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Os isotopic evidence for a carbonaceous chondritic mantle source for the Nagqu ophiolite from Tibet and its implications

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Early-crystallizing chromian spinel (Cr-spinel) in the Nagqu ophiolite has high Os and low Re contents, and it is resistant to alteration during serpentinization, weathering and metamorphism. The chemical composition of primitive magma is preserved in Cr-spinel, which makes it suitable for determining the initial Os-isotope composition of the mantle source. This study presents Cr-spinel Os isotopes and zircon U-Pb ages for cumulate dunite and gabbro, respectively, in the same cumulate section of the ophiolite at Nagqu in Tibet. The results shed light on the formation and evolution of lithospheric mantle. The Nagqu ophiolite is located in the central part of the Bangong-Nujiang suture zone. It is a remnant of the Neotethyan oceanic crust, and contains cumulate dunite and gabbro. Zircon from the gabbro yielded a weighted mean $^{206}Pb/^{238}U$ age of 183.7±1 Ma. Cr-spinel exhibits γ_{Os} values of −0.2 to −0.3, suggesting that the mantle source for the dunite is similar to that of carbonaceous chondrites. Thus, the Tibetan lithosphere is primarily a relic of Tethyan oceanic lithosphere, which has formed by the transformation of the normal asthenospheric mantle in the Mesozoic. This is the first study to combine the spinel Os isotopes with accurate zircon U-Pb ages to constrain the geochemical characteristics of the mantle source for the ophiolite.

Re-Os isotopes, spinel, ophiolite, Nagqu, Tibet

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Ophiolites are remnants of oceanic lithosphere that have been thrust over continental lithospheres and thus preserved from subduction. A complete ophiolitic section is composed of peridotites, overlain successively by mafic and ultramafic igneous rocks and sedimentary rocks [1]. Studies evaluating the mantle source of ophiolites can play a significant role in the identification ofthe nature and evolution of ancient oceanic lithosphere [2,3]. The Re-Os isotopic system is a useful tool to investigate melting and differentiation processes in the mantle of Earth [4,5]. Os isotopes can reveal information about melting events in the convecting asthenospheric mantle that are not recorded by incompatible lithophile-element isotopic tracers (e.g. Sm-Nd and Lu-Hf).

Mantle peridotites in ophiolites are thought to represent the mantle restite after extraction of basaltic melts from the asthenospheric mantle. Many studies have suggested that there are significant differences in the Os-isotope composition of mantle peridotites [6–13]. Subsequent to their formation, mantle peridotites may be modified by partial melting processes and interaction with melts percolating through them [14–16]. Recent studies indicate that refractory subcontinental lithospheric mantle (SCLM) can survive during the opening of ocean basins and become part of the oceanic lithosphere [10,17–22]. Given the such preservation of refractory domains in ophiolitic mantle peridotites [6,8], their Re-Os isotopic characteristics cannot precisely reflect the nature of the convecting mantle at the time of ophiolite formation.

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A basic principle of isotope geochemistry is that partial melting at mantle temperatures, pressures and timescales achieves complete equilibrium between melts and solid residues [23]. Thus, Os-isotope studies of a melt also can reflect the characteristics of the mantle source. Previous studies of mid-ocean ridge basalts (MORB) have revealed that the Os contents of MORB are very low (<100 ppt), and that assimilation of seawater and post-eruptive decay of ^{187}Re to ^{187}Os would complicate interpretation of MORB data [24–26]. Furthermore, whether abyssal peridotites are direct residues of MORB melting is disputable. Thus, Re-Os isotope data for normal MORB cannot determine the true Os-isotope characteristics of the convecting mantle. In addition, there is a suite of cumulate complexes between lavas and residual mantle peridotites in a complete ophiolitic sequence. A recent study of the Oman ophiolite revealed that the lower, cumulate oceanic crust dominates the Os budget of oceanic crust [27]. In cumulate dunites, Cr-spinel is one of the earliest minerals to crystallize from the magma, and it is enriched in Os relative to Re. Cr-spinel not only may preserve its Os isotopic composition during later contamination of the bulk rock [28–30], but also can rapidly and precisely record geochemical information from the convecting upper mantle source. Thus, Cr-spinel can provide a unique insight into the Os isotopic characteristics of oceanic lithospheric mantle.

In this paper, we present Os-isotope data for Cr-spinel from cumulate dunite and U-Pb ages of zircon from gabbro in the Nagqu ophiolite, central Tibet. The Os-isotope ratios in Cr-spinel areused to determine the initial ^{187}Os/^{188}Os ratio of the mantle source of the parental magma of the cumulates. In addition, the U-Pb ages of zircon in gabbro are used to constrain the formation age of the cumulates, based on field evidence that the two rock types are genetically linked. Using these links, we were able to investigate the Os-isotope characteristics of the mantle source of the magmatic rocks in the Nagqu ophiolite.

1 Geological background and samples

The Bangong-Nujiang suture zone is an important plate boundary in northern Tibet, which is mainly composed of the Bangong Lake, Dongqiao, Nagqu and Dingqing ophiolites. The Nagqu ophiolite is located in the central part of the Bangong-Nujiang suture zone, about 20 km northwest of the county town of Nagqu (Figure 1). The Nagqu ophiolite predominantly contains harzburgites that tectonically overlie a cumulate complex. The ophiolite was tectonically emplaced into the Jurassic Mugagangri Group. Previous studies have suggested that the Nagqu ophiolite formed in a mature back-arc basin [31–34].

The cumulate complex consists of dunite at the base and layered gabbro in the upper part, and contains interleaved olivine-pyroxenite and pyroxenite horizons (Figure 1). The cumulate complex is vertically continuous, and as thick as 30 m (Figure 2). There is a gradational contact between dunite and gabbro. The crystallization sequence is olivine, followed by pyroxenite and then plagioclase, suggesting that they are products of a single magma chamber [35]. For this work, we sampled dunite (No. 09039) and gabbro (No. 09038) to unravel the nature of their source mantle.

2 Analytical methods and results

Zircon and spinel grains were separated from 10 to 15 kg slabs of gabbro and dunite, respectively, using standard techniques at the Institute of Regional Geological and Mineral Survey, Hebei. The representative zircon grains were mounted in epoxy, polished, and photographed with transmitted and reflected light, followed by cathodoluminescence (CL) imaging at the Institute of Geology and Geophysics, Chinese Academy of Sciences (CAS). Zircons were analyzed for U, Th, Pb and other trace elements using LA-ICP-MS at the Institute of Tibetan Plateau Research, CAS. Laser sampling

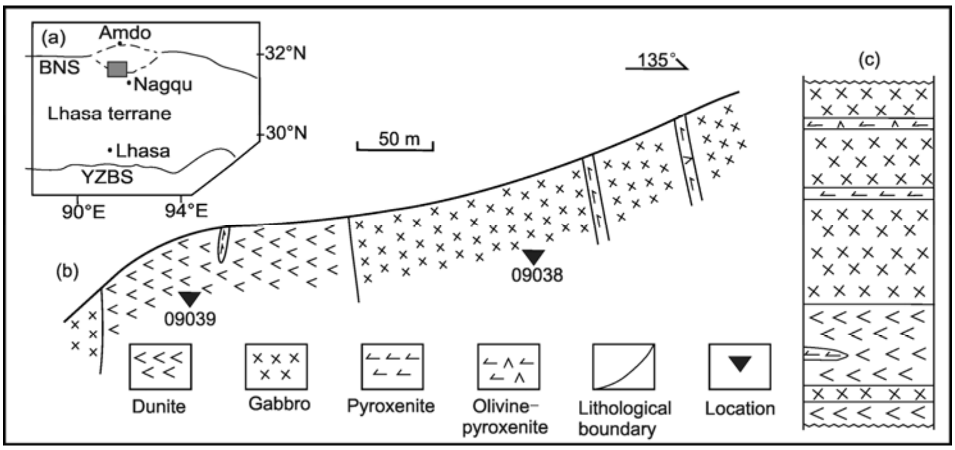

Figure 1 Tectonic map of Tibet, showing locations of the Nagqu ophiolite and sample localities along the cumulate complex. (a) Tectonic map of Tibet; (b) cross-section of cumulate complex; (c) lithologic column of cumulate complex.

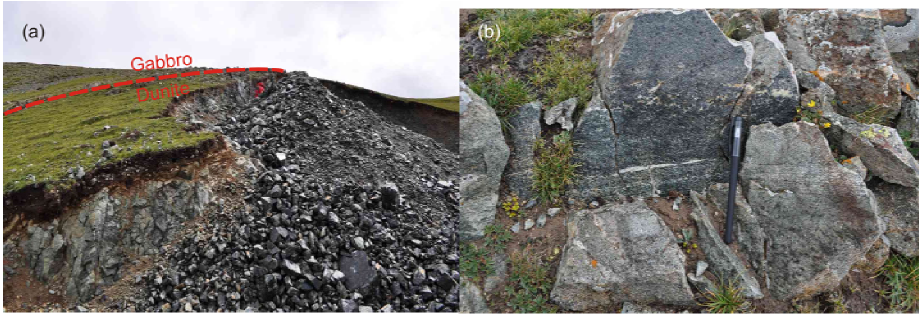

Figure 2 Field photos from the Nagqu ophiolite, depicting the internal structure and relationships among different units. (a) Gradational contacts between dunite and gabbro; (b) cumulate texture of gabbro.

was performed using a New wave UP 193 laser ablation system, and an Agilent 7500a ICP-MS was used to determine zircon U-Pb ages. All analyses were carried out with a beam diameter of 25 μm, 8 Hz repetition rate (eroding time: 40 s). During the analysis, Plešovice zircon was used as external standard for U-Pb dating [36]. A common-Pb correction was made according to the method of Anderson [37]. Uncertainties in mean $^{206}Pb/^{238}U$ ages are given at the 95% confidence level. The U-Pb isotope and age results are listed in Table 1. The Th/U ratio of zircons ranged from 0.13 to 1.15, indicating that they are magmatic in origin [38], as also indicated by the CL images. The seven data points gave a mean Concordia age of 183.7±1 Ma (Figure 3).

Re-Os isotopes were obtained by isotope dilution techniques at the Guangzhou Institute of Geochemistry, CAS, where an increasing volume of Re-Os isotopic data has been published [10,21,39–41]. The experimental procedure is described by Li et al. [4,42]. About 1.5 g powder or 0.2 g spinel was dissolved using inverse aqua regia (2.5 mL 10.8 mol/L HCl, 7.5 mL 14 mol/L HNO_3) in sealed Carius tubes at 240°C for 24 h (48 h for spinel). Isotopic tracers (^{185}Re and ^{190}Os) were added to samples prior to dissolution. Os was purified using CCl_4 and HBr, micro-distilled for 3 h [43] and dried to 3 μL. Os-isotope measurements were carried out by N-TIMS [44,45] with a Thermo Finnigan Triton. Re was extracted and purified by anion exchange using AG1×8 resin. Re concentrations were measured using ICP-MS. Total blank levels were 5 to 10 pg and 3 to 7 pg for Re and Os, respectively, and the $^{187}Os/^{188}Os$ ratio of the blank was 0.20556. Contribution of the blank to measured Os contents and $^{187}Os/^{188}Os$ ratios was minimal. Mass fractionation and blank corrections were made for all data. $^{187}Os/^{188}Os$ ratios of dunite varied from 0.12533 to 0.12603, and $^{187}Os/^{188}Os$ ratios of spinel ranged between 0.12536 and 0.12552 (Table 2).

3 Discussion

3.1 Spinel recording mantle source

Re-Os isotopic data have previously revealed that refractory lithospheric mantle can survive in orogenic peridotites, ophioliticperidotites and abyssal peridotites [10,12,17,18,20,21, 46–50]. Given the heterogeneous distribution of refractory domains in the asthenospheric mantle, it may be unsuitable to determine Os isotopic characteristics of the mantle source from analyses of mantle peridotites.

At oceanic spreading centers, magma is produced by upwelling and decompression melting of the convecting mantle. Melt is removed to make oceanic crust and the residue represents oceanic lithospheric mantle [51–54]. This model for generation of magma and oceanic crust has been accepted as part of plate tectonic theory for a long time [55–58]. However, whether MORBs represent primitive magma, which is complementary in chemical composition

Table 1 U-Pb isotopic data for zircons from gabbro in the Nagqu ophiolite[a)]

Spot	$^{232}Th/^{238}U$	$^{207}Pb/^{206}Pb$	±%	$^{207}Pb/^{235}U$	±%	$^{206}Pb/^{238}U$	±%	$^{208}Pb/^{232}Th$	±%	$^{206}Pb/^{238}U$ Age (Ma)	±σ
38-01	0.71	0.04964	1.8	0.19811	1.7	0.02896	0.8	0.00698	0.9	184	1
38-02	0.79	0.04684	2.0	0.18705	1.9	0.02898	0.8	0.00677	0.9	184	1
38-03	0.13	0.04988	5.8	0.19695	5.6	0.02865	1.4	0.00738	6.6	182	3
38-04	0.24	0.04708	4.4	0.18593	4.2	0.02866	1.2	0.00683	4.4	182	2
38-05	1.03	0.05029	4.4	0.20200	4.2	0.02915	1.2	0.00711	1.7	185	2
38-06	0.44	0.04998	3.0	0.19856	2.9	0.02883	1.0	0.00709	1.8	183	2
38-07	1.15	0.04988	3.7	0.19807	3.6	0.02882	1.0	0.00745	1.3	183	2

a) 1σ error.

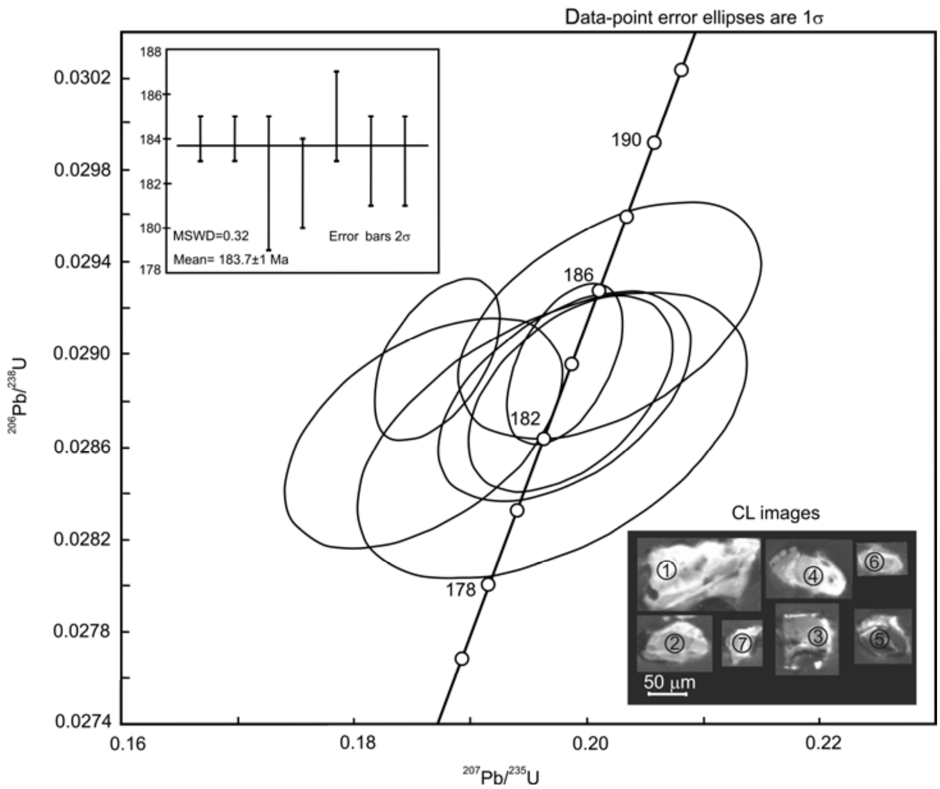

Figure 3 U-Pb Concordia plots, mean age plot, and CL images of zircons from gabbro. The circles in CL images of zircons indicate the test spots.

Table 2 Cumulated unite (09039) and spinel (SP) Re-Os isotope data

Sample	Re (ppb)	Os (ppb)	$^{187}Re/^{188}Os$	2σ	$^{187}Os/^{188}Os$	2σ	$\gamma Os_{(183.7\ Ma)}$ a)
09039-7	0.023	4.743	0.023	0.002	0.12533	0.00043	–0.4
09039-10	0.018	0.958	0.093	0.010	0.12613	0.00041	0.1
09039-11	0.014	2.652	0.026	0.004	0.12603	0.00047	0.1
SP39-7	0.083	20.173	0.020	0.001	0.12536	0.00024	–0.3
SP39-11	0.046	10.859	0.021	0.002	0.12552	0.00035	–0.2

a) Carbonaceous chondrites: $^{187}Os/^{188}Os_{chon}$=0.12700, $^{187}Re/^{188}Os_{chon}$=0.40186 [4].

to abyssal peridotites, is still debated. One view is that melting degree inferred from abyssal peridotites is consistent with that inferred from MORB. In this context, MORB is thought to be primitive magma produced by two mantle sources: one produces picrate magmas by 20% to 30% partial melting at 2–3 GPa; the other produces tholeiitic magmas by 10% to 20% partial melting at shallower depths (~1 GPa) [59]. However, another idea holds that there are reactions between melts and residues [60–63], and neither MORB nor continental alkali basalts can represent primitive magmas. Subsequently more research was undertaken to investigate this mechanism, suggesting that the composition of MORB is homogenized by magma-chamber mixing, rather than derivation from a homogeneous mantle source [23,64,65]. Hence, it is still difficult to define the Os-isotope characteristics of the mantle source.

In this paper, we chose for analysis an early-stage cumulate complex spatially associated with mantle peridotites to estimate the composition of the mantle source from Os isotopic composition of dunite and spinel. During the process of magma formation at spreading centers, relatively primitive convecting upper mantle will preferentially melt. Conversely, refractory, previously depleted lithospheric mantle will not participate in partial melting without water [6,20]. Although about 4% eclogite may be subducted into the asthenospheric mantle [66,67], its contribution to the $^{187}Os/^{188}Os$ ratios of the convecting upper mantle is less than 0.5% (within experimental error). It has been widely accepted that the distribution of Os is mainly controlled by sulfides and oxides [4,68]. In cumulate complexes, sulfides and spinel form as early-stage phases. Moreover, sulfide will be preserved in spinel as micro-inclusions in dunite, and will be resistant to alterations during weathering of extrusive rocks [28,29,69–71]. Thus, we can hope to obtain robust estimates of $^{187}Os/^{188}Os$ ratios in the mantle source for ophiolite from analyses of spinels in cumulate dunites.

In this case, the Os-isotope composition of bulk rock and spinel is consistent ($^{187}Os/^{188}Os$: 12533 to 0.12603 and 0.12536 to 0.12552, respectively), and significantly different from the more radiogenic Os-isotope compositions of arc lavas and some mantle-wedge peridotites [72–74]. This suggests that the addition of slab-derived fluids or other secondary infiltration did not affect these samples. Moreover, the high Os contents and low $^{187}Os/^{188}Os$ ratios of spinel may imply that they inherited the Os-isotope composition of primitive sulfides, and can be used to define Os isotopic characteristics of the mantle source of the magmas that formed the cumulates [16,71,75].

3.2 Mantle features of the Nagqu ophiolite

Cr-spinel has high Os and low Re contents. Measured $^{187}Os/^{188}Os$ ratios can directly represent the initial Os isotopic composition of convecting upper mantle without correction for the decay of ^{187}Re since eruption [28]. In the cumulate sequence of the Nagqu ophiolite, zircons in gabbro yielded a mean $^{206}Pb/^{238}U$ age of 183.7±1 Ma, which constrains the formation age of spinel in dunite. Compared to carbonaceous chondrites [4], γ_{Os} values of spinel ranged from –0.2 to –0.3 (Table 2), suggesting that the mantle source for the Nagqu ophiolite is similar to that of carbonaceous chondrites. This result is consistent with the Os isotopic composition of primitive mantle estimated from mantle peridotite xenoliths and orogenic peridotites [76], and also is compatible with the tectonic setting (mature back arc basin) of the Nagqu ophiolite [31,32]. Nevertheless, our result is approximately 1.5% less radiogenic than that estimated from the Dongqiao ophiolite [47]. The contrast may be attributed to mantle heterogeneity. Alternatively, the method applied in this note differs from that of Shi et al. [47], we obtain the age of cumulate dunite directly by using theU-Pb ages of zircon in gabbro.

From the above results, the Os-isotope characteristics of the mantle source forthe Nagquophioliteare consistent with those of carbonaceous chondrites, which mean that there is a carbonaceous chondrite-type mantle [77]. In contrast to primitive mantle values [78,79], the Os-isotope characteristics of the mantle source for the magmas in the Nagquo phioliteare slightly lower, which could imply that the source is a slightly depleted asthenospheric mantle. The Nd-Pb isotopic composition and geochemical data of mafic rocks from Tethyan ophiolites also indicate that they are derived from a geochemically depleted asthenospheric source with a clear Indian MORB-type isotopic signature [80]. Mo et al. [81] measured Linzizong volcanic rocks with ε_{Nd}>0 and interpreted them as derived from reworking of the remaining part of the Tethyan oceanic crust. A stagnant slab was suggested to exist beneath the Tibet plateau by Tapponnier et al. [82]. However, this suggestion was not confirmed by the geophysical observations of Zhao et al. [83], who detected a relatively thin but separate Tibetan lithosphere beneath central and northern Tibet.

Despite the existence of Precambrian basement rocks like the Amdo micro-terrane [84], the Tibetan lithosphere may be primarily of a young Tethyan origin from a geophysical perspective [83]. A series of juvenile crust and arc-continental collisional and accretionary orogens developed along the southern margin of the Asian continent during the Paleozoic and Mesozoic, prior to the Indian and Asian continental collisions [85]. The Nagqu ophiolite is a fragment of juvenile oceanic crust formed in the Early Jurassic and preserved during the later collision between the Amdo micro-terrane and Lhasa terrane. The consistency between the Os-isotope characteristics of the Nagqu ophiolite and the convecting asthenospheric mantle indicates the ophiolite formed in a mature back-arc basin, where both arc-like and MORB-like basalts are generated [86]. Thus, the Tibetan lithosphere is primarily derived from remnants of Tethyan oceanic lithosphere, formed by the transformation of the normal asthenospheric mantle in the Mesozoic.

4 Conclusions

The Nagqu ophiolite formed in a mature back-arc basin, and consists of a complete cumulate sequence from cumulate dunite to gabbro, tectonically overlain by harzburgite. Zircon in the gabbro yielded an U-Pb age of 183.7±1 Ma. Cr-spinel exhibits γ_{Os} values of –0.2 to –0.3, suggesting that the Os-isotope characteristics of the mantle source for the magmatic rocks of the Nagqu ophiolite is similar to that of carbonaceous chondrites. Thus, the Tibetan lithosphere is primarily formed by the transformation of the normal asthenospheric mantle in the Mesozoic.

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