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Vertical depletion of ophiolitic mantle decodes melt focusing and interaction in the asthenospheric column under oceanic spreading centers

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Abstract

Adiabatic decompressional melting of asthenosphere under spreading centers has been accepted to produce vertical compositional variations of oceanic lithospheric mantle. However, theoretical estimates of the compositional gradients are much smaller than those observed from ophiolites, clearly requiring additional processes. Here we conduct systematic high-density sampling and whole-rock and mineral compositional analyses of harzburgites in a Tibetan ophiolitic mantle section (~2 km thick), which shows a primary upward depletion (~12% difference over ~2 km) and local depleted anomalies. Thermodynamic modeling demonstrates that these features cannot be produced by decompressional melting or proportional compression of residual mantle. Instead, they can be explained by reaction between silica-undersaturated melts and peridotite with lateral melt/rock variations in the topmost asthenospheric upwelling column, showing stronger depletion in its melt-focusing center and local zones. This column will split from the center into two parts, which rotate in the mantle flow to become horizontal, thus forming the oceanic uppermost lithospheric mantle characterized by vertical depletion and local anomalies within a sub-spreading-center regime.
Asthenosphere upwelling, lithosphere generation and plate divergence in oceanic spreading centers (such as mid-ocean ridges and forearc/backarc centers) drive the dynamics of plate tectonics and regulate the cycling of mass and heat between Earth’s interior and at least two-thirds of Earth’s surface. The various physiochemical processes (e.g., asthenospheric flow, partial melting, melt migration and melt-rock interaction) and parameters (e.g., mantle potential temperature, spreading and upwelling rates, mantle source composition, plate-lid thickness) in spreading centers have produced oceanic lithosphere of great complexity in structure and composition.

Unlike the oceanic crust, which can be sampled from the present-day ocean floor and fossil ophiolites, the oceanic lithospheric mantle has been studied mainly from abyssal peridotites (commonly serpentinized) collected locally from mid-ocean ridges or related transform faults. The lack of systematic sampling of a complete vertical section of oceanic lithospheric mantle limits our understanding of the formation and evolution of oceanic lithospheric mantle and the mantle dynamic processes beneath spreading centers.

Fortunately, appropriate ophiolites with excellent mantle-rock exposure and limited modification in orogenic belts can provide more direct and complete snapshots of oceanic lithospheric mantle with clear spatial context. They are an indispensable target to reveal the origins of oceanic-mantle heterogeneity and the petrochemical and dynamic processes under oceanic spreading centers, which are poorly constrained by abyssal peridotites. For example, the fractal dunite melt-channel system in the upwelling residual mantle has been revealed by studies of ophiolites (mainly the Oman example) to illustrate the melt-extraction processes and mantle dynamics under oceanic spreading centers.

In this study, we have selected the well-exposed Kangjinla ultramafic massif (eastern part of the Luobusa ophiolite) in the Yarlung Zangbo suture zone (South Tibet; Fig. 1), which
displays the vertical architecture of an uppermost lithospheric mantle section in the Neo-Tethyan Ocean\textsuperscript{19,25,26}. We have carried out systematic high-density sampling, detailed petrographic investigations and geochemical analyses of whole-rock and mineral compositions. Our aims are to provide a high-resolution view of the lithological and compositional variations in a section of the oceanic lithospheric mantle, and to reveal the dynamic processes responsible for the compositional features of the uppermost lithospheric mantle under oceanic spreading centers.

\section*{Results}

\textbf{Geology and sample descriptions.} The ophiolites in the ~2000-km-long Yarlung Zangbo (YZ) suture (South Tibet; \textbf{Fig. 1a}) represent relics of oceanic lithosphere formed at various spreading centers in the Neo-Tethyan Ocean\textsuperscript{22,25,27,28}, which separated Greater India in the south and the Lhasa block in the north during the Mesozoic\textsuperscript{29}. The YZ ophiolites expose tens to hundreds of km\textsuperscript{2} outcrops of individual bodies; from east to west the main bodies are the Luobusa, Zedang, Xigaze, Saga, Dangqiong, Xiugugabu, Purang and Dongbo ophiolites (\textbf{Fig. 1b}). The Luobusa ophiolite is the most well-known because it contains the largest chromitite ore deposits in China\textsuperscript{30} as well as peculiar ultrahigh-pressure and super-reduced minerals identified from the mantle rocks\textsuperscript{31}. Contrasting tectonic origins proposed for the Luobusa ophiolite would have it produced in i) a mid-ocean ridge\textsuperscript{25,32,33}, ii) primarily a mid-ocean ridge overprinted by subduction-zone modification\textsuperscript{19,30}, iii) a single-stage nascent forearc\textsuperscript{26}, or iv) multiple episodes of subduction-zone cycling\textsuperscript{34}. However, there is a consensus that the major architecture of the Luobusa ophiolite was generated in an oceanic spreading center controlled by plate divergence and asthenospheric upwelling.

The Luobusa ophiolite is a south-dipping tectonic slice (\textbf{Fig. 1c}) with an exposed length of ~42 km and width of ~1-3 km as well as a geophysically constrained thickness of ~2-3 km\textsuperscript{35}. It
is sandwiched between northern Eocene molasse at the base and the southern Triassic flysch on top\(^{19}\). On the outcrop, from north to south, the ophiolitic sequence includes a serpentinite mélange zone enclosing mafic-ultramafic cumulate lenses, a paleo-Moho transition zone of dunite enclosing harzburgite relics, and a gradation from clinopyroxene-poor harzburgite through to clinopyroxene-rich harzburgite. This zonation reveals that the mantle section was overturned during its emplacement\(^{19,26}\).

From west to east, three segments (Luobusa, Xiangkashan and Kangjinla) can be further subdivided, and they are continuous in the E-W direction. Previous investigations have shown that the three segments have similar internal architecture\(^{19,26,36-38}\), and the primary lithospheric stratigraphy is completely and continuously exposed in the Kangjinla segment and the southern part of the Xiangkashan segment (Fig. 1c). We therefore chose these segments for high-density sampling, aiming to cover the whole mantle section of the Luobusa ophiolite.

The studied segments were then reconstructed as a complete mantle profile defined as “the Kangjinla ophiolitic mantle”, which can be subdivided into four zones based on lithological associations and petrographic features (Fig. 1d; Supplementary Table 1). From north to south (top to bottom of the primary stratigraphy), they are the northern dunite zone (NDZ), northern harzburgite zone (NHZ), central harzburgite zone (CHZ) and southern harzburgite zone (SHZ), forming a continuous mantle section ~2 km thick. At the contact between the CHZ and the overlying Triassic black slates, the peridotites are strongly carbonated (Fig. 1c, 1d). This mantle section thus represents a snapshot of the uppermost lithospheric mantle under the Moho in the Neo-Tethyan Ocean\(^{19,26,36,37}\).

In the reconstructed Kangjinla profile, rare thin chromitite veins grew in the SHZ, small chromitite pods are found in the basal CHZ, and large chromitite ore bodies occur in the upper NHZ and the NDZ (Fig. 1d). Dunites are closely associated with and enclose the chromitites, and
increase in size from the SHZ to the NDZ (Fig. 1c, 1d). Harzburgites constitute the major framework of the mantle profile (Supplementary Fig. 1). They have primary mineral assemblages of olivine + orthopyroxene + spinel ± clinopyroxene ± sulfide and show porphyroblastic textures and plastic deformation. Petrographic variations in the representative 40 harzburgites from the SHZ to the NDZ are systematic, including the gradual upward disappearance of clinopyroxene and sulfide, decrease in modal orthopyroxene and increase in modal olivine (Supplementary Fig. 1b-1e, Supplementary Table 1). In the SHZ, all harzburgites are clinopyroxene-rich (~4-5 vol.%, sometimes occurring as porphyroblasts), contain Fe-Ni sulfides (mainly pentlandite, ~0.05-0.1 vol.%), and show the highest abundance of pyroxene (reaching maximum of ~40 vol.%), except for a few clinopyroxene-free harzburgites close to dunite lenses (e.g., sample KJL14-05C). In the CHZ and NHZ, the harzburgites become more pyroxene-poor and olivine-rich from south to north, with gradual reduction in the grain sizes of both ortho- and clinopyroxenes and enlargement of olivine and spinel grains (Supplementary Fig. 1c, 1d). Some harzburgites from the basal CHZ (e.g., samples 18KJL09-01 and 16KJL20-01) are direct wall-rocks of dunite lenses, and clinopyroxene is extremely rare or absent; they are similar to the clinopyroxene-free harzburgites in the SHZ (dunitization effect; Supplementary Table 1). In the NDZ, the harzburgites occur as relict enclaves with diffuse boundaries in the dunites, and show the most abundant olivine, the least modal orthopyroxene and extremely rare clinopyroxene (Supplementary Fig. 1b). The spinels form trails and become rounded or euhedral, similar to those in the dunites. Sample KJL1522-04 shows higher modal orthopyroxene than other NDZ harzburgites. The petrographic features of the harzburgites are summarized in Supplementary Table 1.
Whole-rock major-element compositions. Whole-rock major-element compositions of the Kangjinla harzburgites are highly variable (Supplementary Table 2), covering two-thirds of the global range of abyssal peridotites (Supplementary Fig. 2). Serpentinization degrees are commonly less than 10%, based on petrographic observation, LOI (0.17-8.13 wt%, with 80% of samples < 4 wt%) and limited MgO loss and SiO$_2$ gain relative to the mantle-melting residual trends in the Al$_2$O$_3$/SiO$_2$ vs MgO/SiO$_2$ space (Supplementary Fig. 2). The lack of correlation between LOI and oxides (not shown) suggests that serpentinization did not affect the primary compositional variations.

Except for samples KJL14-05C, 16KJL20-01 and 18KJL09-01, which display strong dunitization effects and sample KJL1522-04 with excess orthopyroxene (Supplementary Tables 1, 2), all the harzburgites show gradual variations of anhydrous oxides from the SHZ to the NDZ (i.e., upwards from the bottom of the section; Figs. 2, 3), including increasing MgO (from 41.0-43.1 wt% for SHZ to 44.2-47.9 wt% for NDZ; Fig. 2a), decreasing Al$_2$O$_3$ (from 0.94-2.02 wt% to 0.16-0.71 wt%; Fig. 2b) and SiO$_2$ (from 45.0-46.0 wt% to 42.1-44.2 wt%; Fig. 3a), increasing FeO$_T$ (from 7.61-8.38 wt% to 8.04-9.12 wt%; Fig. 3b), and decreasing CaO (from 1.66-2.64 wt% to 0.40-0.92 wt%; Fig. 3c). Sample KJL1522-04 has much lower MgO and FeO$_T$ as well as higher SiO$_2$ than other NDZ harzburgites, indicating possible metasomatic addition of orthopyroxene (Figs. 2, 3).

Mineral major-element compositions. Major-element compositions of spinel, clinopyroxene, orthopyroxene and olivine from the Kangjinla harzburgites show systematic variations from the SHZ to the NDZ, except for samples KJL14-05C, 16KJL20-01 and 18KJL09-01, which were affected by local dunitization.
In the residual harzburgites from SHZ to NDZ, spinel grains exhibit gradually increasing Cr# $(\text{Cr}^{3+}/(\text{Cr}^{3+}+\text{Al}^{3+}))$, 0.19-0.29, 0.27-0.59, 0.44-0.63 to 0.54-0.73; Fig. 2c, Supplementary Fig. 3a) and $\text{V}_2\text{O}_3$ (0.13-0.18 wt%, 0.17-0.33 wt%, 0.20-0.39 wt% to 0.26-0.34 wt%; Supplementary Table 3), as well as decreasing $\text{Mg#} (\text{Mg}^{2+}/(\text{Mg}^{2+}+\text{Fe}^{2+}))$, 0.68-0.73, 0.55-0.72, 0.54-0.65 to 0.52-0.60; Supplementary Fig. 3a). Clinopyroxene grains (when present) show gradual increases in Mg# (0.926-0.937, 0.934-0.951, 0.941-0.952 to 0.945-0.952; Supplementary Fig. 3b) and Cr# (from 0.12-0.15, 0.15-0.26, 0.20-0.26 to 0.20-0.34; Supplementary Table 4), as well as decreases in $\text{Al}_2\text{O}_3$ (from 3.63-4.72 wt% for SHZ to 0.80-2.27 wt% for NDZ; Fig. 2d, Supplementary Fig. 3b) and $\text{Na}_2\text{O}$ (from 0.14-0.23 wt% for SHZ to 0.01-0.11 wt% for NDZ). Orthopyroxene porphyroblasts show gradual increases in Mg# (0.905-0.910, 0.909-0.916, 0.909-0.920 to 0.912-0.920; Supplementary Fig. 3c, Supplementary Table 5) and Cr# (0.08-0.11, 0.10-0.19, 0.15-0.21 to 0.17-0.25; Fig. 2e) from SHZ to NDZ, as well as systematically decreasing $\text{Al}_2\text{O}_3$ (from 3.33-4.16 wt% for SHZ to 0.99-2.10 wt% for NDZ; Supplementary Fig. 3c, 3d). The Mg# of olivine increases gradually from SHZ to NDZ (from 0.900-0.908 for SHZ to 0.910-0.916 for NDZ; Fig. 2f), while NiO and MnO are consistent across the four zones (Supplementary Table 6).

**Mineral trace-element compositions.** Trace-element compositions of clinopyroxene (Supplementary Table 7) and orthopyroxene (Supplementary Table 8) from the Kangjinla harzburgites show systematic variations from SHZ to NDZ, comparable to those observed for the pyroxene major elements (Fig. 2, Supplementary Figs. 4, 5). All the clinopyroxenes exhibit consistent left-leaning REE (Supplementary Fig. 4a-4d) and “U-shaped” multi-element patterns (Supplementary Fig. 5a-5d). They show gradually enhanced depletion from the least incompatible to highly-incompatible trace elements (Supplementary Figs. 4a-4d, 5a-5d), except for the fluid-mobile elements (e.g., Cs, Ba, U, Pb, Li) which show strong enrichments and
positive anomalies. From SHZ to NDZ, the concentrations of incompatible lithophile elements in clinopyroxene, such as Nd (Fig. 2g), Ti (Fig. 2h), Yb (Fig. 2i) and other REE and HFSE (high-field strength elements), gradually decrease while the fluid-mobile elements share similar concentrations and enrichments across the four zones (Supplementary Fig. 5a-5d).

Orthopyroxenes from the Kangjinla harzburgites have REE (Supplementary Fig. 4c-4h) and multi-element patterns (Supplementary Fig. 5e-5h) similar to those of the clinopyroxenes, except for much lower concentrations and positive anomalies of Ti in orthopyroxene. From SHZ to NDZ, the orthopyroxenes exhibit gradual depletion in most lithophile elements, such as Hf (Fig. 2j), Ti (Fig. 2k), Yb (Fig. 2l) and other REE and HFSE and comparable enrichments in fluid-mobile elements (Supplementary Fig. 5e-5h). Most trace elements are strongly depleted in orthopyroxene in the dunitization-affected harzburgites from the SHZ and CHZ (Fig. 2j-2l, Supplementary Figs. 4g-4h, 5g-5h).

Discussion

Compositional variations of oceanic uppermost mantle represented by a Tibetan ophiolite.

Ophiolites have been widely interpreted as relics of juvenile oceanic lithosphere produced in spreading centers (mid-ocean ridges and forearc/backarc centers)\(^ {1,18} \). For example, the Oman ophiolite formed in a fast-spreading center within a time span of \(~1\) Ma, and was obducted soon after rapidly leaving the spreading-center regime\(^ {39} \). This means that the main architecture of ophiolites can largely record the birth and infancy of oceanic lithosphere, but cannot document the later thickening and accretion after the lithosphere moving away from the spreading center, as proposed by the age-related half-space cooling model or plate model\(^ {9,10,40,41} \). Therefore, the detailed observations of the Kangjinla ophiolite from this study can provide a direct close-up view of juvenile oceanic lithospheric mantle (particularly of its uppermost portion), and can
reflect the thermo-dynamic processes from asthenosphere to lithosphere beneath oceanic spreading centers.

The high-density sampling and systematic investigations of the reconstructed Kangjinla ophiolitic profile show a first-order lithological zoning in the harzburgitic mantle framework, with generally increasing olivine but decreasing pyroxenes from bottom to top (Fig. 1d, Supplementary Fig. 1, Supplementary Table 1). The petrographic features are consistent with the gradual variations in whole-rock and mineral compositions, suggesting a primary upward removal of chemical components incompatible with the melting residues (Figs. 2-5). In the Kangjinla lower zones (SHZ and CHZ), some harzburgites close to dunite lenses exhibit consumption of pyroxenes, addition of olivine and much stronger depletion than that of the wall-rock harzburgites (Fig. 2). This local compositional depletion has been interpreted as the results of dunitization of harzburgites by interaction with silica-undersaturated silicate melts. Comparable compositional features of oceanic lithospheric mantle have also been observed in other ophiolites, such as Oman and Troodos, but all with much lower sampling densities (hundreds to thousands of meters). In summary, gradual vertical depletion of ophiolitic mantle (i.e., oceanic uppermost mantle) and local depletion anomalies are the prevailing phenomena, if the sampling density is high enough to resolve the compositional trends of the ophiolitic stratigraphy.

Decompressional melting cannot produce the vertical depletion of oceanic uppermost mantle. Under an oceanic spreading center, adiabatic upwelling and advection of asthenospheric mantle into the space produced by divergent spreading of the overlying plates shapes the dynamic flow field of solid mantle underneath spreading centers. The concomitant decompressional melting and melt extraction result in the focusing of melts towards the axis of
the spreading center and an interplay between melt and the upwelling mantle\textsuperscript{6,44-47}. These processes combined with the variations in mantle potential temperature, spreading and upwelling rates, mantle source composition, asthenospheric flow pattern, plate-lid thickness and melting mechanism have been proposed to produce the great variations of oceanic lithosphere and its compositional complexity in mantle and crust\textsuperscript{3-5,7-11}. The lithospheric mantle variations are best reflected by the first-order upward compositional depletion of residual mantle columns, which have been interpreted as the product of decompressional melting and lateral transformation as the compositionally stratified lithospheric mantle\textsuperscript{4}.

In this study, in order to reproduce the compositional variations of residual mantle columns under oceanic spreading centers, we modeled the isentropic decompressional fractional melting of a depleted-MORB-mantle (DMM) source\textsuperscript{48}, using the pMELTS version\textsuperscript{49} of the \textsc{alphaMELTS} 1.9 software package\textsuperscript{50}, with appropriate mantle potential temperatures of 1300 °C, 1350 °C, 1400 °C and 1450 °C\textsuperscript{51}. Because the melting of volatile- and/or pyroxenite-rich sources will start at deeper levels and plays an important role in the low-melting-degree situations and melt compositions\textsuperscript{52,53}, we focus here on the melting of anhydrous peridotite, which can form the major architecture of oceanic lithospheric mantle\textsuperscript{11}. Our modeling shows that to produce the major-element ranges (Fig. 3, Supplementary Fig. 2) and degrees of partial melting indicated by the major Kangjinla harzburgites (F = ~8.1-20.1%; Fig. 4b), the decompression melting must occur over a pressure range of at least 5 kbar (~15 km in depth; Fig. 4a). However, in the Kangjinla mantle profile these ranges are expressed over a maximum depth of ~2 km (Figs. 1d, 4b). This means that the compositional variations of the Kangjinla mantle profile cannot be generated directly by adiabatic decompressional melting and lateral transformation from residual mantle columns as proposed by Plank & Langmuir\textsuperscript{4}. 

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In theory, an alternative scenario of proportional mechanical stretching and thinning of the residual mantle columns by at least 7-8 times may produce the observed compositional gradients of the Kangjinla mantle section. However, it is impossible for a lithospheric mantle section to be reduced in thickness by factors of 7-8 under an oceanic spreading center, considering the lack of reasonable dynamic forces and constraints from thermal evolution models of oceanic lithosphere. We also have not observed any structural evidence to suggest strong N-S compression or E-W stretching in the Kangjinla ophiolite (Fig. 1, Supplementary Fig. 1). In addition, the highly heterogeneous distributions of ancient melting residues indicated by Os-isotope signatures in the Luobusa mantle cannot form the gradual depletion features observed in this study (Figs. 2-5). We therefore suggest that the vertical depletion of the Kangjinla ophiolitic mantle and probably of other ophiolites may be generated by additional processes, rather than simply adiabatic decompressional melting of asthenosphere or later proportional compression/extension of lithospheric mantle.

Melt focusing and melt-peridotite interaction in asthenospheric upwelling columns. Previous investigations of present-day mid-ocean-ridge samples and ophiolites both suggest that the melts extracted from a broad source mantle will migrate upwards and converge towards the narrow sub-axis zone, and will thoroughly react with the surrounding mantle during melt migration via diffusive and/or channelized flow. Two main scenarios exist. The first is that in the lithospheric mantle, mainly silica-saturated melts react with the peridotite resulting in the addition of pyroxene/plagioclase, and minor silica-undersaturated melts react locally with the peridotite to form dunite lenses, which usually cut the foliation of the harzburgitic mantle. The other scenario is that in the upwelling asthenospheric mantle, the silica-undersaturated melts derived from deeper sources (garnet facies) migrate and focus towards the center of an
asthenospheric diapir, leading to the consumption of pyroxene, the addition of olivine and the
formation of olivine-rich lenses conformable with the deformation patterns of the surrounding
mantle (via the reaction of pyroxene + silica-poor melt → olivine + silica-rich melt). To test if these two scenarios can generate the vertical gradual depletion and local
anomalies observed from the Kangjinla ophiolitic mantle, we modeled the reactions of two types
of mafic melts with the most fertile harzburgite (KJL14-05A) from the Kangjinla SHZ, using the
alphaMELTS program. Melt 1 has been taken as having the composition of aggregated melts
extracted from the garnet-facies DMM source at a Tp of 1350 °C and a melt temperature of
1383.86°C (the last equilibration temperature at the end of garnet-facies melting), while melt 2
represents the aggregated melts from the garnet- to spinel-facies mantle melting region and has
the equilibration temperature of 1318.69 °C (Supplementary Table 9). Melt 1 is silica-
undersaturated, and melt 2 is approaching silica saturation. The pressures (4, 6 and 8 kbar) and
temperatures (1000, 1100, 1200 and 1300 °C) of peridotitic mantle have been set up to mimic the
conditions of a very short mantle column (a few kilometers in depth, similar to the Kangjinla
mantle profile) typically in the uppermost lithospheric mantle and the top of the upwelling
asthenospheric mantle under spreading centers. At each P-T condition, melts with each
parcel of 4 g are added iteratively to the harzburgite with an initial mass of 100 g. The melt-solid
bulk system attains thermodynamic equilibration before next step of melt addition. The residual
melt after each step will be added and mixed with another 4 g melt, and then they participate
together in the next step of melt-rock equilibration. This iteration will stop until the added total
melt mass reaches 200 g (Fig. 5; Supplementary Table 9).

Our modeling shows that for the silica-undersaturated melts (Fig. 5a-5c), the
compositional variations of the Kangjinla harzburgites can be well reproduced by melt-peridotite
reaction at 1200 °C and 1300 °C, but cannot form at lower mantle temperatures (e.g., 1000 °C
and 1100 °C in the lithosphere). Similarly, for the silica-saturated melts, the Kangjinla samples can be generally modeled by high-temperature melt-rock reactions in the asthenospheric mantle (e.g., 1300 °C; Fig. 5d-5f), while the low-temperature reactions mimic the refertilization trends (e.g., MgO decreases and CaO increases; Fig. 5d-5f) in the lithospheric mantle. More importantly, the reactions with higher melt/rock ratios can result in stronger compositional depletion, showing higher whole-rock MgO and FeO$_T$ and lower CaO, as observed in the harzburgites from SHZ to NDZ of the Kangjinla profile (Fig. 5). The dunitization-affected harzburgites in the lower portion of the CHZ and the SHZ also can be formed by reactions at higher melt/rock ratios similar to those for the NDZ.

We therefore propose that within the shallow upwelling asthenospheric column under an oceanic spreading center (~4-8 kbar, 1200-1300 °C), the melts extracted from the deeper source mantle will flow into and focus towards the sub-axis zone of rising residual mantle (represented by the sample KJL14-05A in the Kangjinla case; Fig. 6a). Larger amounts of melts will converge into the middle of the upwelling asthenospheric column to react at higher melt/rock ratios, while less and less melt will react with the bilateral distal regions of the asthenospheric column (Fig. 6b). The melt/rock-controlled compositional variations of the asthenospheric upwelling column at a given P-T condition are laterally symmetrical, with the middle part more depleted and the distal parts less depleted. In addition, the depletion anomalies represented by the dunitization-affected harzburgites in the Kangjinla CHZ and SHZ can be explained by local melt accumulation and reaction in the bilateral distal regions of the asthenospheric column.

This melt-focused and compositionally-symmetrical column revealed by the Kangjinla case can be several kilometers wide, as observed by geophysical studies of current mid-ocean ridges. When this column rises it splits into two symmetrical parts, which will dynamically rotate ~90° in the mantle-flow regime to become the juvenile uppermost lithospheric mantle.
with the primary middle part of the column at the top and the distal part to the bottom (Fig. 6c).

This perpendicular rotation of the split asthenospheric column can thus explain the vertical
gradient in depletion and the local depleted anomalies in oceanic uppermost lithospheric mantle
and ophiolitic mantle.

Implications. On the global scale and in single mid-ocean ridges, residual abyssal peridotites
show large major-element compositional ranges in bulk rocks and minerals (Figs. 3, 5,
Supplementary Fig. 2)\(^{13-15,58}\). These large-scale heterogeneities have been broadly explained by
the variations in mantle source composition, mantle potential temperature, plate spreading rate,
thickness of thermal boundary layer, partial melting manner and melt-mantle
interaction\(^{3,4,7,11,13,14,43-47}\). However, within the same sampling site on a spreading center, such as
the narrow ~22-24 Ma sector in the Vema Fracture Zone of the Mid-Atlantic Ridge, spinel Cr#
values of the abyssal peridotites also show a large range, indicating major compositional
variations\(^{59}\). The large variations are difficult to explain by the almost consistent physiochemical
conditions and sources within this small domain, but may be easily resolved by the sampling of a
short profile of the vertical uppermost lithospheric mantle produced by the processes proposed in
this study (Fig. 6).

The understanding from this study of how melt focusing and melt-mantle interaction can
produce lateral compositional variations in the asthenospheric upwelling column provides a novel
reconcilable solution for the debate regarding melt-mantle interaction modes in the oceanic
uppermost mantle under spreading centers, i.e., focused dunite channel model\(^{24}\) vs pervasive melt
migration model\(^ {14}\). The upwelling asthenospheric column beneath the axial zone of the spreading
center can be regarded as a giant melt-focusing channel made up of reactive transitional
lithologies from harzburgite to dunite\(^{46}\), with local melt accumulation regions forming so-called
This new understanding thus provides novel insights into processes at oceanic spreading centers and the mechanisms of plate tectonics on Earth.

**Methods**

**Whole-rock major element analyses.** Whole-rock major-element compositions were measured using a Shimadzu Sequential 1800 X-ray fluorescence spectrometer in the State Key Laboratory of Geological Processes and Mineral Resources (GPMR), China University of Geosciences (CUG, Wuhan). Each rock powder of 0.7 g was fully mixed with 5 g of flux ($\text{Li}_2\text{B}_4\text{O}_7;\text{LiBO}_2 = 12:22$), 0.3 g $\text{NH}_4\text{NO}_3$, 0.4 g LiF and a few drops of LiBr. The mixed samples were melted in a high-frequency furnace at ~1050 °C, and then quickly cooled as glass disks. Analytical times for each element were ~30-60 s with a voltage of 40 kV and a current of 70 mA. Calibration curves used for quantification were produced by bivariate regression of data from 39 reference materials encompassing a wide range of silicate compositions. The measurement procedure and data quality were monitored by the repeated analysis of two Chinese National ultramafic standards GBW07101 and GBW07102. Unknown duplicates were measured to check the reliability of sample preparation and instrument analysis. Loss on ignition (LOI) was additionally measured. The analytical relative standard deviations of major oxides for the monitoring standards are less than 3%.

**Mineral major-element analyses.** Before the mineral major-element analyses, thick (~200 μm) sections of the Kangjinla harzburgites were examined and imaged using a Nikon microscope and a Zeiss Sigma 300 field emission scanning electron microscopy (SEM). Back-scattered electron (BSE) images were taken by SEM, using a beam current of 20 nA, an accelerating voltage of 15 kV and a beam size of ~1 μm. Mineral major-element compositions were determined using two
electron microprobe analyzers (EMPA). The first is a JEOL JXA-8100 EMPA equipped with
four wavelength-dispersive spectrometers at the Key Laboratory of Submarine Geosciences,
Second Institute of Oceanography (MNR, China), and the second is a JEOL JXA-8230 EMPA
with five wavelength-dispersive spectrometers at the State Key Laboratory of GPMR of CUG
(Wuhan). Both instruments used an accelerating voltage of 15 kV, a beam current of 20 nA and a
beam size of <1 μm. The peak counting time was 10 s for Na, Mg, Al, Si, K, Ca, Fe and Cr, and
was 20 s for Mn, Ti, V and Zn. The background was counted for half as long as the peak, on both
high- and low-energy background positions. The following standards were used: jadeite (Na),
olivine (Si), diopside (Ca, Mg), sanidine (K), rutile (Ti), almandine garnet (Fe, Al), rhodonite
(Mn), chromium oxide (Cr), native metals V and Zn (V, Zn). The ZAF correction was used to
calibrate the peaks by measurements of the above standards. The relative standard deviations of
analyses on standards are less than 1%. During the analyses, the exsolved phases in pyroxene
were avoided by careful selection of analytical spots.

Mineral trace-element analyses. Trace-element compositions of clinopyroxene and
orthopyroxene from the Kangjinla harzburgites were measured using a laser ablation-inductively
coupled plasma mass spectrometer (LA-ICPMS) in the State Key Laboratory of GPMR of CUG
(Wuhan). A 193 nm RESOlution laser ablation system was attached to a Thermo iCAP-Q ICPMS
for the analysis. For clinopyroxene, laser-ablation conditions of beam size 50 μm, pulse rate of 8
Hz, and an energy density of 3 J/cm² were applied. Each analysis includes 30 s on background at
the beginning and then 40 s collection of sample signals. Multiple reference materials (NIST 610,
NIST 612, BIR-1G, BCR-2G and BHVO-2G) were used as external standards without the
application of an internal standard for data reduction. Selection and integration of background
and sample signals, the calibration of fractionation derived from ablation, transportation and
excitation processes, and the matrix effect on the data were all processed using the off-line program ICPMSDataCal 11\textsuperscript{60}. The data collection and calibration processes for orthopyroxene were similar to those for clinopyroxene, except for the usage of a laser beam size of 130 μm. The analytical uncertainty is better than 5% for REEs and 10% for the remaining elements (1 s level).

**References**


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Author contributions

Q.X., J.P.Z., W.L.G. and S.Y.O’R. co-designed this project. Q.X., H.D.Z. and L.W. collected the samples and carried out the geochemical analyses. H.K.D. conducted the thermodynamic modeling. Q.X. wrote the manuscript with contributions from H.K.D., J.P.Z., W.L.G. and S.Y.O’R.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information contains supplementary figures and tables.
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Fig. 1 Major tectonic units of the Himalayan-Tibetan orogenic system (a; modified after DeCelles et al.\textsuperscript{61}), geological sketch map of South Tibet showing the Yarlung Zangbo Suture and major ophiolites (b; modified after Dai et al.\textsuperscript{62}), and the simplified geological map illustrating the Luobusa ophiolite and adjacent tectonic units (c; modified after Liang et al.\textsuperscript{63}). This study focused on the Kangjinla segment and the southernmost portion of the Xiangkashan segment, both of which display intact occurrence, direct exposure and minimum alteration. We collected representative harzburgites by hammers on the well-exposed outcrops with sampling spacing of several to tens of meters. The studied segments were then reconstructed as four zones (d), from north to south including the northern dunite zone (NDZ), northern harzburgite zone (NHZ), central harzburgite zone (CHZ) and southern harzburgite zone (SHZ). The four zones can represent the major architecture of the Luobusa ophiolitic mantle, and construct a mantle profile.
defined as “the Kangjinla ophiolitic mantle” in this study (d). Yellow dashed curves in e and d mark the suggested boundaries between the four zones, and circles with different colors show the sampling positions. Abbreviations: MBT, Main Boundary Thrust; MCT, Main Central Thrust; STDS, South Tibetan Detachment System; YZS, Yarlung Zangbo Suture; BNS, Bangong-Nujiang Suture; JS, Jinsha Suture; AKMS, Anyimaqen-Kunlun-Muztagh Suture; NQO, North Qaidam Orogen; NQS, North Qilian Suture; ATF, Altyn Tagh Fault.
Fig. 2 North-south compositional variations of whole rocks (a, b) and minerals (c-l) of harzburgites from the four zones of the Kangjinla ophiolitic mantle. The distance of each sample was calculated by transformation of each longitude relative to the north end as 0 m. Petrological columns were shown at the right sides to illustrate the N-S lithological variations and zoning of the Kangjinla ophiolitic mantle, with the same legends as those in Fig. 1. (a) whole-rock anhydrous MgO (wt%), (b) whole-rock anhydrous Al$_2$O$_3$ (wt%), (c) spinel Cr# (Cr$^{3+}$/(Cr$^{3+}$+Al$^{3+}$)), (d) clinopyroxene Al$_2$O$_3$ (wt%), (e) orthopyroxene Cr#, (f) olivine Mg# (Mg$^{2+}$/(Mg$^{2+}$+Fe$^{2+}$)), (g)
clinopyroxene Nd$_N$ (PM, normalized to primitive mantle), (h) clinopyroxene Ti$_N$ (PM), (i)
clinopyroxene Yb$_N$ (PM), (j) orthopyroxene Hf$_N$ (PM), (k) orthopyroxene Ti$_N$ (PM) and (l)
orthopyroxene Yb$_N$ (PM). Two grey bands mark the harzburgite zones strongly affected by melt-
peridotite interaction during dunitization. Abbreviations: WR, whole rock; Sp, spinel; Ol, olivine;
Opx, orthopyroxene; Cpx, clinopyroxene; harz., harzburgite.
Fig. 3 Variations of whole-rock MgO (wt%) versus SiO$_2$ (wt%, a), FeO$_T$ (wt%, b) and CaO (wt%, c) for the Kangjinla ophiolitic peridotites. The symbols for the Kangjinla samples are the same as those in Fig. 2. Isentropic decompressional fractional melting trends (color-coded) for residual
peridotites from a depleted-MORB-mantle (DMM) source were modeled using the pMELTS version of alphaMELTS 1.9 program, with mantle potential temperatures of 1300 °C, 1350 °C, 1400 °C and 1450 °C. The color-coded pressure-decreasing gradient is of 0.1 kbar, and the white circles mark the pressure steps of 0, 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 GPa. The detailed melting conditions were listed in Supplementary Table 9. Small grey circles represent global abyssal peridotites without those veined by gabbro, pyroxenite and dunite.
Fig. 4 Variations of partial melting degrees (F) versus pressure (P, kbar) for the isentropic decompressional melting residues (a), and F versus distance from the north end (m) for the Kangjinla peridotites (b). F in a was acquired by thermodynamic modeling as shown in Fig. 3, while F in b was calculated using spinel Cr# and the updated equation \( F = 9 \times \ln(\text{Cr#}) + 23 \)\(^{13}\). Petrological column shown in b is the same as those shown in Fig. 1d. Grey zones in a and b mark the mantle “depletion” extents of the Kangjinla peridotites and the required pressure differences produced by the isentropic decompressional fractional melting. The symbols in b are the same as those in Figs. 2 and 3.
**Fig. 5** Variations of whole-rock MgO (wt%) versus SiO$_2$ (wt%, a, d), FeO$_T$ (wt%, b, e) and CaO (wt%, c, f) for the Kangjinla ophiolitic peridotites (symbols are the same as those in Fig. 2), compared to the solid-rock products modeled by isentropic melt-peridotite reaction. The melt-peridotite reaction modeling was done using the alphaMELTS program. Two scenarios of reaction are shown as “Melt 1 + Harzburgite KJL14-05A” in (a, b, c) and “Melt 2 + Harzburgite KJL14-05A” in (d, e, f). The modeled reaction conditions (P and T) and the compositions of Melt 1, Melt 2 and Harzburgite KJL14-05A have been shown in Supplementary Table 9. Grey circles represent abyssal peridotites as those in Fig. 3.
Fig. 6 Schematic cartoons (a-c) illustrate melt focusing and melt-peridotite interaction in the upwelling asthenospheric columns under a typical oceanic spreading center. Cartoon a shows a vertical cut plane (100 km deep and 600 km wide) of a sub-spreading-center regime far from...
transform faults, modified from Ligi et al. Lithosphere spreading and asthenosphere upwelling produce the color-coded decompressional melting regions with melting degrees (F) of 1%-20% marked (a). Red dashed curves with temperatures from 1300 °C to 200 °C show the thermal structure of the lithosphere and asthenosphere, and the 1100 °C curve marks the lithosphere-asthenosphere boundary (LAB) as proposed by Niu & Green. Two black dashed lines show the boundaries between spinel- and garnet-facies mantle and the garnet-spinel transitional zone (85-60 km) in between. The white dashed curve encloses the upwelling asthenospheric mantle where anhydrous melting occurs. The red short arrows show that the melts converge and focus into the sub-axis narrow zone under the spreading center. The black thick curves with black arrows display the flow patterns of upwelling asthenosphere. The residual mantle columns represented by the color-coded zones have the compositional gradients too small to be consistent with the Kangjinla situation. A model of melt focusing and melt-rock reaction (pyroxene consumption and olivine addition) in the top region of the upwelling asthenospheric column can well explain the vertical depletion and local depleted anomalies displayed in c. The variations of melt/rock (M/R) ratios in the column result in the lithological and compositional variations, which form the laterally symmetrical mantle column. After it splits into two parts which each rotates ~90° to become the oceanic uppermost lithospheric mantle, the primarily more-depleted axial region forms the top of the lithospheric mantle section while the more-fertile bilateral region becomes the bottom, as observed in the Kangjinla and other ophiolites. Abbreviations: Sp, spinel; Gt, garnet; Py, pyroxene; Ol, olivine; NDZ, northern dunite zone; NHZ, northern harzburgite zone; CHZ, central harzburgite zone; SHZ, southern harzburgite zone.
Supplementary Files

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