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Short Communication

Sodium in olivine as a potential pressure indicator for orogenic dunite

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Orogenic mantle peridotite, mainly derived from the lithospheric mantle wedge, was initially incorporated into the subduction channel at depths of mostly 30–120 km and then underwent ultradeep (>150 km) subduction and crustal metasomatism [1]. Therefore, orogenic peridotite provides a window into subduction-zone mantle geodynamics. Compared with garnet lherzolite showing abundant metamorphic and metasomatic evidence, orogenic dunite can better preserve their initial compositions and thus sheds light on their origins and mantle evolution prior to subduction [2]. Given that dunite has different chemical and physical properties (e.g., wave velocity, viscosity and magnetic conductivity) from garnet lherzolite [3], constraining the distribution and evolution of orogenic dunite in subduction zones is critical to our understanding of mantle wedge heterogeneities and geodynamic processes. However, it is still a challenge to obtain the subsolidus pressure of dunite because of its simple mineral assemblage and the lack of suitable barometers.

As most orogenic dunites bear spinel, they are usually considered as fragments from the shallow mantle wedge (<80 km) that have never been dragged to sub-arc depths (80–150 km). However, experimental work argues that spinel can be stable to much greater depths in depleted harzburgite and dunite [4]. Moreover, the occurrence of dolomite dissociation texture (Dolomite = Aragonite + Magnesite) in the Lijiatun dunite confirms the possibility of ultradeep subduction of the spinel-bearing dunite [5]. Thus, the key question is how to evaluate whether orogenic dunite has indeed ever subducted to ultrahigh-pressure (UHP) conditions. Although the transition from spinel dunite to spinel-garnet (or garnet-bearing) dunite generally occurs at UHP conditions [4], garnet is very rare and small in dunite because of its low bulk Al content, making pressure estimation difficult. Alternatively, olivine is the dominant mineral in peridotite. Previous studies suggest that minor elements (e.g., Ca and Na) in olivine may shed light on peridotite pressures [6,7]. Our recent work shows that garnet-facies orogenic peridotites (mainly lherzolite) have overall higher Na contents of olivine than spinel-facies peridotites [8] (Fig. S1 online). This reminds us that Na in olivine may be used to constrain the pressure of orogenic dunite. To further test this supposition, we chose the Raobazhai spinel dunites, the Ugelvik garnet dunites, and the Lijiatun and Maowu spinel–garnet dunites, and performed detailed analyses of olivine Na contents using a high-precision electron probe microanalyzer (HP-EPMA).

The Raobazhai dunites from the north Dabie orogen are fresh and contain spinel but neither garnet nor plagioclase (see the Appendix for microphotographs online). It is suggested that the Raobazhai massif originated from the shallow (plagioclase facies) mantle wedge and was then subducted to a deeper level (spinel facies) before exhumation (Fig. 1a) [9]. The Ugelvik dunites are located on Otrøy Island of the Western Gneiss Region (WGR) and contain ~2% porphyroblastic (≤1 cm) garnet with thin kelyphite rims. These dunites experienced high degrees of melting in the deep mantle (>5 GPa); they were later incorporated into the subducted Baltic continental crust and underwent prograde subduction to 200 km depth (Fig. 1a) [10]. Dunites from Lijiatun in the Sulu orogen and Maowu in the Dabie orogen have similar mineral assemblages. Spinel is ubiquitous in both localities. The Lijiatun dunites contain trace interstitial garnets with small grain sizes of 10–80 µm, whereas the Maowu dunites have relatively more abundant and larger garnet grains (up to 500 µm). As shown in Fig. 1b, the Lijiatun and Maowu dunites have nearly identical metamorphic *P-T* paths. They represent mantle melting residues at shallow depths and were subducted to UHP conditions (~5 GPa) from lower pressure (1–2 GPa) levels [5,11]. Since these dunites underwent different pressure metamorphism in

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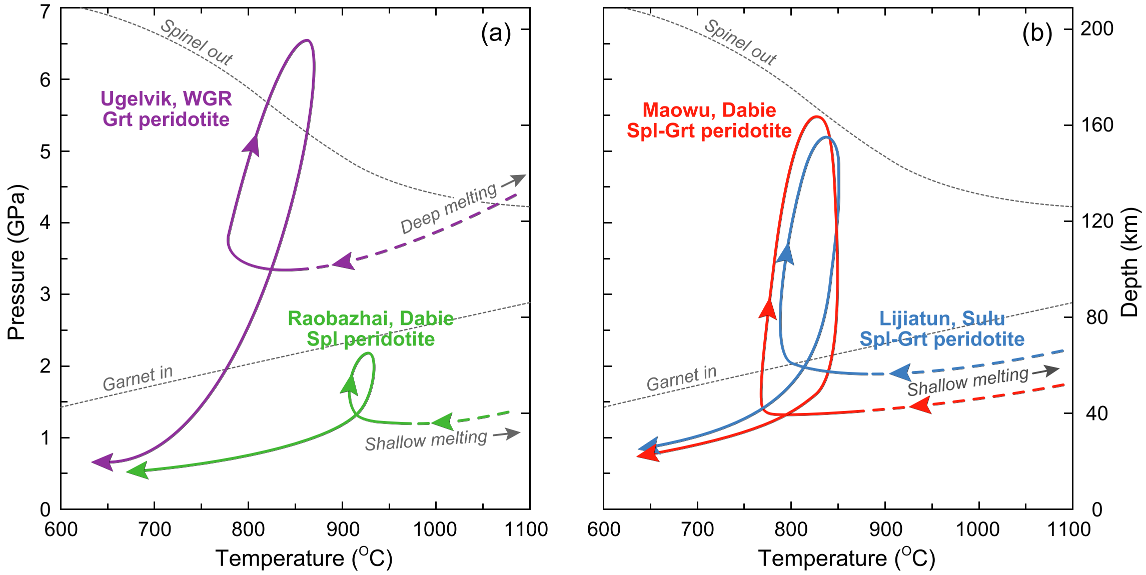

Fig. 1. (Color online) Pressure-temperature paths for the Raobazhai spinel peridotites [9], the Ugelvik garnet peridotites [10] and the Lijiatun [5] and Maowu [11] spinel-garnet peridotites. The stabilities of garnet and spinel (gray dotted lines) are constrained based on THERMOCALC calculation using the bulk rock composition of the Lijiatun dunite. WGR: Western Gneiss region; Grt: garnet; Spl: spinel.

subduction zones, they are ideal for evaluating the role of Na in olivine as a pressure indicator for orogenic dunite.

Detailed analytical methods and all data are presented in the Appendix (online). The Na contents of olivine are relatively homogeneous on the intra-grain scale and show no significant variation in a specimen (±20 ppm relative to the mean). In Fig. 2, the olivine Na contents of spinel dunites, garnet dunites and spinel–garnet dunites show distinct distribution patterns. The Raobazhai spinel dunites have Na contents of olivine mostly below the HP-EPMA detection limit of 11 ppm (3σ). In contrast, the Na contents of olivine from the Ugelvik garnet dunites are typically greater than ~18 ppm, similar to the garnet-facies orogenic peridotites shown in Ref. [8]. The Lijiatun and Maowu spinel-garnet dunite olivines both show a wide range of Na contents from <11 to 80 ppm, covering the total ranges of the spinel and garnet dunite olivines. Since diffusion of Na in olivine is so fast as to allow it to achieve re-equilibrium during circumstance changes [12], the measured Na contents can well represent the thermal state of subduction zones, rather than of the lithospheric mantle.

Many experiments have demonstrated that the partition coefficient for Na in olivine shows significant pressure dependence and increases with pressure up to 14 GPa [7,13]. This pressure dependence can be attributed either to the compression of Na$^+$ polyhedra due to its larger ionic radius (1.02 Å) relative to the position of the M site parabola peak (0.70–0.76 Å) or to the compensation of electrostatic valence by cation substitution, such as (Mg^{2+}, Mg^{2+}) ↔ (Na$^+$, Al^{3+}) at high pressure [7]. Although a positive correlation between olivine Na contents and temperatures was observed in a set of high-*T* (1000–1400 °C) peridotite xenoliths, such a correlation disappears in lower-*T* (750–1000 °C) peridotites [14]. Moreover, these high-*T* peridotite xenoliths plotted along the 43 mW/m^2 conductive geotherm and were derived from different mantle depths (~100–200 km) [14]. The potential pressure effect on olivine Na content has been neglected and may obscure some of the temperature-dependency.

The studied orogenic dunites span a narrow range of equilibrium temperatures (800–950 °C) in subduction zones (Fig. 1). Specifically, the Raobazhai dunites have relatively higher temperature (~950 °C) [9] but lower Na contents in olivine than other dunites [5,10,11]. In this regard, we can first exclude a significant contribution of temperature to olivine Na distribution patterns in these dunites. Thus, the difference in Na distribution patterns may result from different pressure conditions. As shown in Fig. 1, the Ugelvik garnet dunites underwent UHP metamorphism from ~3.5 to 7 GPa, whereas the peak pressure for the Raobazhai spinel dunites was <2 GPa. The former have clearly higher olivine Na contents than the latter (Fig. 2), corresponding with their contrasting pressure conditions. The Lijiatun and Maowu spinel-garnet dunites were subducted from the low-*P* spinel stability field to the UHP spinel-garnet stability field. During the process of pressure increase, Na in olivine would readily re-equilibrate with surrounding phases due to its fast diffusion rate [12], and thus olivines formed at different metamorphic stages in these spinel-garnet dunites can have a broad Na range covering those of spinel and garnet dunites. Our spinel-garnet dunite data do agree with the expected pattern (Fig. 2), confirming the pressure sensitivity of Na in olivine.

This study, combined with previous experimental work, suggests that Na in olivine can be used as a pressure indicator for orogenic dunite. The dunite subducted to UHP conditions (garnet growth) typically has olivine Na contents greater than ~18 ppm. This finding has important implications for understanding mantle geodynamics in subduction zones. Except for orogenic dunite, whether supra-subduction zone ophiolitic peridotite (mainly harzburgite and dunite) and fore-arc serpentinite have experienced UHP metamorphism remains poorly constrained [15–18] due to lacking appropriate geobarometers. The pressure dependence of Na in olivine presented here may open up a new avenue to investigate the metamorphic evolution of these ultramafic rocks.

Conflict of interest

The authors declare that they have no conflict of interest.

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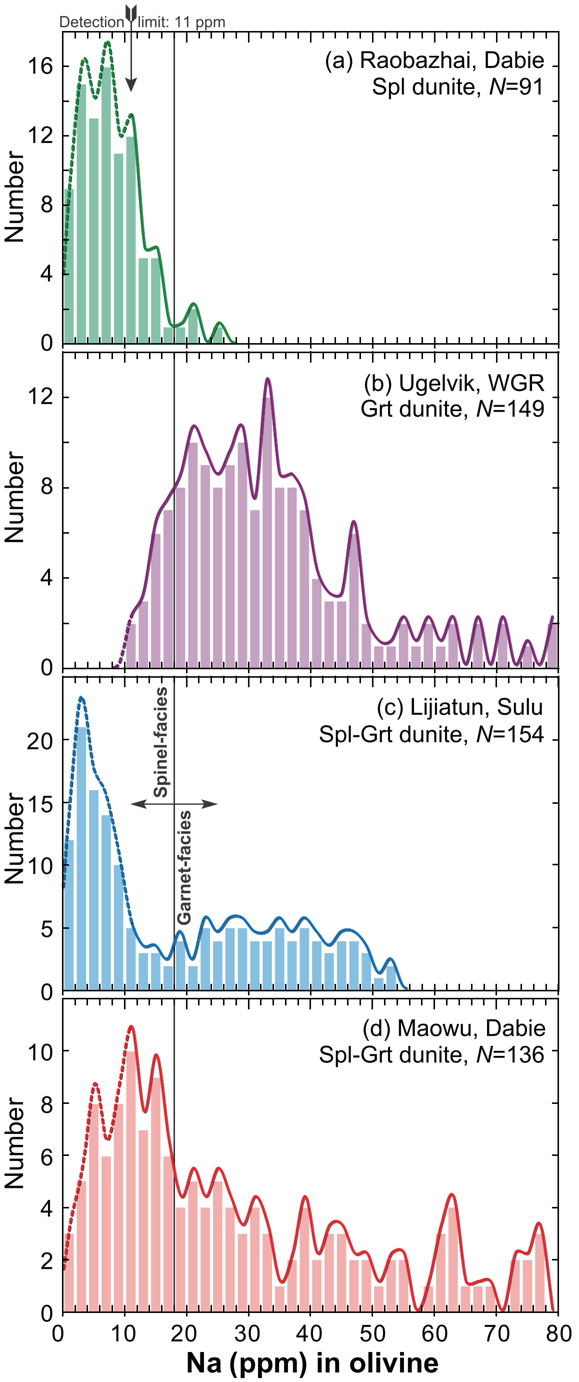

Fig. 2. Histograms of Na contents in olivine from the Raobazhai spinel dunites (a), the Ugelvik garnet dunites (b), the Lijiatun (c) and Maowu (d) spinel-garnet dunites. Dashed lines represent the Na data below the HP-EPMA detection limit (11 ppm). The boundary (shown by the vertical solid line) between spinel-facies and garnet-facies orogenic peridotites is taken from Fig. S1 (online).

Author contributions

Bin Su and Yi Chen designed the study and co-wrote the manuscript. Bin Su and Qian Mao performed the experimental analyses.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2019.10.007.

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