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Thermodynamic Model for the Exhumation of Oceanic Crust

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The exhumation mechanism of high-pressure (HP) and ultrahigh-pressure (UHP) metamorphic rocks formed by the subduction of oceanic crust is one of the primary uncertainties associated with the subduction factory. Based on a worldwide compilation of key information for oceanic eclogites including petrologic characteristics, peak *P–T* conditions, exhumation *P–T* paths and exhumation velocities, this study reappraises the exhumation of oceanic eclogites, which have received much less attention than continental ones during the last two decades.

Oceanic crust is transformed into blueschist and high-pressure (HP) or ultrahigh-pressure (UHP) eclogite when it is subducted into mantle depths. Abundant experimental studies on MORB at HP and UHP conditions have shown that oceanic eclogites are denser than the surrounding mantle (e.g. Aoki & Takahashi, 2004; Litasov & Ohtani, 2005); therefore, oceanic eclogites are generally considered difficult to exhume to the earth's surface when driven by buoyancy forces. However, some oceanic eclogites have been observed to be exhumed to the earth's surface in several oceanic subduction zones (e.g. Agard *et al.*, 2009; Wei *et al.*, 2009a; Brovarone *et al.*, 2011; Plunder *et al.*, 2012); some of them are even coesite-bearing UHP eclogites that were exhumed from mantle depths greater than 90 km (Lü *et al.*, 2009; Groppo *et al.*, 2009; Angiboust *et al.*, 2012). The occurrence of natural HP and UHP oceanic eclogites indicates that at least parts of the subducted oceanic crust detached from the down-going slab and were exhumed back to the Earth's surface.

The oceanic eclogites reported in typical oceanic subduction zones worldwide can be subdivided into three groups based on peak mineral assemblages, *P–T* conditions, and geothermal gradients as follows: (1) Coesite-bearing UHP lawsonite eclogites (2.7–3.2 GPa, 470–610 ºC, 5–7 ºC/km); (2) HP lawsonite eclogites (1.7–2.6 GPa, 360–620 ºC, 5–8 ºC/km); and (3) HP epidote eclogites (1.5–2.3 GPa, 540–630 ºC, 7–12 ºC/km) (Fig. 1). Compared with HP and UHP eclogites in continental subduction–collision zones, oceanic eclogites have lower peak *P–T* conditions and contain abundant light hydrous minerals, such as glaucophane (density: 3.14 g/cm^3), phengite (2.80 g/cm^3), lawsonite (3.13 g/cm^3), chlorite (2.58 g/cm^3) and talc (2.73 g/cm^3) (Hacker *et al.*, 2003). Kyanite, a common dense mineral in continental eclogites, is extremely rare in natural oceanic eclogites. All the hypotheses for the exhumation of oceanic eclogites are based on the assumption that oceanic eclogites were denser than the surrounding mantle; therefore, their exhumation must be aided by low-density serpentinites or metasedimentary rocks.

Thermodynamic modeling for MORB suggests that the mineral assemblages, mineral proportions and density of oceanic crust subducted along a cold *P–T* path are quite different from those of crust subducted along a warm *P–T* path and that the density of oceanic eclogites is largely controlled by the stability of low-density hydrous minerals, such as lawsonite, chlorite, glaucophane and talc (Chen et al., 2013). Along a cold subduction *P–T* path with a geotherm of ~6 ºC/km, the density of subducted oceanic crust is always lower than that of the surrounding mantle at depths shallower than 110–120 km (*P* <3.3–3.6 GPa). However, along a warm subduction *P–T* path with a geotherm of ~10 ºC/km, the subducted oceanic crust becomes denser than the surrounding mantle at depths greater than 60 km (*P* >1.8 GPa).

Thermodynamic modeling for depleted mantle suggests that serpentine and chlorite in the subduction channel can be only stable at depth shallower than 80-120 km, therefore, serpentinized subduction channel only plays important roles on the exhumation of oceanic eclogites at depth < 80-120 km. Most natural metasediments in the accretionary wedge record blueschist to HP eclogite facies metamorphism. However, several metasediments also preserved mineralogical evidence of UHP metamorphism (e.g. Wei et al., 2009b) and experienced similar subduction-exhumation process to the UHP oceanic

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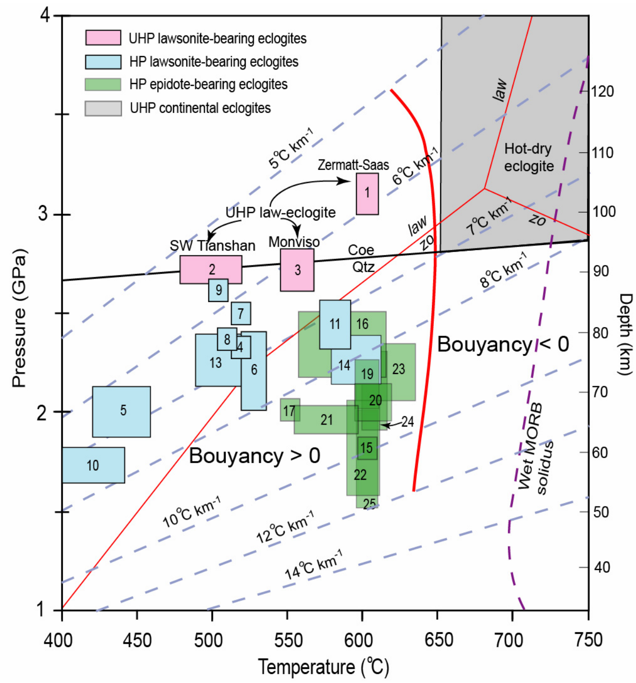

Fig. 1. Plots of the peak metamorphic *P–T* conditions of the reported natural oceanic eclogites (the numbers are the same as in Table 1).

For comparison, the estimated *P–T* region of UHP continental eclogites is also shown. The lawsonite and zoisite stability curves and the wet MORB solidus were taken from Schmidt & Poli (1998). The transition of quartz and coesite was calculated using THERMOCALC. The red solid line is depth limit curve for the exhumation of oceanic eclogites calculated on the basis of various geothermal gradients. The left side of the curve represents the *P–T* region that is suitable for buoyancy-driven exhumation. Note that all of the estimated *P–T* conditions associated with the worldwide natural oceanic eclogites are located within the left side of the curve.

eclogites, suggesting that metasediments also provide additionally driven force for the exhumation of oceanic eclogites. A number of seismicity profiles suggest that there is an increase in dip angle of subducted oceanic slab at 60-120 km, consistent with the modeled results in the MORB system. The increase of dip angle of subducted oceanic slabs may act a geometric hindrance that the rocks at greater depth must overcome during exhumation.

On the basis of natural observations and our calculations, we suggest that beyond depths around ~120 km (1) oceanic eclogites are not light enough, (2) there are no serpentinites to compensate the negative buoyancy of the oceanic crust, and (3) increasing the dip angle of subducted oceanic plate inhibits the exhumation of HP–UHP metasedimentary rocks and eclogites from greater depth. They may be the reasons for explaining the lack of oceanic eclogites returned from ultradeep mantle (> 120 km) to the Earth's surface. At shallow depths in the forearc region (<110–120 km), the cold-hydrous eclogites with high Mg, Al, Fe^{3+} and H_2O and low Ca are lighter than the mantle, and serpentinites can be stable in the subduction channel. We suggest that the cold–hydrous eclogites and blueschists are scraped off from the top of the subducting slab at shallow depths in the forearc region (<110–120 km) and are exhumed inside serpentinized subduction channel (Gerya *et al.*, 2002; Gorczyk *et al.*, 2007; Guillot *et al.*, 2009; Malatesta *et al.*, 2012). The formation of kyanite through lawsonite breakdown reactions would hamper the exhumation of oceanic crust, that may be the reason for the fact that lawsonite-free kyanite-bearing eclogite is extremely scarce in the oceanic subduction zones worldwide.

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Key words: exhumation, subducted oceanic crust, density, light hydrous minerals, serpentinized subduction channel, accretionary wedge

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