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Notes

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ABSTRACT

The Os isotope compositions of sulfides in mantle xenoliths from the Penghu Islands, Taiwan Strait, reveal the presence of Proterozoic subcontinental lithospheric mantle beneath the highly extended southeast margin of the South China block. Both T_{RD} (Re depleted) model ages for individual sulfides and model ages estimated from the initial $^{187}\text{Os}/^{188}\text{Os}$ ratios of Re-Os mixing lines require that some volumes of the subcontinental lithospheric mantle formed prior to 2.3–1.9 Ga. Later events in the subcontinental lithospheric mantle may be recorded by T_{RD} model ages of 1.5–1.2 Ga and ca. 0.9 Ga. The events recognized in the subcontinental lithospheric mantle are consistent with those known in the crust of the mainland South China block. The sulfide Os isotope data show that Proterozoic lithosphere beneath the South China block has survived the extensive Mesozoic Yanshanian magmatism on the continental margin and has not been delaminated even during the severe lithospheric extension that led to the subsidence of the Taiwan Strait.

Keywords: lithospheric mantle, Re-Os, sulfides, Taiwan Strait, Proterozoic, South China block.

INTRODUCTION

The continents are underlain by roots of subcontinental lithospheric mantle that vary in thickness, composition, and thermal state depending on the age and tectonothermal history of the overlying crust (e.g., O'Reilly et al., 2001, and references therein). Most undisturbed Archean (older than 2.5 Ga) cratonic areas have thick (180–250 km deep) subcontinental lithospheric mantle keels. However, the breakup and reassembly of continents through time suggests that these keels can be disrupted or thinned, as in active rift zones and passive-margin situations. These mechanisms are poorly understood in detail, and new tools that can track mantle volumes through these processes are needed.

Whole-rock Re-Os isotope data from mantle-derived peridotites have contributed much information on the age of the subcontinental lithospheric mantle (Shirey and Walker, 1998; Pearson, 1999). However, recent studies have demonstrated that Os in these rocks is concentrated in sulfide phases and that these can be mobile within the subcontinental lithospheric mantle, so that whole-rock Re-Os model ages probably reflect mixing processes,

rather than single melting events (Alard et al., 2002; Griffin et al., 2002b). Recent developments in the in situ analysis of the Re-Os system in sulfide phases allow us to unravel some of this complexity and improve the interpretation of the age information contained in the mantle-derived samples (Pearson et al., 2002; Alard et al., 2002; Griffin et al., 2002b). The mobility of Os within the subcontinental lithospheric mantle also may provide new insights into the timing and processes of metasomatism in the subcontinental lithospheric mantle.

Studies of mantle xenoliths from Paleozoic kimberlites and Cenozoic basalts in the North China craton suggest that a thick, cool, and depleted Archean subcontinental lithospheric mantle was largely replaced by a thin, hot, and fertile subcontinental lithospheric mantle in late Mesozoic to early Cenozoic time (Griffin et al., 1998; Gao et al., 2002). Relicts of the Archean lithosphere, preserved locally at shallower levels, coexist with fertile Phanerozoic subcontinental lithospheric mantle beneath the eastern part of the North China craton (Zheng et al., 2001). Detailed seismic tomography (Yuan, 1996) suggests that the Archean subcontinental lithospheric mantle was disrupted by extension (a brittle failure model) and that

asthenospheric material has welled up between the relict blocks.

Scattered xenolith data and seismic tomography suggest that the eastern part of the Proterozoic South China block is underlain by thinner and less depleted subcontinental lithospheric mantle than the western part (e.g., Xu et al., 2000). Here we present in situ Re-Os isotope data for sulfides in mantle xenoliths from the Penghu Islands, in the Taiwan Strait (Fig. 1). These data demonstrate the survival of ancient subcontinental lithospheric mantle beneath the extended margin of the South China block, which underwent widespread late Mesozoic magmatism, followed by lithospheric extension and crustal subsidence.

GEOLOGIC BACKGROUND AND SAMPLE DESCRIPTIONS

The South China block is composed of the Yangtze craton in the northwest and the Cathaysian fold belts (Cathaysia), including the Cenozoic mountain ranges of Taiwan, in the southeast (Fig. 1). The Yangtze craton has a Late Archean–Paleoproterozoic (1.7 Ga or older) nucleus surrounded by late Mesoproterozoic orogenic belts; the Cathaysia block is floored by Paleoproterozoic to Mesoproterozoic continental crust (Chen and Jahn, 1998, and references therein). The eastern Cathaysia block was strongly affected by the late Mesozoic Yanshanian bimodal magmatism. Eastern China has undergone extension due to the late Mesozoic subduction of the paleo-Pacific plate beneath Eurasia and/or the Indo-Eurasia collision since the early Paleogene. Along the continental margin, this extension led to the formation of early Tertiary basins, and subsidence of the Taiwan Strait accompanied the opening of the South China Sea (Chung et al., 1994). Meanwhile, widespread intraplate basaltic volcanism (65 Ma to Holocene; Fig. 1), some carrying abundant mantle-derived xenoliths, has occurred in these basins in conjunction with the regional extension.

The xenoliths discussed here come from

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Figure 1. Tectonomagmatic map of southeastern China. Black areas—late Cenozoic intraplate basalts; stars—localities of mantle xenoliths; solid star—locality of xenoliths in this study. Inset: main sample localities in Penghu Islands.

two localities in the Penghu Islands in the Taiwan Strait: Kueipi in the main island and the Tungchiyu islet (Fig. 1). The islands are made up of Miocene alkaline and tholeiitic basaltic lavas (16–8 Ma; Chung et al., 1994). The Kueipi xenoliths are 13 to 10 Ma (Lee, 1994) alkali basalt flows. The Tungchiyu xenoliths are from a pyroclastic layer (13.2–11.2 Ma; Ho et al., 2000) in the lower sequence. The xenoliths are dominantly spinel peridotites with minor spinel pyroxenites. At least two episodes of metasomatism are reflected in the fluid-inclusion distributions and the trace element patterns of clinopyroxenes. The range of observed compositions indicates that the lithospheric mantle beneath this region is a mixture of moderately refractory and fertile lherzolites, similar to mantle xenolith suites from several mainland localities (Xu et al., 2000). Like these suites, they are compositionally distinct from oceanic peridotites (Griffin et al., 1999) and their olivine contents and Fo values¹ fall off the “oceanic peridotites” trend of Boyd (1989).

Sulfides $\geq 50 \mu\text{m}$ across were analyzed in polished thin sections of peridotites and pyroxenites. Most sulfides are interstitial, but some are enclosed in olivine. Element-distribution maps derived from electron-microprobe imaging in this study show that nearly all sulfide grains from Kueipi consist of interfingered Ni-rich and Fe-rich monosulfide solid solutions

(MSS), with an outer rim of chalcopyrite. Those from Tungchiyu mostly have Fe-rich MSS cores, surrounded by Ni-rich MSS and a Co-rich rim. There is no convincing difference between enclosed and interstitial sulfides in terms of their major and trace element composition in either locality.

ANALYTICAL METHODS

Analytical procedures and the precision and accuracy of the method for in situ Re-Os isotope analysis were described in detail by Pearson et al. (2002) (also see www.es.mq.edu.au/GEMOC). Analyses were carried out in He, using a Merchantek LUV266 laser microprobe with a modified ablation cell, attached to a Nu plasma multicollector inductively coupled plasma-mass spectrometer (ICP-MS) at Macquarie University, Sydney. A synthetic NiS bead spiked with a known Os isotope composition (PGE-A) was used for calibration of the instrument.

RESULTS AND DISCUSSION

Metasomatism and Interpretation of Model Ages

Alard et al. (2000, 2002) argued that silicate-enclosed sulfides may represent MSS residual from melting processes in the subcontinental lithospheric mantle, whereas interstitial sulfides are the crystallization products of sulfide-bearing metasomatic fluids. Most Penghu sulfides are interstitial and therefore may represent secondary metasomatic events, rather than primary melt-depletion events in the subcontinental lithospheric mantle. Because sulfide melts have low melting points and viscosities, in the same range as volatile-rich melts (Gaetani and Groves, 1999), they are

likely to be mobile in the subcontinental lithospheric mantle. Thus, once a metasomatic melt and/or fluid formed, sulfides might move with such fluids through the subcontinental lithospheric mantle, to be precipitated as interstitial phases. They would become enclosed if trapped by later recrystallization and grain growth (Griffin et al., 2002b). Metasomatism may have been continuous or episodic ever since the subcontinental lithospheric mantle first was isolated from the convecting part of the mantle, and the sulfide data thus are most likely to date metasomatic events; however, such ages would provide minimum estimates for the age of the subcontinental lithospheric mantle.

Estimated Os contents of the analyzed sulfides range from 5 to 110 ppm (median 16 ppm) (see footnote 1). Most Penghu sulfides have subchondritic $^{187}\text{Os}/^{188}\text{Os}$ ratios (<0.1249) that preclude the possibility that the interstitial sulfides represent host-rock contamination; alkali basalts typically have $^{187}\text{Os}/^{188}\text{Os} > 0.135$ (Shirey and Walker, 1998). Griffin et al. (2002b) suggested that sulfides with $^{187}\text{Re}/^{188}\text{Os} > 0.07\text{--}0.08$ may have undergone significant disturbance of their Os isotope systematics, and only those grains with lower ratios could yield realistic model ages of separation from the chondritic mantle (T_{MA}). The Penghu sulfides mostly have $^{187}\text{Re}/^{188}\text{Os}$ ratios ranging from 0.12 to 1.07, and T_{MA} model ages derived from such sulfides may be meaningless in terms of subcontinental lithospheric mantle age. Two sulfides with low $^{187}\text{Re}/^{188}\text{Os}$ ratios (0.063 and 0.025), both from Tungchiyu, yield T_{MA} ages of $2.28 \pm 0.38 \text{ Ga}$ (TC0242/2-S6; peridotite) and $0.92 \pm 0.16 \text{ Ga}$ (TC0223-S3; pyroxenite) (see footnote 1). Despite the high Re/Os ratios of Penghu sulfides, their model ages for Re depletion (T_{RD}) will still provide minimum estimates of subcontinental lithospheric mantle age. The T_{RD} model ages of the 17 sulfides with the best analytical precision range from 2.6 to 0.7 Ga (Fig. 2E) and indicate that many of the samples have resided in the subcontinental lithospheric mantle at least since Proterozoic time.

The presence of both positive and negative correlations in Figure 2 strongly suggests that all of the correlations represent mixing lines and that the positive correlations do not have age significance. The three enclosed sulfides (S5, S6, and S8) in Kueipi peridotite sample KP0215 with the lowest analytical uncertainty define an age of $1424 \pm 440 \text{ Ma}$ and initial $^{187}\text{Os}/^{188}\text{Os}$ ratio of 0.1116 ± 0.0023 (2 σ ; MSWD [mean square of weighted deviates] = 0.13; Fig. 2A). The T_{RD} model ages of these three sulfides range from 1.52 to 1.13 Ga (see footnote 1). If the correlation line is treated as a mixing trend, it has an end member with a

¹GSA Data Repository item 2003100, Table DR1, in situ Re-Os data of Penghu sulfides, Taiwan, and Figure DR1, plot of Mg-number versus modal olivine of host peridotites, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.

low Re/Os ratio and $^{187}\text{Os}/^{188}\text{Os} \approx 0.1116$, and the enriched component can have a $^{187}\text{Os}/^{188}\text{Os}$ ratio similar to the primitive upper mantle (PUM) and $^{187}\text{Re}/^{188}\text{Os}$ ratio of 0.7–0.8 (Fig. 2A). The initial $^{187}\text{Os}/^{188}\text{Os}$ value corresponds to a T_{RD} model age of 2.26 Ga.

Three sulfides in Tungchiyu peridotite sample TC0242/2 with the lowest uncertainties also define an age of 880 ± 400 Ma with an initial $^{187}\text{Os}/^{188}\text{Os}$ ratio of 0.1125 ± 0.0022 (2σ ; MSWD = 0.55; Fig. 2A); this ratio corresponds to a T_{RD} model age of 2.13 Ga, similar to that of KP0215. This mixing trend also can be defined by the depleted and enriched end members derived from KP0215 (Fig. 2A). A similar but subtly higher initial $^{187}\text{Os}/^{188}\text{Os}$ ratio of 0.1140 from sulfides in another Kueipi peridotite (KPH9826; Fig. 2A), which defined an age of 1998 ± 780 Ma (2σ ; MSWD = 0.023; Fig. 2A), yields a T_{RD} model age of 1.91 Ga.

The inverse correlations between $^{187}\text{Os}/^{188}\text{Os}$ and $^{187}\text{Re}/^{188}\text{Os}$ in Kueipi peridotite samples KPH9816/3-1 and KP0201 (Fig. 2B) demonstrate that their radiogenic Os isotope signature has not been developed by in situ Re decay, and different mixing components are needed to generate the inverse correlation. The mixing trends for these two samples converge toward a low Re/Os component with $^{187}\text{Os}/^{188}\text{Os} = 0.13$ –0.14. This signature suggests that radiogenic Os, but not Re, has been transported from a reservoir having a high Re/Os ratio via a metasomatic fluid. This is similar to the Re-Os characteristics of subduction-related peridotites described by Brandon et al. (1996), who proposed that Os has been transported by highly oxidizing fluids from the subducted slab into the overlying mantle wedge. The sulfide with the most subchondritic Os isotope composition in each sample has a relatively high Re/Os ratio (0.295 in samples KPH9816/3-1, 1.08 in sample KP0201). This pattern suggests that significant Re addition had occurred before the sulfides were exposed to the oxidizing fluid carrying radiogenic Os, but little Re.

Sulfides from other Kueipi peridotites display subchondritic $^{187}\text{Os}/^{188}\text{Os}$ ratios over a large range of $^{187}\text{Re}/^{188}\text{Os}$ ratios (0.118–0.720; Fig. 2C). A similar flat distribution is

seen in sulfides from the Kueipi and Tungchiyu pyroxenites, whose range of $^{187}\text{Re}/^{188}\text{Os}$ is 0.025–0.439 (Fig. 2D), but whose T_{RD} ages vary from 1.48 to 0.7 Ga. The Os isotope compositions clearly are not related to time-integrated in situ ^{187}Re decay, and the sulfides apparently were subjected to recent Re addition. The combination of high Re/Os ratios with relatively unradiogenic Os implies that the Re-bearing metasomatic fluid and/or melts, if they carried Os, came from a reservoir with low Re/Os ratios. The most likely candidate for this reservoir is the surrounding ultramafic subcontinental lithospheric mantle.

In summary, sulfides from Penghu peridotites and pyroxenites have recently undergone three types of disturbance in their Os isotope systematics: (1) addition of Re with no apparent addition of Os, or with only lithospheric Os with low $^{187}\text{Os}/^{188}\text{Os}$ ratios; (2) addition of Re, and of Os with an isotope composition near the present-day PUM; (3) addition of radiogenic Os, but little or no Re. The highly radiogenic Os in disturbance type 3 could be derived from lithospheric sources such as pyroxenites or subducted basalts, and the transporting medium may have been an oxidizing fluid derived from the Mesozoic subducting slab beneath the area.

Processes 2 and 3 involve the introduction of Os that is radiogenic relative to that expected in old subcontinental lithospheric mantle; in this case, neither T_{MA} nor T_{RD} model ages may date specific events, except perhaps in the case of rare sulfides having low Re/Os ratios (Griffin et al., 2002b). However, T_{RD} model ages will still provide minimum estimates for the age of the subcontinental lithospheric mantle, whether the sulfides originally were residual from melt-depletion events or were deposited from metasomatic fluids derived from the asthenosphere. The T_{RD} model ages of the Penghu sulfides with the best analytical precision range from 2.64 to 0.70 Ga (Fig. 2E), and the T_{RD} model ages derived for the component of the mixing lines having low Re/Os ratios (Fig. 2B) are all in the range 2.3–1.9 Ga.

These data require that parts of the subcontinental lithospheric mantle beneath the Taiwan Strait have been segregated from the convecting mantle since at least Middle Proterozoic time, and some parts may have formed as early as the Late Archean.

Tectonic Implications

U-Pb dating of zircons from basement rocks in northwestern Fujian and southwestern Zhejiang Provinces gives minimum ages of 1.77 Ga for the Cathaysia block crust (Li, 1996). No Proterozoic crustal ages have been reported from the coastal Fujian-Taiwan region,

Figure 2. Plots of $^{187}\text{Os}/^{188}\text{Os}$ vs. $^{187}\text{Re}/^{188}\text{Os}$ for sulfides. Error bars shown in A–D are $\pm 2\sigma$. A: Sulfides from Kueipi and Tungchiyu show positive correlation trends. B: Sulfides from Kueipi show negative correlation trends. C: Other sulfides from Kueipi peridotites. D: Sulfides from Kueipi and Tungchiyu pyroxenites. Solid symbols represent enclosed sulfides; open symbols represent interstitial sulfides. PUM—primitive upper-mantle values (Meisel et al., 2001). E: T_{RD} (Re depletion) model ages.

which is totally overprinted by the Yanshanian magmatic activity related to Mesozoic subduction and extension. However, Sm-Nd model ages (T_{DM}) of Yanshanian granites (Chen and Jahn, 1998) and Hf model ages of zircons from such rocks (Griffin et al., 2002a) indicate that lower crust at least 1.8–0.9 b.y. old existed beneath the region. Li et al. (2002) reported 1.43 Ga granodiorites from Hainan Island in southern Cathaysia. These ages might link crustal formation at 1.5–0.9 Ga in the Fujian-Taiwan coastal margin and the 1.4 Ga transcontinental magmatism in southern Laurentia (Nyman et al., 1994).

Our sulfide age data indicate that at least part of the subcontinental lithospheric mantle beneath the thinned margin of the Cathaysia block is as old as some crust in its interior and survived the Yanshanian magmatism and subsequent extension and crustal thinning. The similarity in the range of crustal Nd and Hf model ages and our sulfide T_{RD} ages (Fig. 2E) suggests that the sulfide ages may actually date metasomatic events in the subcontinental lithospheric mantle, related to mantle thermal events that affected the lower crust.

Most mantle xenoliths in Tertiary basalts from the South China block are relatively fertile, suggesting that the old Proterozoic lithosphere beneath it has been largely replaced by younger mantle, probably during late Mesozoic to Cenozoic time. However, some strongly depleted xenoliths also suggest that older lithospheric-mantle material persists in the lithosphere beneath the southeastern China region (Xu et al., 2000). Our Os isotope data from the mantle beneath the Taiwan Strait further support this scenario. Relicts of the subcontinental lithospheric mantle, older than upper crust in the region, have survived both lithospheric replacement and Cenozoic lithospheric thinning and extension. This observation is directly relevant to the question of whether the delamination (or convective removal; e.g., Houseman et al., 1981) of Archean or Proterozoic subcontinental lithospheric mantle is possible. The mixture of ancient (refractory) and younger (fertile) peridotites suggests that the Proterozoic subcontinental lithospheric mantle is not simply the thinned upper part of the subcontinental lithospheric mantle, underlain by fertile younger material. A model involving brittle failure of the lithosphere during extension, with upwelling of asthenospheric material into tensional zones (mushroom cloud model; Yuan, 1996), would explain the mixture observed here. Delamination mechanisms may be most relevant to regions with denser Phanerozoic subcontinental lithospheric mantle (Poudjom Djomani et al., 2001).

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