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Multiple Genesis of Fluid and Melt during Exhumation of Deeply-Subducted UHP Eclogite

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Supercritical fluid and granitic melt are commonly generated as pressure decreases during exhumation of deeply subducted continental crust from mantle depths, promoting crust–mantle interaction, changing the rheology of material along much of the subduction channel and, in a feedback loop, facilitating ongoing exhumation. However, extensive overprinting of ultrahigh pressure (UHP) metamorphic rocks by late-stage deformation and metamorphism has hindered our full understanding of fluid-melt evolution during exhumation. Compared to other UHP metamorphic rocks, particularly the common host orthogneisses, UHP eclogites at rare localities preserve evidence of early deformation and metamorphism (Wang et al., 2018). Therefore, these localities become critically important study targets to improve our understanding of processes during deep subduction and exhumation of continental crust. Of particular importance is a better understanding of the mechanisms and reactions in eclogite by which supercritical fluid and hydrous melt are generated during exhumation.

The Sulu belt was formed by the deep subduction of the passive margin of the Yangtze Craton under the North China Craton, with exhumation occurring during the Mesozoic (c. 240–210 Ma). Eclogites at Yangkou Bay in the Sulu belt record a maximum pressure of > 5.5 GPa (Xia et al., 2018), which is among the highest reported from collisional belts in the world (Brown and Johnson, 2019); they also preserve intergranular coesite (Wang et al., 2018). Elsewhere in the belt there is abundant evidence in eclogite at both outcrop and thin section scales of partial melting. Here we present results from studies undertaken during the past decade in the central and northern sectors of the Sulu belt (Taohang, General's Hill, Yangkou Bay and Weihai; see Fig. 1) that demonstrate a much wider range of processes and reactions in eclogites than simply hydrate-breakdown melting, as has been frequently reported in Dabie–Sulu and other UHP-HP collisional belts (Gao et al., 2013; Chen et al., 2014; Cao et al., 2018, 2021).

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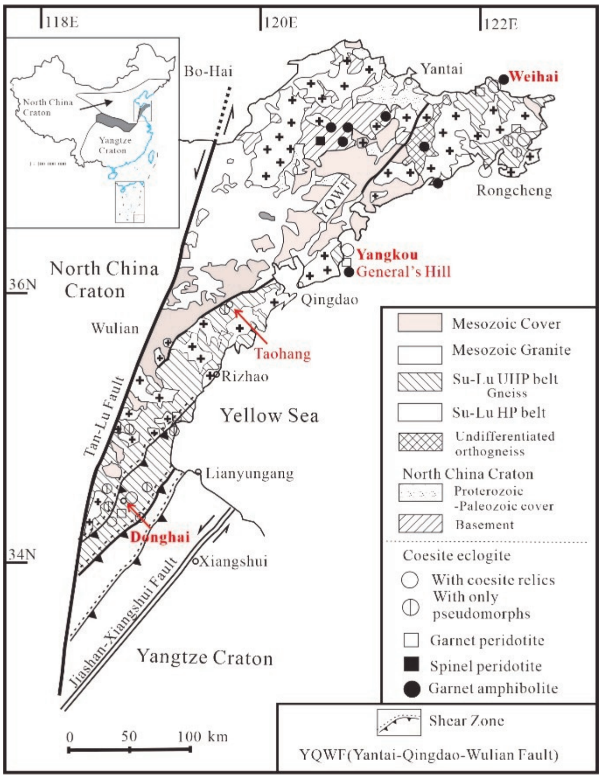

Fig. 1. Geological map of Sulu belt, Eastern China (bolded red location names are the places reported with evidence of partially-melted eclogite).

Mechanism and products of melting at the UHP-HP stage of exhumation

Wang et al. (2014) were the first to report migmatites formed by partial melting of UHP eclogite and gneiss from General's Hill, central Sulu belt. In the migmatitic eclogite area, melt has crystallized along grain boundaries forming thin leucosome films that develop into interconnected intergranular networks in 3-D. With increasing melt volume, the melt segregated and

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accumulated forming leucosome in pressure shadows before merging to form sheets and dikes of granite that represent transport channels that allowed melt to reach higher levels in the crust. Leucosomes and residues are complimentary, being enriched and depleted, respectively, in the light rare earth elements, large-ion lithophile elements and heavy rare earth elements compared to the protolith (Wang et al., 2014; Wang et al., 2020).

Further detailed investigation of the leucosome sheets within the migmatitic eclogites at General's Hill (Wang et al., 2017, 2020) identified that: 1) they have variable mineral modes and deformation fabrics—some are composite with marginal and interior facies, whereas others are not—and range from trondhjemite to granite, with high abundances of SiO_2, K_2O+Na_2O and Al_2O_3, similar to hydrous melts; 2) newly-crystallized zircon in the leucosomes records weighted mean ages of c. 223–218 Ma; 3) early-formed leucosome from the marginal facies has Sr-Nd isotope compositions similar to those of nearby unretrogressed UHP eclogites, whereas younger leucosomes have Sr-Nd isotope compositions intermediate between the eclogites and surrounding gneisses; and, 4) leucosomes crystallized between ~850°C and ~770°C, over a wide range of pressures from UHP to HP stages (P = 3.5–2.2 GPa), which correlates with age from older (higher P) to younger (lower P).

At the metamorphic peak, which may have exceeded 5.5 GPa (Xia et al., 2018), the source rocks were likely fluid deficient or fluid absent. During exhumation from UHP conditions, we posit that exsolution of water stored in nominally anhydrous minerals generated a silicate-rich supercritical fluid in eclogite that evolved to a denser, more viscous and more polymerized hydrous melt. Infiltration of solute-rich supercritical fluid from the surrounding gneisses blended with melt in the eclogites generating variable Sr-Nd isotope compositions intermediate between these end-members, as recorded by leucosomes that crystallized at lower pressures. Subsequently, towards the end of exhumation, in the lower–middle crust (P of 1.0–0.9 GPa, T > 640°C), limited phengite-breakdown melting in the leucosomes is recorded by aggregates of plagioclase + biotite around phengite and thin films and cuspate veinlets and patches of K-feldspar along grain boundaries (Wang et al., 2017, 2020).

Mechanism and products of melting at the HP stage of exhumation

The metamorphic reactions responsible for partial melting are rarely well-documented from natural eclogite examples. Recently, we reported, for the first time, evidence from the Sulu belt of *in situ* partial melting dominated by breakdown of omphacite in UHP eclogites from Taohang and Weihai, respectively. These eclogites are phengite + zoisite-bearing eclogite at Taohang and bimineralic eclogite at Weihai, which, at subduction *P–T* conditions, are generally considered to melt via phengite breakdown (e.g. at Taohang) or to not melt at all due to the anhydrous mineral assemblage and low primary bulk water content (e.g. at Weihai). *P–T* estimates for melting events yield P = 1.6–1.2 GPa and T = 780–690°C for the Taohang eclogite, and P = 1 GPa and T = 880–820°C for the Weihai eclogite. Diagnostic evidence of partial melting includes: (1) in situ leucosome pockets composed of plagioclase and euhedral amphibole, with minor K-feldspar±epidote within both types of host eclogite; (2) skeletal omphacite within the leucosome pockets that has a lower jadeite content than rock-forming omphacite; and, (3) seams of Na-rich plagioclase and quartz that extend along grain boundaries separating rock-forming minerals, which exhibit low dihedral angles where they terminate at triple grain-boundary junctions.

Major oxide and trace element compositions of leucosome pockets, calculated using mineral modes and compositions, are consistent with partial melting dominated by omphacite breakdown, rather than other rock-forming minerals, such as garnet, phengite and/or zoisite, generating a leucodioritic primary melt composition at the transition from eclogite to amphibolite facies (Feng et al., 2021; Wang et al., 2021). Weighted mean ages of c. 217–214 Ma from thin overgrowths on zircon are interpreted to record melt crystallization for the Taohang eclogite, but a wider range of ages (c. 230–210 Ma) was retrieved from metamorphic zircons from the Weihai eclogite. Subsequently, the eclogites were partially overprinted by extensive amphibolite facies symplectite.

We conclude that deeply subducted eclogites in continent-continent collisional belts experience various fluid-melt evolutionary processes along the exhumation *P–T* path. The UHP eclogites can develop a solute-rich supercritical fluid or melt along grain boundaries by dehydroxylation of nominally anhydrous minerals during the early stage of decompression, and/or trigger partial melting by phengite breakdown and/or by breakdown of omphacite during the later stages of exhumation. This is consistent with the hypothesis that fluid exsolution and partial melting were important in facilitating exhumation of UHP metamorphic rocks from mantle depths, as indicated by numerical modelling and experimental petrology studies.

Key words: partial melting, eclogite, omphacite breakdown, supercritical fluid, Sulu belt

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