Eclogites in Different Tectonic Settings

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Introduction

Eclogites have been documented for almost two centuries in the Earth's orogenic (mountain) belts and as xenoliths in kimberlite. Eclogite is interpreted to be a recorder and/or driving force for planetary-scale processes and evolution. For example, eclogite formation in subducting oceanic crust releases fluids, resulting in flux melting in the overlying mantle wedge, feeding arc magmatism and building new continental crust. The conversion of basalt to eclogite substantially increases the negative buoyancy of subducting oceanic lithosphere; this 'slab pull' is the major driver of plate tectonics. However, occurrence of eclogites is not limited to paleo-subduction zones and kimberlites. Some exceptional occurrences occur in the roots of thick continental crust, deep-crustal paleoseismic faults, and even in chondritic meteorites. Eclogite and eclogite-facies metamorphism encompass a wide range of pressure–temperature (*P*–*T*) space from deep crustal depth to mantle depth. Hence different occurrences and types of eclogites reflect different tectonic settings and environments.

Eclogites and the Eclogite Facies

Eclogite (Fig. 1) is an unusually dense (~3.3–3.5 g/cm^3) metamorphic rock, commonly of basaltic composition, and consists mainly of bright green omphacite and red/pinkish garnet with minor amounts of quartz (or coesite), kyanite, and rutile, in the absence of plagioclase. Eclogitic garnets contain high-Mg [pyrope ($Mg_3Al_2Si_3O_{12}$)], Fe [almandine $\left(Fe^{2+}{}_3Al_2Si_3O_{12}\right)$], and significant amounts of Ca [grossular ($Ca_3Al_2Si_3O_{12}$)], whereas omphacite is a pyroxene-group mineral with compositions close to $Ca_{0.5}Na_{0.5}(Mg,Fe^{2+})_{0.5}Al_{0.5}Si_2O_6$. Other minor or trace minerals in eclogites include amphiboles (barroisite/katophorite [subcalcic amphibole], hornblende [calcic amphibole] or glaucophane [sodic amphibole]), epidote (zoisite and clinozoisite), lawsonite, phengite, paragonite, talc, carbonate minerals, diamond and olivine.

The strict definition of eclogite by the International Union of Geological Sciences (IUGS) Subcommission on the Systematics of Metamorphic Rocks (SCMR) is a "plagioclase-free metamorphic rock composed of >75 vol% of omphacite and garnet, both of which are present as major constituents, the amount of neither of them higher than 70 vol%" (Desmons and Smulikowski, 2007). Given the rock's beauty and preciousness (Fig. 1), French mineralogist René-Just Haüy of the Museum of Natural History in Paris in 1822 introduced the term "eclogite" to describe the rocks from Saualpe, Austria. The name is derived from the Greek description ekloge, with the suffix "-ite," meaning "chosen rock." The name "eclogite" was created before Scottish geologist Charles Lyell in 1833 coined the term "metamorphic rocks."

Eclogite has been synonymous with eclogite facies, since Finnish geologist Pentti Eskola introduced the concept of "metamorphic facies" in 1915, 1920 and 1939. The eclogite facies represents a *P*–*T* field where the eclogitic mineral assemblage is stable at both crustal and mantle regions (Fig. 2). The eclogite facies is bounded by the blueschist facies on the low-*T* side, by the granulite facies on the high-*T* side, and by the epidote-amphibolite and amphibolite facies on the lower-*P* side (Fig. 2A). Eclogite transforms from other facies rocks gradually in *P*–*T* space; yet the eclogitization process can be limited by reaction kinetics strongly controlled by the amounts of fluids in the rocks. Four subfacies have been proposed: amphibole eclogite, epidote eclogite, lawsonite eclogite and dry eclogite (Fig. 2B). These subfacies are characterized by the presence or absence of additional minerals including amphibole, epidote and lawsonite with phengite depending on the host rock composition. Stability of mineral assemblages of eclogites is a function of *P*–*T*–*X*, where the *X* stands for composition. Recently, phase-equilibria modeling (*P*–*T* pseudosections) for

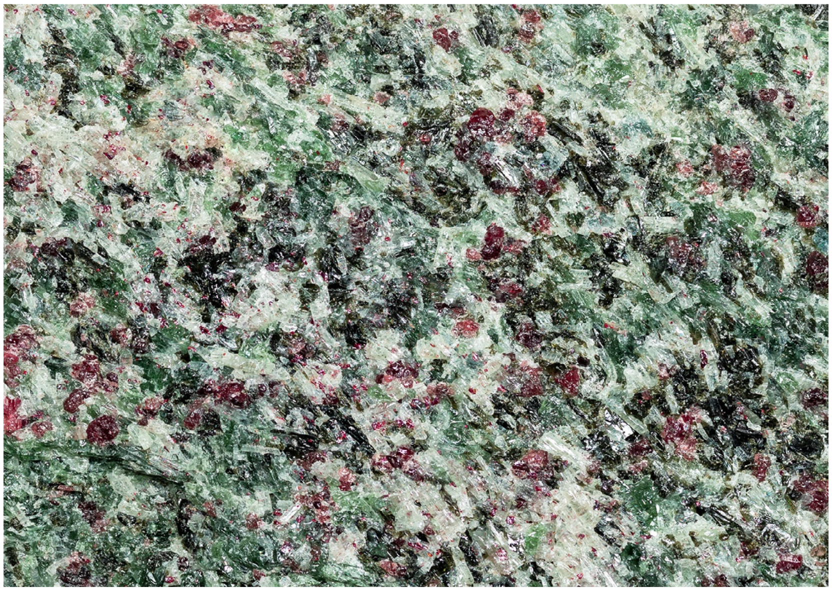

Fig. 1 Appearance of eclogite from the type locality (Saualpe, Austria) [4 cm in wide].

subducted oceanic crust with MORB (mid-ocean ridge basalt) composition provides a prediction of various properties, such as mineral assemblage, modal volume, and water contents (e.g., Hacker et al., 2003; Wei and Clarke, 2011; Xia et al., 2018; Hernández-Uribe and Palin, 2019).

The *P* range of the eclogite facies is further subdivided to ultrahigh-*P* (UHP) and high-*P* (HP) by the quartz–coesite equilibrium transition. At *T* higher than the dry basalt solidus (beginning of melting curve), eclogite starts to partially melt (Fig. 2C), and causes mantle heterogeneity. The eclogite facies encompasses wide *P*–*T* regions from deep crustal to mantle depths. Hence different occurrences of eclogites reflect different tectonic settings and host oceanic/continental crustal compositions.

Occurrence of Eclogites

Subduction/Collision-Related Orogenic Eclogites

Two distinct paleo convergent plate-tectonic regimes, namely the Pacific-type and the collision-type orogens, have been identified (Maruyama et al., 1996; Liou et al., 2004; Stern et al., 2013), although a continuum of intermediate types exists (Fig. 3). Orogenic eclogite occurs in both types of orogenic belts (Smith, 1988; Carswell, 1990; Coleman and Wang, 1995) (Fig. 4). Pacific-type eclogites are commonly associated with serpentinite, blueschist, epidote-amphibolite, metachert and rare jadeitite (Fig. 5A–C). Lenses and tectonic blocks or sheets in metasedimentary rocks and serpentinite are common (Fig. 5D). Eclogitization of subducting oceanic crust is visible by high-resolution seismic images of the Alaska and Cascadia subduction zones (Rondenay et al., 2008). Most Pacific-type eclogites reflect a relatively short, rapid exhumation, less than ~10–15 m.y. (Agard et al., 2009). However, some eclogite blocks are stored in the mantle wedge for a considerable time before exhumation to shallow depths; here they are incorporated with the overlying serpentinized forearc mantle wedge to form a typical block-in-matrix mélange (Fig. 3A). Recent zircon U–Pb studies of Sambagawa eclogites suggest ~30 m.y. duration of eclogite-facies metamorphism (Aoki et al., 2020); such a process may have involved recrystallization of subducted oceanic arc materials rather than a subducted accretionary complex. Thermomechanical modeling suggests that the presence of low-density, low-viscosity sedimentary rocks and seafloor serpentinites are critical for the exhumation of Pacific-type eclogites (Wang et al., 2019).

In contrast, collision-type eclogites are associated with continental host rocks such as gneiss, aluminous metapelite, granulite, amphibolite, migmatite, impure marble, and rare garnet peridotite (Fig. 5E–H). Lenses and lenticular boudins of eclogites enclosed in quartzo-feldspathic gneiss and migmatitic gneiss are common (Fig. 5F and H). Continental subduction and collision normally follow Pacific-type oceanic subduction. The underflow of continental crust is a key for the buoyancy-driven exhumation of collision-type eclogite (Ernst, 2001). Based on numerical modeling of continental subduction/collision and exhumation of eclogites, Gerya et al. (2008) proposed a model in which deeply subducted continental crust achieves temperatures of 700–900 °C by intense viscous shear plus radiogenic heating; consequently, the high-*T* causes buoyancy-driven upward extrusion of the UHP slab due to melting. In the Italian Western Alps, zircon U–Pb geochronology of multiple eclogite-facies metamorphism suggests ~25 m.y. for duration of the eclogite-facies metamorphism (Rubatto et al., 2011).

The presence of exhumed eclogite and its *P*–*T* conditions of formation record secular cooling of the Earth; the occurrence of high-*P*/*T* rocks such as eclogite in combination with lower-*P*/*T* rocks records the contrasting high vs. low geothermal gradients created over time by plate tectonic processes (Ernst, 1972; Maruyama and Liou, 1998; Brown, 2007; Tsujimori and Ernst, 2014). Secular metamorphic change provides evidence that plate tectonics has operated on Earth since at least 2.8 Ga (Brown and Johnson, 2018;

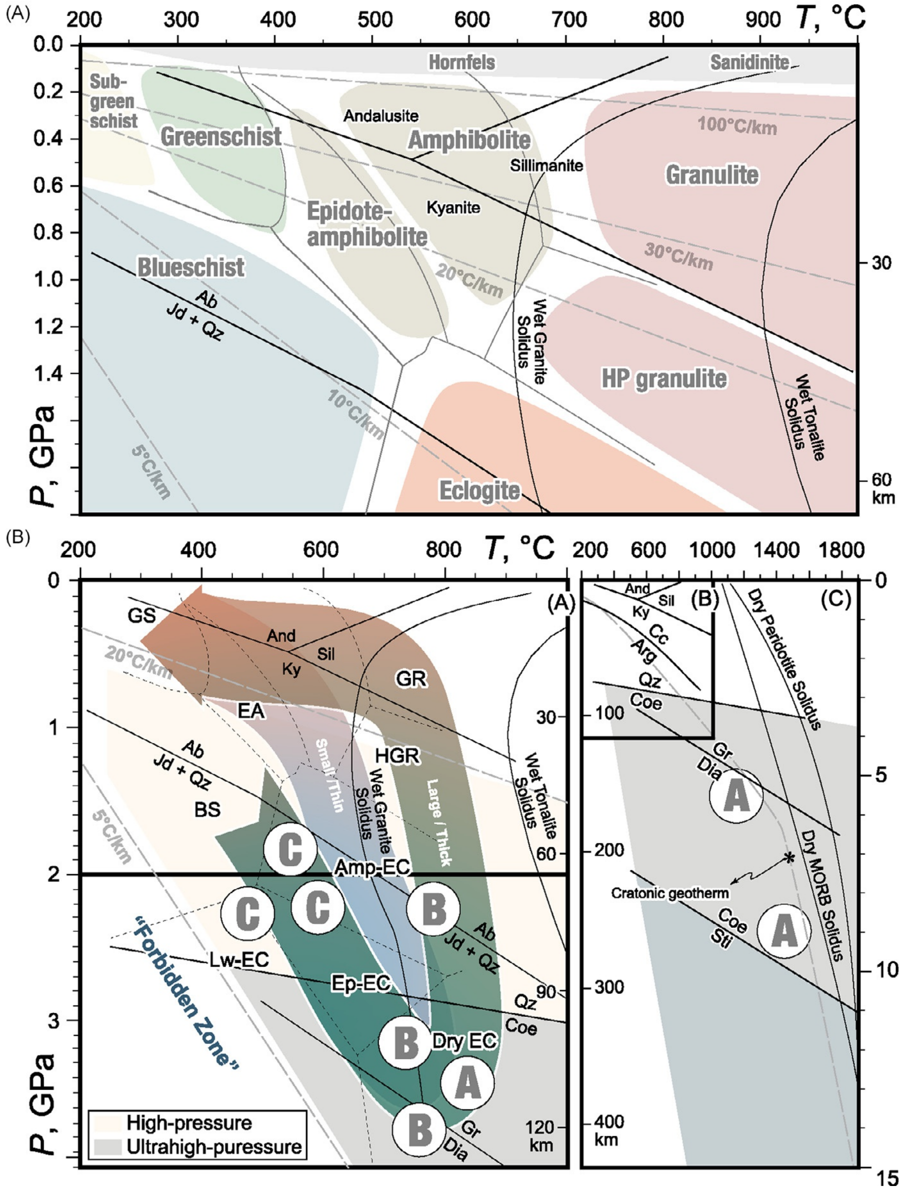

Fig. 2 (A) Pressure–temperature (*P–T*) diagram showing metamorphic facies. (B) *P–T* regime at different scales assigned to various metamorphic type: HP—high-pressure, UHP—ultrahigh-pressure, and "Forbidden Zone." Metamorphic facies abbreviations: BS—blueschist; AM—amphibolite; Lw-EC—lawsonite eclogite; Ep-EC—epidote eclogite; Amp-EC—amphibole eclogite; DryEC—dry eclogite; GS—greenschist; EA—epidote-amphibolite; GR—granulite; HGR—high-pressure granulite. *P–T* paths of small/thin UHP terranes and large/thick terranes are also shown. The circled A, B, and C refer to the Coleman et al. (1965) classification (see text). (C) High-*T* limit of eclogite defined by dry MORB solidus. (B) Modified after Kylander-Clark ARC, Hacker BR, Mattinson CG (2012) Size and exhumation rate of ultrahigh-pressure terranes linked to orogenic stage. *Earth and Planetary Science Letters* 321–322: 115–120.

Palin et al., 2020). The oldest crustal eclogites are latest Early Proterozoic age (~2.0 Ga), associated with HP granulites. In contrast, coesite-bearing UHP eclogites and lawsonite eclogites are restricted to Neoproterozoic and younger ages, suggesting that subduction-zone thermal structures evolved towards lower geothermal gradients. Evaluation of *P–T* conditions of orogenic eclogites has shown that the *P–T* conditions recorded in exhumed eclogites are ~100–300 °C higher than the *P–T* estimates predicted by geodynamic models (Penniston-Dorland et al., 2015). Nevertheless, phase-equilibria modeling predicts the partial melting of epidote eclogites at a depth >2.7 GPa in a warm subduction zone (Hernández-Uribe et al., 2019).

Mantle Eclogites in Kimberlitic Pipes and Plume-Related Ocean Island Basalts

Kimberlites—potassic, volatile-rich ultramafic rocks—contain a range of deep mantle fragments (xenoliths, xenocrysts), including mantle eclogites and bimineralic garnet clinopyroxenites (Fig. 5I and J). Most kimberlitic mantle eclogites are metamorphosed fragments of deeply-subducted recycled oceanic crust (e.g., Jacob, 2004; Giuliani and Pearson, 2019). As economic diamond-

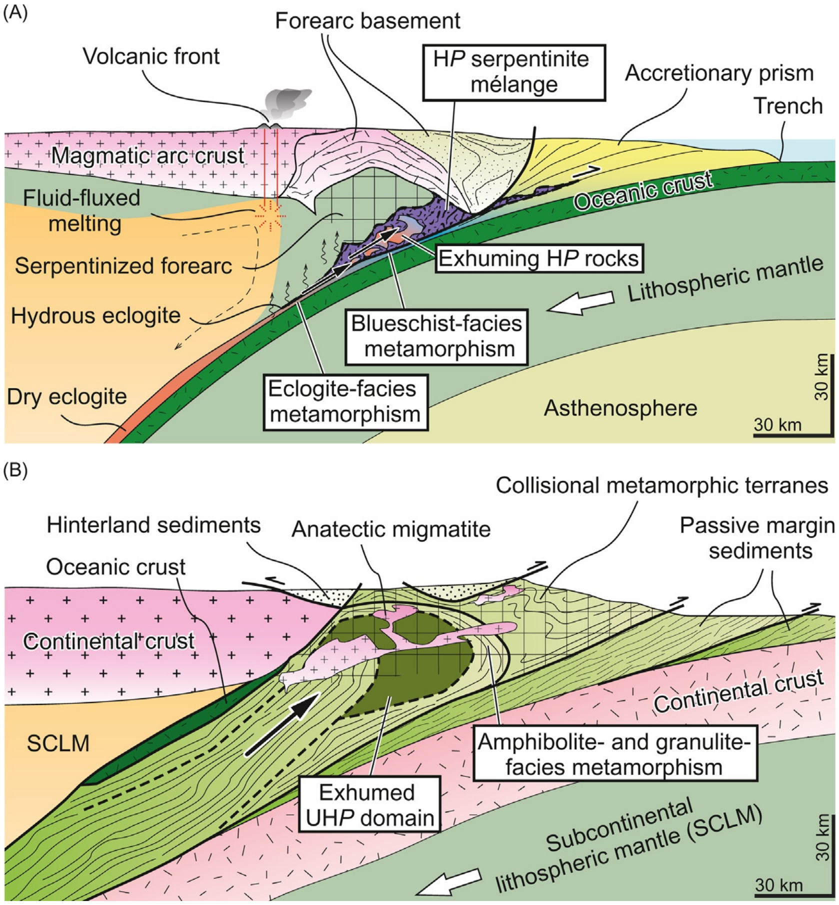

Fig. 3 Cross sections showing two different convergent plate margins. (A) Pacific-type subduction zone. (B) Continental collision zone. Modified after Stern RJ, Tsujimori T, Harlow GE and Groat LA (2013) Plate tectonic gemstones. *Geology* 41: 723–726.

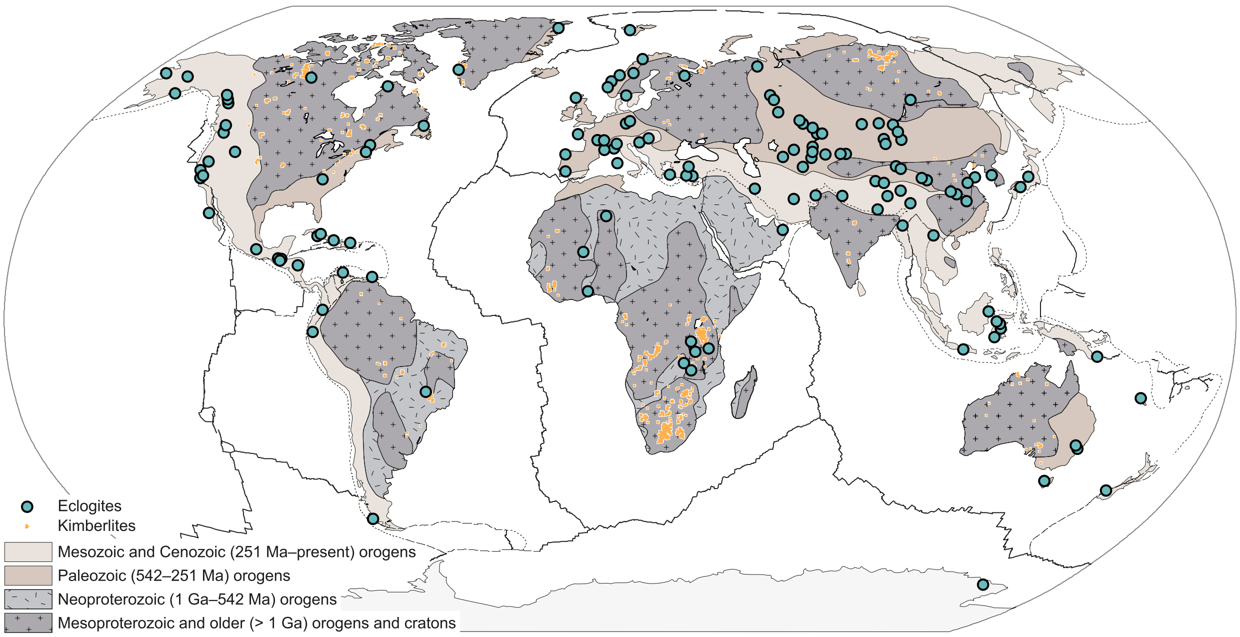

Fig. 4 Global distribution of eclogites and kimberlites (modified after Tsujimori T, Ernst WG (2014) Lawsonite blueschists and lawsonite eclogites as proxies for palaeo-subduction zone processes: A review. *Journal of Metamorphic Geology* 32(5): 437–454). Kimberlite localities are based on database of Giuliani A, Pearson DG (2019) Kimberlites: From deep earth to diamond mines. *Elements* 15(6): 377–380.

bearing rocks, kimberlitic eclogites are of economic importance for understanding their origin and distribution (Tappert and Tappert, 2011). Very rare occurrence of xenoliths of lawsonite eclogite (Fig. 5I), resembling orogenic eclogites occur in kimberlitic diatremes of the Colorado Plateau (Helmstaedt and Doig, 1975). Orogenic eclogites with ages greater than ~2.5 Ga have not been documented. However, diamond-bearing eclogites in kimberlitic pipes with older ages (> ~2.5 Ga) are rather common.

Rare eclogite-facies mantle garnet clinopyroxene and garnetite are present as xenoliths in plume-related ocean island basalt, like those of Hawaii and the Ontong Java Plateau. The discovery of nano-diamonds suggests that some eclogitic materials were brought up from >180 km depth by mantle plumes (Wirth and Rocholl, 2003).

Eclogites in Other Environments

Deep crustal eclogite and eclogite-facies garnet clinopyroxene xenoliths have also been found in volcanic rocks (e.g., Ducea and Saleeby, 1996; Hacker et al., 2005). Such eclogites were derived from a subducted crustal slab that existed beneath thick-continental crust and/or unusually thick (~65–70 km) continental (or magmatic arc) crust roots. Recrystallization of such deep continental crustal roots (>60 km) can produce metacumulates of HP granulite with eclogites (e.g., Fiordland, New Zealand: De Paoli et al., 2009). Eclogites, particularly those formed in a transitional eclogite–granulite facies *P*–*T* range, thus are not necessarily indicators of subduction-zone metamorphism. The high density of these rocks leads to sinking of the mafic lower crust into the mantle (Ducea

Fig. 5 Representative appearances, textures, and occurrence of eclogites in different tectonic settings. (A) Lawsonite eclogite in the South Motagua Mélange, Guatemala, showing a foliation (Tsujimori et al., 2006). (B) Eclogite (EC) associated with blueschist (BS) in the Franciscan Complex (Jenner, California, United States). (C) Photomicrograph of the low-*T* Franciscan eclogite from Healdsburg, California, United States (Sample 62-RGC-58: Coleman et al., 1965). Scale bar is 1 cm. (D) Eclogite 'knockers' of the Franciscan Complex (Tiburon Peninsula, California, United States). (E) Kyanite eclogites in the Western Gneiss Region, Nordfjord, Norway, showing a "Christmas rock" appearance. (F) Eclogite lenses (EC) enclosed in quartzo-feldspathic gneiss (qfg) in the Western Gneiss Region. (G) Photomicrograph of the Neoproterozoic medium-*T* eclogite of the Ufipa Terrane, Ubendian Belt. Scale bar is 1 cm. (H) Eclogite lenses (EC) enclosed in quartzo-feldspathic gneiss (qfg) in North Qaidam, NW China. (I) Appearance of mantle eclogite xenoliths in kimberlitic pipes: RV—Roberts Victor, South Africa (Group I, and Group II, Photo credit: Akira Ishikawa); UD—Udachnaya, Siberia, Russia, GR—Garnet Ridge, Colorado, United States. Scale bars are 1 cm. (J) Photomicrograph of Udachnaya eclogite. Scale bar is 1 cm. (K) View of the Garnet Ridge diatremes of the Navajo Volcanic Field, Colorado, United States. Credit*s*: (E) Kennet Flores, (I) Dmitry Zedgenizov, Akira Ishikawa, *and* Yoshihide Ogasawara, (J) Dmitry Zedgenizov, and (K) Yoshihide Ogasawara.

and Saleeby, 1996), leaving behind a more silicic crust that better matches average continental crust compared to the original magmas rising from the upper mantle.

Deep-crustal paleoseismic faults are another rare tectonic environment of eclogite-facies mineral assemblages (Austrheim and Boundy, 1994; Steltenpohl et al., 2011). Continental subduction locally causes coseismic faulting and frictional melting to form pseudotachylyte at eclogite-facies conditions.

Extra-terrestrial eclogite fragments of a few millimeters in size have been reported from a CR2 carbonaceous chondrite. Kimura et al. (2013) described a few-mm size clasts containing garnet and omphacite that might have originally been derived from a fragment of a deep interior of large ($> \sim$1000 km) parent body.

Tectonic Origin and Classification of Eclogites

Based on mineral compositions and tectonic origin, an American geologist Robert G. Coleman (Fig. 6) grouped orogenic and mantle eclogites into three types (Coleman et al., 1965) (Fig. 2B). Group A high-*T* eclogites occur as xenoliths in kimberlite (or lamprophyres) and layers in orogenic peridotite; Group B eclogites are associated with HP granulites within the crustal basement of collisional orogenic belts; and Group C eclogites are common in Pacific-type orogenic belts. In general, the pyrope component of garnet increases and the $Fe^{2+}\leftrightarrow Mg$ distribution coefficient between garnet and clinopyroxene decreases in the order of group $C < B < A$. Carswell (1990) proposed three divisions based on the formation temperature namely: high-*T* at $\sim$900–1600 °C, medium-*T* at $\sim$550–900 °C, and low-*T* at $\sim$450–550 °C; these respectively correlate to Coleman's Group A, B and C eclogites. Following the Coleman scheme, Liou et al. (2014) extended his classification to UHP conditions. Although several eclogite classifications have been proposed (e.g., Banno, 1970; Smulikowski, 1968; Carswell, 1990; Miyashiro, 1994), Coleman's simple classification remains valid today inasmuch as various type eclogites have formed in different tectonic (*P*–*T*) settings.

High-*T* (Group A) eclogites mostly occur as minor xenoliths in kimberlite and lamproite pipes in pre-Cambrian continental basement. Based on emplacement sites, kimberlites were "on-craton" (cratonic) and "off-craton" (non-cratonic or craton margins). Most of the eclogites from "off-craton" kimberlites are associated with HP granulites that are less common from "on-craton" localities. Coesite-and diamond-bearing UHP eclogite xenoliths typically occur in "on-craton" pipes. These mantle eclogite xenoliths from kimberlitic pipes are remnants of subducted oceanic crust (including subducted cumulate as a protolith) or HP cumulates from mantle melts. Eclogite in kimberlites can be further classified as Group I (Fe-rich) and Group II (Mg-rich) (Jacob, 2004) based on the coexisting garnet composition. Diamond-bearing Group I eclogites tend to show higher-*T* and -*P* than Group II eclogites. Recent geochemical studies of eclogitic inclusions (garnet, omphacite, kyanite, coesite) in diamonds support a recycled oceanic crust origin (e.g., Schulze et al., 2013). Some eclogitic inclusions are present in diamonds from the mantle transition zone (300–660 km) and even in the uppermost lower mantle $> \sim$660 km (Cartigny et al., 2014).

Medium-*T* (Group B) eclogites are common in continental collision zones. HP–UHP eclogite are volumetrically minor constituents of gneissic metamorphic belts; most eclogites have been highly retrograded during exhumation. Trace amounts of coesite or micro-diamond inclusions are preserved in rigid minerals such as garnet, omphacite and even in phengite, epidote and tourmaline. Kylander-Clark et al. (2012) classified two types of eclogite-bearing UHP terranes: small, thin terranes evidently were subducted and exhumed rapidly, whereas large, thick terranes were subducted and exhumed much more slowly (Fig. 2B). Considering global occurrences and numerical geodynamic modeling, the buoyancy of low-density material is a critical driving force for exhumation of high-density eclogite fragments immersed in a low-density gneissic (granitic composition) matrix.

Low-*T* (Group C) eclogites occur as blocks or lenses (Fig. 5) in blueschist belts, and blueschist-bearing serpentinite mélanges of Pacific-type orogens. Except for a few UHP eclogites, exhumed low-*T* eclogites record *P*–*T* histories at pressures below the quartz-to-

Fig. 6 Professor Emeritus Robert G. Coleman of Stanford University talking about his research in the 1960s. Photo taken by T. Tsujimori in December 2019.

coesite transformation. In the *P–T* field of low-*T* eclogite, the lawsonite-epidote transition is an important boundary because of the different H_2O content of the rock across the transition zone. Tsujimori et al. (2006) and Tsujimori and Ernst (2014) proposed a classification of lawsonite eclogites based on mineral assemblages included in prograde-zoned garnet; L-type grew only within the lawsonite stability field, and E-type records the maximum temperature in the epidote *P–T* stability field.

Eclogite xenoliths in diatremes from the Colorado Plateau include L-type coesite-bearing UHP lawsonite eclogite of oceanic affinity (Usui et al., 2006). Although some subduction-related orogenic eclogites contain pseudomorphs after lawsonite (e.g., Lü et al., 2019), pristine lawsonite has not been confirmed yet even as mineral inclusions in zircon. Preservation of lawsonite in exhumed eclogites is very limited. In any case, geochemical studies of lawsonite in eclogites can decipher the behavior of *syn*-metamorphic fluids in fossil cold subduction zone complexes (Hara et al., 2018; Whitney et al., 2020).

Perspectives

Nearly a century has passed since Eskola introduced the concept of "metamorphic facies," and over 35 years has passed since coesite was discovered in orogenic eclogites by Chopin in the Alps and Smith in Western Norway. Thus was established "Continental Subduction and UHP Eclogite-Facies Metamorphism." Studies of eclogitic rocks and eclogite-facies *P–T* space have significantly advanced our understanding of a broad range of physicochemical-tectonic processes. Because plate tectonics operated in the ancient Earth, the subduction of crustal material to the Earth's deep interior plays a crucial role in the evolution of a solid planet over geological time. Large-scale mass-circulation due to underflow of eclogitized oceanic crust has occurred not only at plate convergence margins, but the whole mantle throughout Earth history. Advanced research in nanometer-scale mineral inclusions and new analytical methods/tools have provided new findings of complex multiple-stages of formation of mineral assemblages in eclogites. Findings of recycled "deep-subducted" crustal materials of both oceanic and continental affinity terranes have also modified the concept of plate tectonics (Liou et al., 2014). In order to evaluate eclogitization and related geodynamic processes (including earthquakes), quantitative understanding of the reaction kinetics of eclogite-facies mineral growth, reassessment of grain-scale stresses, dynamics of diffusion-limited mineral growth, dynamic domain equilibrium during fluid infiltration, and elemental fractionation and chemical transportation during metamorphic differentiation + mineral growth are still crucial topics requiring further research. New findings and innovative ideas should kindle renewed interest in the exploration of eclogite-facies rocks in diverse tectonic settings.

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