czo+Phe/ Pg+Qtz assemblage contain rare lawsonite inclusions (Gonçalves et al., 2000). Sm–Nd glaucophane–whole rock isochron age yields 84 Ma for the eclogite-facies metamorphism (Perfit and McCulloch, 1982); in contrast, phengite ³⁹Ar–⁴⁰Ar ages range from 49 to 25 Ma (Catlos and Sorensen, 2003). All these rocks are comparable to a metamorphosed accretionary complex from 'Pacific type' orogenic belts.

The lawsonite eclogite described by Zack et al. (2004) consists of glaucophane (40%), garnet (25%), omphacite (15%), phengite (10%), lawsonite, epidote and rutile. The cores of garnet porphyroblasts with prograde zoning contain inclusion assemblages of Lws+Omp (up to

44 mol%jd)+Pg+Phe (3.4 Si p.f.u.)±Gln+Qtz, whereas abundant epidote inclusions occur in the rims. Lawsonite porphyroblasts in the matrix contain Lws+Omp+Gln and are partially replaced by epidote. Rutile in matrix is partially replaced by titanite. Grt–Cpx–Phe thermobarometry yields $P = \sim 1.6$ GPa at T = 360 °C for the lawsonite-eclogite stage; the Samaná lawsonite eclogite records prograde evolution to the zoisite-eclogite facies (T = 410-450 °C and $P = \sim 1.6$ GPa) (Zack et al., 2004).

2.3. Schistes Lustré, Corsica

The Alpine HP schists of the Schistes Lustré complex occur in northeastern Corsica Island in the western Mediterranean Sea. The Schistes Lustré complex is best exposed in the Western Alps, and consists mainly of meta-ophiolitic rocks with meta-pelagic sediments and calcschists (e.g., Agard et al., 2002); coesite-bearing micaschists have been described in the Cignana area (e.g., Reinecke, 1991). On Corsica, these rocks structurally rest on the autochthonous Hercynian basement (e.g., Caron et al., 1981; Fellin et al., 2005). Lawsonite eclogites occur within a meta-ophiolitic unit including jadeite-bearing metadiorite, omphacite-lawsonite-phengite metagabbro, piedmontite quartzite, jadeite-omphacite orthogneiss and dolomitic marble (Caron et al., 1981; Caron and Péquignot, 1986; Lahondére, 1988; Padoa, 2001). Mafic eclogites yield an Sm-Nd internal isochron age of 85 Ma (Lahondére and Guerrot, 1997) and a phengite Ar-Ar age of \sim 64 Ma (Brunet et al., 2000). Protoliths of the Schistes Lustré consist mainly of Tethyan oceanic crust and some passive margin lithologies such as dolomitic marble and peralkaline rhyolites (Caron et al., 1981; Tribuzio and Giacomini, 2002).

Caron and Péquignot (1986) describes lawsoniteglaucophane-bearing eclogites with Grt+Omp (up to 40 mol% jd)+Gln (\pm Act)+Lws+Phe (3.5–3.6 Si pfu)+ Ttn+Qtz; garnet porphyroblasts contain inclusion trails of lawsonite and actinolite. Albite and rare epidote occur as late stage micro-veins. Grt-Cpx-Phe thermobarometry yields *P*=ca. 2.0 GPa at *T*=390 °C.

2.4. Central Pontides, Turkey

Tectonic blocks of lawsonite eclogite occur in a serpentinite-matrix mélange unit of the Elekdag ophiolite, northern Turkey (Altherr et al., 2004). The HP metamorphosed ophiolitic belt is part of the Alpine-Himalayan blueschist chain (e.g., Okay, 1989; Maruyama et al., 1996), and contains chloritoidjadeite-bearing lawsonite-blueschists, garnet-bearing lawsonite blueschists and minor lawsonite eclogite (Okay and Kelley, 1994; Okay, 2002). The lawsonite eclogite has a MORB bulk-rock composition and contains Grt+Omp (up to 44 mol% jd)+Lws+Gln+Rt+Qtz as a peak-metamorphic assemblage that characterizes the rims of garnet porphyroblasts and matrix omphacite. Peak eclogite-facies conditions were estimated by garnet–omphacite geothermometry as and T=ca. 400–430 °C at P>1.4 GPa. Cores of garnet porphyroblasts with prograde zoning contain inclusions of epidote, lawsonite, glaucophane, chlorite, omphacite, Ba-rich phengite (up to 2.7 wt.% BaO), actinolite, winchite and quartz. The eclogitic assemblages are replaced by retrograde chlorite, phengite, titanite and tourmaline.

2.5. Port Macquarie, New England fold belt, Australia

Lawsonite eclogites with intense blueschist-facies overprinting occur as tectonic blocks within serpentinite-matrix mélange at Port Macquarie, Australia (Watanabe et al., 1997; Och et al., 2003). The serpentinite mélange is located along the southern New England fold belt and contains various blueschist-facies blocks yielding Ordovician phengite K-Ar ages (Fukui et al., 1995). The protolith of eclogite show an affinity with intra-plate basalt (Enami and Kimura, 2000). The relict eclogite-facies stage is characterized by Grt+Omp (~47 mol%)+Lws+Qtz+ Ttn \pm Rt \pm Phe (3.5–3.7 Si pfu); lawsonite occurs as porphyroblasts and as rare inclusions in garnet porphyroblasts (Enami et al., 1999; Och et al., 2003). The eclogitic assemblage is replaced by a blueschist-facies assemblage Gln+Act +Chl+Ep+Ttn+Cc+Ab. Geobarometry using the Grt-Cpx-Phe assemblage yields P=2.0-2.4 GPa and T=420-570 °C (Enami et al., 1999).

2.6. Pinchi Lake, British Columbia, Canada

Lawsonite eclogites and blueschists occur as tectonic blocks along the Pinchi fault zone of British Columbia (Ghent et al., 1993): phengite K–Ar ages of these rocks range from 211 to 218 Ma (Paterson and Harakal, 1974). Petrologic characteristics of lawsonite eclogite suggest that the protolith was basalt with some Mn-rich pelagic sediment. The Pinchi Lake lawsonite eclogites contain Grt+Omp (~45 mol% jd)+Lws+Gln+Rt+Phe (3.4– 3.8 Si pfu)+Qtz±Tlc; garnet porphyroblasts with prograde chemical zoning contain inclusions of lawsonite, omphacite and phengite. Rutile grains are rimmed by titanite. In some samples, garnets are pseudomorphed by stilpnomelane, retrograde lawsonite, chlorite and glaucophane. The lawsonite-eclogite facies metamorphism was estimated to be P > 1.3 GPa and $T = \sim 565$ °C (Ghent et al., 1993). Our P-T estimate, based on the Grt–Cpx–Phe thermobarometry, is $P = \sim 2.2$ GPa and T = 450 °C for the garnet core and $P = \sim 3.8$ GPa and T = 510 °C for the rim, although we cannot evaluate whether phengite was in equilibrium with garnet and omphacite. It is noteworthy that UHP garnet peridotite and rare eclogite pebbles were recently discovered from Early Jurassic forearc basin sediments in British Columbia (MacKenzie et al., 2005).

2.7. Ward Creek, Franciscan Complex

Lawsonite eclogites occur in a coherent metabasite (type-III blueschist) unit of the Ward Creek, Franciscan Complex, California. They have been described as garnet-glaucophane schist/in-situ eclogitic schist or eclogitic metabasite (Oh et al., 1991; Maruyama and Liou, 1998; Shibakusa and Maekawa, 1997). Several coarse-grained exotic eclogite blocks (type-IV eclogite) occur in type-III metabasite (Coleman and Lee, 1963; Maruyama and Liou, 1988). Moreover, rare quartz-bearing jadeitite is associated with type-III metabasite (Banno et al., 2000). Phengite from type-III metabasites yields a plateau ⁴⁰Ar-³⁹Ar age of 145 Ma (Wakabayashi and Denio, 1989).

The Ward Creek lawsonite eclogites contain Grt+ Omp (~50 mol% jd)+Lws+Ep±Pmp+Gln (±Act)+ Rt±Ttn+Qtz±Phe (3.5 Si pfu); garnet porphyroblasts have prograde zoning with mineral inclusions of omphacite, lawsonite, aragonite, titanite and quartz. Our *P*-*T* estimate based on the Grt-Cpx-Phe thermobarometry using mineral compositions of both Maruyama and Liou (1988) and Shibakusa and Maekawa (1997) yield P = ~ 1.8 - 2.2 GPa and T = 430 - 40 °C.

2.8. Barru Complex, Sulawesi, Indonesia

Glaucophane-bearing lawsonite eclogites together with serpentinite and garnetiferous quartz micaschists occur in a Cretaceous accretionary complex in Sulawesi, Indonesia (Parkinson et al., 1998; A. Kadarusman, pers. comm. 2005). Micaschist yielded a phengite K–Ar age of 106 Ma (Wakita et al., 1994). The lawsonite eclogite with Grt+Omp+Gln+Ep+Phe+Rt+Lws+Qtz assemblage gives peak conditions of $P=\sim 2.1$ GPa and T=520 °C.

2.9. Pam Peninsula, New Caledonia

Glaucophane-bearing epidote-eclogites and blueschists are common in the Pam Peninsula of the northeastern New Caledonia (e.g., Black and Brother, 1977; Yokoyama et al., 1986; Ghent et al., 1987; Clarke et al., 1997; Carson et al., 2000; Fitzherbert et al., 2003). New Caledonian eclogites and blueschists yield phengite ⁴⁰Ar-³⁹Ar ages of ca. 37 Ma (Ghent et al., 1994). Eclogite-facies metapelite vields zircon SHRIMP U-Pb ages of 44 Ma (Spandler et al., 2005). Cluzel et al. (1995) divided the high-P rocks into two terranes: the Diahot Cretaceous to Eocence metasedimentary terrane and the Pouébo eclogite and glaucophanite. Although eclogite was characterized by assemblage Grt+Omp (~43 mol% Jd)+Ep+Phe (<3.4 Si pfu)+Pg+Rt+Otz, garnet grains in some gabbroic eclogites contain lawsonite inclusions (Clarke et al., 1997). The garnet cores may record a prograde lawsonite-eclogite facies with peak P-Tconditions of P=2.1 to 2.4 GPa and T=475-580 °C (Fitzherbert et al., 2004).

2.10. Motalafjella, Western Spitsbergen

The Motalafjella complex is composed of lowgrade lawsonite blueschists and eclogite-bearing micaschist (Hirajima et al., 1988). Eclogite occurs only in the upper unit of metamorphosed passive margin sediments and impure limestone. Dallmeyer et al. (1990) obtained phengite ${}^{40}\text{Ar}{-}^{39}\text{Ar}$ ages of 450– 475 Ma. Motalafjella eclogites are characterized by the assemblage Grt+Omp (~50 mol% jd)+Ep+Phe (3.4 Si pfu)+Pg+Rt+Qtz; zoned garnet cores preserve rare inclusions of lawsonite together with omphacite, which establish the lawsonite-eclogite facies (Hirajima et al., 1988).

2.11. UHP lawsonite-eclogite xenoliths from 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 and Morton, 1969; Helmstaedt and Schulze, 1988; Usui et al., 2003, 2006). Ion-microprobe analyses for zircon U–Pb ages of eclogite xenoliths range from 81 to 33 Ma (Usui et al., 2003). Lawsonite eclogites have MORB bulk-rock compositions and contain Grt+Omp (~43 mol% Jd)+Lws+ Rt±Phe (~3.8 Si pfu)+Coe (Usui et al., 2003). Coesite occurs as micro-inclusions in garnet. Lawsonite is partly replaced by zoisite aggregates. Grt-Cpx-Phe thermobarometry yields P=ca. 3.5 GPa at T=540 °C, which is consistent with UHP conditions.

3. Possible lawsonite-eclogite localities

3.1. Prograde lawsonite pseudomorph in blueschist/ eclogite transitions

There are numerous descriptions of rhombic shaped inclusions of paragonite, clinozoisite/zoisite plus quartz aggregates in garnet from Alpine-Cycladic garnetepidote blueschists and glaucophane-epidote eclogites (e.g., Okrusch et al., 1978; Schliestedt, 1986; Pognante, 1989; Will et al., 1998; Schmädicke and Will, 2003; Ballevre et al., 2003), Alaskan garnet-epidote blueschists (e.g., Forbes et al., 1984; Thurston, 1985; Patrick and Evans, 1989), Caribbean eclogites (Green et al., 1968) and eclogite-facies meta-rodingites of the Maksyutov Complex, Russia (Schulte and Sindern, 2002; Beane and Liou, 2005). These mineral aggregates with well-preserved relict prismatic forms have been interpreted as lawsonite pseudomorphs; in fact, rare relict lawsonite is found. Numerical calculations of P-Tpseudosections suggest a P-T condition of P>1.8-2.0 GPa at T<600 °C (Will et al., 1998; Schmädicke and Will, 2003; Ballevre et al., 2003) for the stabilities of Grt+Lws±Gln or Omp+Lws. Because the appearance of omphacite in the blueschist/eclogite transition is sensitive to subtle differences of bulk-rock composition and blueschist-facies overprinting likely erases eclogitic omphacite, the garnet-bearing lawsonite blueschists or lawsonite pseudomorphs in garnet-bearing epidote blueschist may be candidates for precursors of lawsonite eclogite. In fact, Guatemalan lawsonite eclogites occur together with garnet-bearing lawsonite blueschists (Tsujimori et al., 2006). Similar garnet-bearing lawsonite blueschist is also known from the Sabzebar ophiolite of central Iran (Alavi-Tehrani, 1976).

3.2. Possible lawsonite pseudomorph in UHP eclogites

Polycrystalline aggregates of Ky+Ep/Czo+Qtz have been described as a possible pseudomorph after prograde lawsonite in UHP kyanite eclogites from several localities of the Sulu-Dabie terrane (Castelli et al., 1998; Mattinson et al., 2004; Li et al., 2004). Relatively low-*T* eclogite mineral assemblages with epidote-group mineral and talc characterize the lawsonite pseudomorph-bearing eclogites, whereas their Fe²⁺-Mg partitioning coefficients between garnet and clinopyroxene apparently yield higher temperature (Table 1). Castelli et al. (1998) suggested that lawsonite was transformed to Ky–Zo–Qtz aggregates during prograde eclogite-facies metamorphism. In contrast, Li et al. (2004) concluded that lawsonite decomposed during initial exhumation from peak pressure (P= 3.3 GPa at T=670 °C) to zoisite-eclogite field.

Rhombic-shaped clinozoisite/zoisite aggregates as possible pseudomorphs after lawsonite occur in kyanite eclogite at Verpeneset of the Nordfjord area of the Western Gneiss Region, Norway (Krogh, 1982). Although coesite has not yet been confirmed at Verpeneset, the presence of poly-crystalline quartz inclusions and Grt–Cpx–Phe geothermobarometry suggest a UHP condition (P=2.9 GPa and T=710 °C: Carswell et al., 2003).

4. Mineralogic characteristics of lawsonite eclogites

Clinopyroxene from lawsonite eclogites is in the augite-jadeite series with less than 30 mol% aegirine component, predominantly plotting in the omphacite field (Fig. 3); other components such as Ca-Tshermak component are negligible. Some omphacites are heterogeneous and vary in jadeite content in individual grains (e.g., Helmstaedt and Schulze, 1988; Ghent et al., 1993; Altherr et al., 2004). Omphacite with a higher jd component (up to 62 mol%) has been found in lawsonite-eclogite xenoliths from Colorado Plateau (Helmstaedt and Schulze, 1988). Moreover, impure jadeite (61-75 mol% jd) occurs in some Guatemalan lawsonite eclogites and has recrystallized into jadeite (74-87 mol% jd) plus omphacite (42-50 mol% jd) (Tsujimori et al., 2005, 2006). In Corsican lawsonite eclogites, the size of antiphase domains in omphacite observed in TEM is consistent with temperature estimated by Grt-Cpx thermometry: ~20 °C (Lardeaux et al., 1986).

Garnet in lawsonite eclogites belong to the pyropealmandine-spessartine series with a moderate grs component (10-40 mol%) (Fig. 4). Most garnets have prograde chemical zoning with increasing X_{Mg} and decreasing sps or alm components away from the crystal core (e.g., Fig. 2b). This implies a progressive increase in temperature during the growth of garnet porphyroblasts (e.g., Sakai et al., 1985; Enami, 1998; Inui and Toriumi, 2004). The sudden increase in grs component at the rim of garnet in lawsonite-eclogite xenoliths from Colorado Plateau (Helmstaedt and Schulze, 1988) may be related to the breakdown of lawsonite. This suggestion is consistent with experimental results that grs component increases with pressure in the lawsoniteeclogite facies (Okamoto and Maruyama, 1999). In most garnets, however, the grs component is nearly constant or decreases slightly from core to rim (e.g., Shibakusa and Maekawa, 1997; Altherr et al., 2004; Tsujimori et al., 2005). This trend most likely reflects the fact that



Fig. 3. Compositional variation of clinopyroxene in lawsonite eclogites from the literature.

chlorite-consuming reactions yield more pyralspite garnet than lawsonite-consuming reactions that produce more grs component.

Lawsonite in lawsonite eclogite contains trace ferric iron, commonly less than 1.5 wt.% Fe₂O₃. Lawsonite from Port Macquarie lawsonite eclogites contain up to 2800 ppm Sr and 280 ppm Ce (Enami et al., 1999). Prograde lawsonite from Guatemalan lawsonite eclogites contains up to 3000 ppm Sr (T. Tsujimori, unpublished data).

Phengite in lawsonite eclogite is commonly characterized by high Si (>3.4 pfu). Altherr et al. (2004) described low Si (3.1 pfu) phengite from Turkish lawsonite eclogite, which contains up to 2.7 wt.% BaO; Harlow (1995) has shown Ba commonly enters high-P-low-T phengite from Guatemala via the exchange $Ba^{[4]}AlK_{-1}Si_{-1}$, which lowers the silica content.

5. P-T paths of lawsonite eclogites

5.1. Prograde P–T paths

Garnet compositional profiles and their mineral inclusions in lawsonite eclogite can help delineate quantitative or qualitative prograde P-T trajectories. We use changes of the inclusion mineralogy within garnet, to identify two types of lawsonite eclogite: L-type and E-type. L-type lawsonite eclogites contain garnet porphyroblasts that grew only within the lawsonite stability. Lawsonite eclogites from Guatemala and British Columbia are type examples of the L-type.



Fig. 4. Compositional variation of garnet in lawsonite eclogites from the literature. Symbols are the same as in Fig. 3.

In contrast, E-type lawsonite eclogites record maximum temperatures in the epidote-stability field; prograde epidote inclusions occur in the rims of zoned garnet with lawsonite inclusions in the cores. For example, in Dominican Republic lawsonite eclogite, there is a remarkable zonation from lawsonite-bearing cores to epidote-bearing rims (Zack et al., 2004). Precursor lawsonite occurs in the cores of zoned garnet in glaucophane–epidote eclogites from Spitsbergen and New Caledonia (Hirajima et al., 1988; Clarke et al., 1997).

Lawsonite and epidote-group mineral can coexist in H_2O -undersaturated system (Poli and Schmidt, 1997, 2002). However, if we consider ubiquitous occurrence of various hydrous phases in relatively low-*T* eclogites with basaltic protolith, it is most likely to have been

saturated in H_2O -rich fluid during the lawsonite eclogitization of basaltic rocks.

5.2. Retrograde P-T paths

Most surviving lawsonite eclogites have not been heated and stayed relatively cool during decompression. Thus, commonly most terrains have blueschistfacies retrogression of their eclogitic assemblages rather than a Barrovian-type overprint. In general, post eclogite-stage blueschist-facies overprinting suggests a faster rate of subduction that is predicted by steady-state thermal models of old oceanic crust in subduction zones (Ernst, 1988). Extremely low-*T* conditions during decompression may prevent complete overprinting by blueschist-facies assemblages. In any case, presence of stable lawsonite indicates that retrograde path did not cross terminal stability field for lawsonite (Zack et al., 2004).

In the Turkish lawsonite eclogites, Altherr et al. (2004) described retrograde tourmaline. The tourmaline δ^{11} B values (-2.2‰ to+1.7‰) suggest involvement of a slab-derived fluid during their exhumation.

6. Formation, preservation and exhumation of lawsonite eclogites

As summarized here, reports of lawsonite-eclogite occurrences are not as plentiful as those for UHP eclogites. The limited stability of lawsonite within the eclogite facies requires abnormally low geothermal gradients, less than ~ 7 °C km⁻¹ (Fig. 5). Such environments can be attained only by the subduction of old, cold, oceanic crust with its lithosphere and possibly minor pelagic sediments or ancient continental crust (e.g., Liou et al., 2000). Maruyama and Liou (1998) pointed out that the typical geotherm of subduction zones dropped from $\sim 15 \text{ °C km}^{-1}$ to 6–7 °C km⁻¹ at 750–540 Ma. In other words, secular cooling of Earth, and subductionzone geotherms as well, could have stabilized lawsoniteeclogite assemblages since the Phanerozoic (e.g., Ernst, 1972; Stern, 2005; Maruyama and Liou, 2005). The presence of Early Paleozoic lawsonite-eclogite facies mineral assemblage in the Spitsbergen and the New England fold belts supports this hypothesis. Moreover, numerical simulations suggest that eclogitization within the lawsonite stability field is expected in present-day steady-state subduction zones such as northeastern Japan and Costa Rica (e.g., Peacock and Wang, 1999; van Keken et al., 2002; Hacker et al., 2003a,b). For example, lawsonite-bearing eclogitized oceanic crust at 60-150 km depths is predicted beneath northeastern Japan (e.g.,



Fig. 5. P-T diagram showing approximate metamorphic conditions of lawsonite eclogites around the world. The data includes the inferred P-T conditions and recalculated values using the Grt–Cpx–Phe geobarometry and the Grt–Cpx thermometry (Krogh Ravna, 2000; Krogh Ravna and Terry, 2004). Abbreviations for localities are the same as in Table 1. Hatched areas represent the inferred P-Tconditions for oceanic crust beneath present-day NE Japan ('cold') and SW Japan ('warm') subduction zones (Peacock and Wang, 1999). For comparisons, P-T estimates of Phanerozoic (<630 Ma) subduction/ collisional metamorphic rocks (Maruyama and Liou, 2005) are also shown as filled pale-gray circles. The metamorphic facies and their abbreviations are after Liou et al. (2004).

Hacker et al., 2003a,b). Thus, lawsonite-bearing eclogites should be common throughout the Phanerozoic. The question that arises, therefore, why is lawsonite eclogite so rarely recognized in orogenic belts? Based on available petrotectonic interpretations of lawsonite eclogites worldwide, two scenarios should be considered.

First, complete overprinting of lawsonite eclogite during exhumation could explain its rarity. As evident in the Etype lawsonite eclogites, the higher temperature of epidote stability can lead to the complete breakdown of pre-existing lawsonite eclogitic mineral assemblages. The occurrence of lawsonite pseudomorphs in some low-*T* eclogites supports this scenario. Moreover, the ubiquitous Barrovian-type overprinting of UHP rocks may have erased evidence for the cold subduction conditions; prograde lawsoniteeclogitic mineral assemblages could have been reacted away on their trajectory toward Earth's surface.

Second, exhumation processes may also explain the rare occurrences of lawsonite eclogites. In other words, lawsonite eclogites may not return to the surface by the typical exhumation mechanisms of HP-UHP rocks. In general, the buoyancy of low-density materials plays a critical driving force for exhumation of high-density mafic HP-UHP rocks (e.g., Cloos, 1993; Maruyama et al., 1996; Ernst et al., 1997; Ernst and Liou, 1999; Guillot et al., 2000; Ernst, 2005). Moreover, the changes of physical conditions by episodic processes such as slab detachment or subduction of a spreading-ridge may trigger buoyancy-driven exhumation of HP-UHP terranes. In both of these cases, there will be high heat flow entering the channel, a change of the subduction angle and rock viscosity; these factors play an important role in buoyancy-driven exhumation of the deeply buried accretionary prism (e.g., Maruyama et al., 1996; Aoya et al., 2003). It appears, however, that both slab detachment and ridge subduction will raise the subduction geotherm, which may prevent blueschist-facies overprinting during exhumation. Thus, ridge subduction and slab detachment may not be the mechanism that exhumes lawsonite eclogites. Considering the global occurrences of lawsonite eclogites, it is clear that serpentinite exhumation and subsequent mélange formation may be important to the preservation of lawsonite eclogites. The presence of lawsonite eclogites in major strike-slip plate boundaries suggests plate-boundary-parallel stretching and fragmentation of the accretionary prism can cause flow lines to form parallel to the boundary (e.g., Avé Lallemant and Guth, 1990; Mann and Gordon, 1996; Gonçalves et al., 2000). Fitch (1972) demonstrated that the displacement-rate vector of obliquely converging lithospheric plates could be decomposed into a boundarynormal and a boundary-parallel component. The normal component forms boundary-parallel thrust faults and folds; the parallel component produces strike-slip displacements and flow lines parallel to the plate boundary. This model is consistent with our data for the lawsonite eclogite in Guatemala. It may help exhume other lawsonite-eclogite occurrences.

7. Lawsonite as major carrier of trace elements and fluid to the mantle

Lawsonite is an excellent vehicle for transporting water and a variety of trace elements into the mantle. Previous studies have emphasized that lawsonite may be an important hydrous phase that will store water within subducted oceanic crust to mantle depths (e.g., Pawley, 1994; Schmidt, 1995; Pawley et al., 1996; Comodi and Zanazzi, 1996; Poli and Schmidt, 1997; Schmidt and Poli, 1994, 1998; Okamoto and Maruyama, 1999). Moreover, lawsonite contains several petrogenetically important trace elements, especially REE (Tribuzio et

al., 1996; Ueno, 1999), Sr (Enami, 1999) and Pb, Th and U (Spandler et al., 2003). The occurrence of itoigawaite, a Sr-analogue of lawsonite, in Japanese jadeitite (Miyajima et al., 1999) suggests a strong affinity for Sr in lawsonite structure and chemistry.

In a cold subduction zone with geothermal gradients less than ~5 °C km⁻¹, water will be continuously released by lawsonite breakdown between 100 and 300 km depth (e.g., Poli and Schmidt, 1997; Okamoto and Maruyama, 1999; Hacker et al., 2003a,b). During this process, significant amounts of Sr may be released to overlying mantle wedge, while the remaining REEs (especially the HREEs) may be retained in garnet as a reaction product.

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