Research paper

Mesozoic accretion of juvenile sub-continental lithospheric mantle beneath South China and its implications: Geochemical and Re–Os isotopic results from Ningyuan mantle xenoliths

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ABSTRACT

The mechanism for the widespread Mesozoic magmatism in South China has been ascribed to either the paleo-Pacific plate subduction or intra-continental lithospheric extension. Mantle xenoliths entrained in the Jurassic Ningyuan alkaline basalts from southern Hunan Province, including twelve lherzolites and one harzburgite, have been studied to constrain the composition and age of the Mesozoic sub-continental lithospheric mantle. The lherzolites contain 2.06–4.09 wt.% Al₂O₃ and 2.03–3.91 wt.% CaO, which are higher than the abundances of these species in the harzburgite (1.72 wt.% and 1.17 wt.%, respectively). The Cr# of spinel varies from 0.07 to 0.24. Orthopyroxene contains 3.61–4.96 wt.% Al₂O₃ and 0.51–0.8 wt.% CaO, whereas clinopyroxene contains 4.78–7.32 wt.% Al₂O₃ and 1.04–2.01 wt.% Na₂O. Both whole rock and mineral compositions suggest that the Ningyuan mantle xenoliths have been subjected to low degrees of partial melting. Modeling of Y and Yb contents of clinopyroxene indicates that the lherzolites have been subjected to ~3–5% degrees of partial melting, while the harzburgite has experienced about 12% melting. Clinopyroxene in most Ningyuan mantle xenoliths shows variable depletion in incompatible elements, suggesting that they have been weakly enriched after melting. Clinopyroxene in one sample (TYS01-3) displays strong enrichment in incompatible elements, reflecting the local occurrence of melt metasomatism. Equilibrium temperatures estimated by two-pyroxene geothermometry vary from 994 to 1081 °C, indicating that the Mesozoic mantle lithosphere has a hot geotherm. All lherzolites display consistent highly siderophile element (HSE) patterns and have suprachondritic Ru/Ir and Pd/Ir ratios. The harzburgite shows remarkable depletion in Pt, Pd and Re. The lherzolites have 187Os/188Os ratios of 0.12116–0.12929, which are higher than that of the harzburgite (0.11681). A correlation between 187Os/188Os and Al₂O₃ exists among the Ningyuan mantle xenoliths, which if interpreted as an isochron analog yields a model age of ~2.2 Ga. This age is older than the Re depletion age (TₐRe) of the harzburgite (~1.8 Ga), which represents a minimum age of melt depletion. The old ages either support the existence of ancient lithosphere relics beneath the Ningyuan region or reflect the accretion of ancient mantle materials from the asthenosphere during the Mesozoic. Although the tectonic implication of the old ages is ambiguous, compositions of the Ningyuan mantle xenoliths suggest that ancient mantle lithosphere beneath South China has been thinned and replaced by hotter, younger mantle during the Mesozoic, which has led to extensive lithospheric extension and abundant magmatism.

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1. Introduction

A remarkable geological feature of the South China Block (SCB) is the widespread Mesozoic magmatism, in which granites and ryholites predominate volumetrically over basalts (Zhou et al., 2006). The tectonic regime responsible for the Mesozoic magmatism in South China has been an issue of long-term debate. Current views on the Mesozoic tectrogenesis can be grouped into two general categories. One suggests that the early Mesozoic tectonic setting of South China was an Andean-type active continental margin related to the subduction of the paleo-Pacific plate (Holloway, 1982; Faure et al., 1996; Zhou and Li, 2000). The other emphasizes the intracontinental lithospheric upwelling (Gilder et al., 1996; Fan et al., 2003; Li et al., 2003; Wang et al., 2003; Li et al., 2004; Wang et al., 2004). A better understanding of the composition and age of the lithospheric mantle beneath South China during the Mesozoic could provide effective constraints on these different models.

Furthermore, the composition and age of the Mesozoic lithospheric mantle are of key importance for constraining the timing of the lithospheric transformation beneath South China. Compositions of garnet lherzolite entrained in the Paleozoic Dahongshan lamproites indicate

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that the lithospheric mantle had a thickness larger than 110 km and a paleogeotherm distinctly colder than the oceanic geotherm (Zhang et al., 2001). This is in stark contrast to the Cenozoic lithosphere inferred from the Cenozoic basalts and their entrained mantle xenoliths (Fig. 1). The Cenozoic mantle xenoliths commonly have fertile compositions and high equilibrium temperatures, suggesting a hot geotherm (Fan and Hopper, 1989; Qi et al., 1995; Xu et al., 2000; Xu et al., 2002; Yu et al., 2003; Zheng et al., 2004; Yu et al., 2006; Huang and Xu, 2010). Previous studies have suggested that the old (i.e., Archean and Proterozoic) mantle that existed beneath the SCB has been largely or completely removed and replaced by younger, hotter and more fertile mantle (Xu et al., 2000; Xu et al., 2002). However, it remains unclear when the mantle thinning and replacement processes occurred in South China.

In contrast to the widespread distribution of the Cenozoic basalts, the Mesozoic basaltic rocks outcrop sporadically in the interior of the SCB (Zhao et al., 1998; Wang et al., 2003; Li et al., 2004; Wang et al., 2004; Wang et al., 2005; Xie et al., 2005; Xu and Xie, 2005; Jiang et al., 2009). The Jurassic alkaline basalts in both Ningyuan (170–173 Ma) and Daoxian (147–152 Ma) from southern Hunan Province contain abundant lower crustal and mantle xenoliths, including gabbros, pyroxenites, lherzolites and harzburgites (Guo et al., 1997; Wang et al., 1997; Guo et al., 1999; Kong et al., 2000; Zheng et al., 2004; Dai et al., 2008; Zhang et al., 2008; Xia et al., 2010). In this study, we present the comprehensive geochemical compositions of Ningyuan mantle xenoliths to discuss the accretion of juvenile mantle during the Mesozoic and the implications for the widespread Mesozoic magmatism in South China.

2. Geological setting and petrography

2.1. Geological setting

The South China Block (SCB) has been commonly divided into two major blocks, with the Yangtze block to the northwest and the Cathaysia block to the southeast (Fig. 1). The Yangtze block consists of an Archean to Paleoproterozoic basement (Chen and Jahn, 1998; Zheng et al., 2006), including occurrences of 2.90–2.95 Ga tonalite–trondhjemite–granodiorite (TTG) gneiss (Qiu et al., 2000). The basement of the Cathaysia block exhibits Paleoproterozoic to Mesoproterozoic ages and possibly Neoarchean ages (Li et al., 1989; Yu et al., 2007). These two tectonic units were amalgamated along the Jiangshan–Shaoxing fault at 820–970 Ma (Li, 1999; Zhao and Cawood, 1999; Wu et al., 2006). Subsequently, the SCB has experienced a breakup event at ca. 820 Ma, possibly caused by
of intraplate basalts, which are widespread in the coastal areas (Chung et al., 2002). During Jurassic–Cretaceous times, the SCB has been reworked by several tectonic and magmatic events, as represented by granitic intrusions, acidic and intermediate volcanism, ductile and brittle normal and strike-slip faulting, extensional doming and syntectonic terrigenous sedimentation (Faure et al., 1996; Lin et al., 2000; Wang et al., 2001). The Mesozoic tectonic and magmatic events have been related to either the subduction of the paleo-Pacific oceanic plate beneath the Chinese continent (Zhou and Li, 2000; Xie et al., 2005; Xu and Xie, 2005; Zhou et al., 2006; Jiang et al., 2009), or the intracontinental rifting (Fan et al., 2003; Li et al., 2003; Wang et al., 2003; Li et al., 2004; Wang et al., 2004; Wang et al., 2005).

Mesozoic magmatic rocks are widely distributed in the SCB, and can be roughly divided into two periods. The Early Mesozoic intrusions occur mainly in the interior of the SCB, whereas the Late Mesozoic granitoids and volcanic rocks are confined mostly to coastal areas (Zhou et al., 2006). In particular, the Jurassic volcanic rocks outcrop along an east–west trending array in the interior of the Cathaysia block (Zhou et al., 2006; Xu, 2008), among which both Ningyuan (170–173 Ma) and Daoyuan (147–152 Ma) basalts contain various crustal and mantle xenoliths (Guo et al., 1997; Wang et al., 1997; Guo et al., 1999; Kong et al., 2000; Zheng et al., 2004; Dai et al., 2008; Zhang et al., 2008). During the Cenozoic, the continental margin of South China was characterized by an extensional tectonic environment (Russell and Piggot, 1986). Upwelling of asthenosphere as a response to the extension produced large volumes of intraplate basalts, which are widespread in the coastal areas (Chung et al., 1997; Zhu et al., 2004). The Cenozoic basalts in several localities contain abundant mantle xenoliths (Fig. 1), and garnet peridotites have been reported in Xinchang, Xilong, and Mingxi (see reviews in Huang and Xu, 2010).

2.2. Petrography

Twelve lherzolites and one harzburgite were selected for study. They have sizes of ca. 6 cm across and show porphyroclastic textures with little deformation. Secondary minerals (e.g., amphibole and phlogopite) were not observed in any xenolith. All Ningyuan mantle xenoliths have been subjected to variable degrees of alteration. Olivine displays mesh textures and is commonly crosscut by serpentine veins (Fig. 2a). Spinel phryocrysts (~300 μm) are surrounded by small olivines (Fig. 2c, d). Clinopyroxene porphyrocrysts with sizes of ~1 mm are commonly anhydral, with round–elliptical shapes (Fig. 2b), and occasionally a round shape (Fig. 2b). Exsolution lamellae are well developed in both clinopyroxene and orthopyroxene (Fig. 2d, e). The harzburgite (TYS07) is characterized by low content of clinopyroxene (~5%). The clinopyroxene is of small size and displays a poikilitic texture around orthopyroxene (Fig. 2f). Sulfides, which are either included in silicates or in the interstitial silicate matrix, have been observed in some Ningyuan mantle xenoliths.

3. Analytical methods

Whole rock major elements were determined at Northwest University and other analyses were performed at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS).

3.1. Major and trace elements

Whole-rock major element compositions were determined by the X-ray fluorescence technique (XRF), which has been described in Rudnick et al. (2004). Precision are 1–3% for elements present in concentrations higher than 1%, and about 5% for elements with concentrations less than 1%. Mineral major elements were measured on a JEOL JXA-8100 electron probe using an accelerating potential of 15 kV and a sample current of 10 nA.

Trace elements in clinopyroxene were analyzed in situ by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). The detailed description of the method has been given in Liu et al. (2010). The LA-ICP-MS system consists of a Lambda Physik LPX 1201 pulsed ArF excimer laser coupled to an Agilent 7500 ICP-MS. Isotopes were measured in a peak-hopping mode. A spot size of 80 μm and a repetition rate of 8 Hz were used for analysis. Counting times were 25 s for background and 75 s for the analysis of clinopyroxene and standards. The data were reduced by the GLITTER 4.0 program. Isotope δ43Ca was used as an internal standard and NIST 610 glass as an external calibration standard. Reference values of NIST 610 are selected from Pearce et al. (1997).

3.2. Highly siderophile elements (HSEs) and Re–Os isotopes

Both HSEs and Re–Os isotopes were measured by the isotope dilution method following the procedure described by Chu et al. (2009). About 2 g sample powder, together with Re–Os (180Re and 186Os) and HSE (186Ru, 184Pd, 189Ir and 194Pt) isotope tracers, was mixed with reverse aqua regia (i.e., 3 ml 12N HCl and 6 ml 16N HNO3) and digested in a Carus Tube at 240 °C for ~48–72 h. Osmium was extracted from the aqua regia solution by solvent extraction into CCl4 and further purified by micro-distillation. Afterwards, Ru, Pd, Ir and Pt were sequentially separated from the solution by anion exchange resin (AG-1 × 8, 100–200 mesh).

Osmium isotopes were determined using negative thermal ionization mass-spectrometry (N-TIMS) technique (Creaser et al., 1991; Volkering et al., 1991) and conducted on a GV Isotope–T instrument in static mode using Faraday cups. To increase the ionization efficiency, Ba(OH)2 solution was used as the ion emitter. The measured Os isotopes were corrected for mass fractionation using the 184Os/186Os ratio of 3.0827. The Nier oxygen isotope composition (18O/16O = 0.002045) has been used for oxide correction. The in–run precisions were better than 0.2% (2σ, δ = relative standard deviation) for all the samples. The Johnson–Matthey standard of UMD was measured as an external standard and gave 187Os/188Os ratios of 0.11378±2. The concentrations of other HSEs were measured on a Thermal- Electron Neptune MC-ICPMS in peak-jumping mode or static mode, according to their measured signal intensities. In-run precisions for 185Re/187Re, 189Ir/187Ir, 196Pt/196Pt and 194Pt/196Pt were 0.1–0.3% (2σ). The total procedural Os blank was 3–5 pg with a 185Os/186Os ratio of ca. 0.15, which was negligible for all samples in this study. Total procedural blanks were about 3 pg for Re, 7 pg for Ir, 7 pg for Ru, 4 pg for Pt and 4 pg for Pd. The blank corrections were negligible (<1%) for Ir, Ru, Pt and Pd, but up to 3% for Re.

4. Results

4.1. Whole-rock chemistry

Whole-rock major element compositions of Ningyuan mantle xenoliths are shown in Table 1. The Ningyuan mantle xenoliths have variable values of loss on ignition (LOI; 3.94–5.89 wt.%). On the basis of water-free contents, the lherzolites contain 22.75–35.56 wt.% MgO, 8.61–10.22 wt.% Fe2O3, 0.05–0.12 wt.% Na2O and 0.02–0.16 wt.% TiO2. Compared to the lherzolites, the harzburgite (TYS07) has distinct lower Al2O3 (1.73 wt.%) and higher MgO (38.21 wt.%) contents. Most samples have MgO contents substantially lower than that of the primitive mantle (McDonough and Sun, 1995), which might reflect magnesius loss by alteration (Snow and Dick, 1995). The Ningyuan mantle xenoliths contain 2.07–4.12 wt.% Al2O3 and 2.04–3.93 wt.% CaO, giving CaO/Al2O3 ratios...
of ~0.68–1.2. The bulk-rock MgO contents show negative correlations with Al₂O₃, CaO, Na₂O and TiO₂ contents (Fig. 3a–d).

4.2. Mineral compositions

Major element compositions of olivine, spinel, orthopyroxene and clinopyroxene are given in Table 2. Trace element compositions of clinopyroxene are listed in Table 3.

4.2.1. Major elements

Olivine from the Ningyuan mantle xenoliths has fosterite contents \( [\text{Fo} = 100 \times \frac{\text{Mg}}{\text{Mg} + \text{Fe}}] \) of 88.3–90.8 and contains 0.35–0.39 wt.% NiO. The Fo contents do not correlate with the NiO contents. Spinel have Mg# \([= \text{Mg}/(\text{Mg} + \text{Fe})] \) of 0.76–0.79 and Cr# \([= \text{Cr}/(\text{Cr} + \text{Al})] \) of 0.07–0.24 (Fig. 4a). It contains 0.29–0.39 wt.% NiO and 0.04–0.12 wt.% TiO₂. Orthopyroxene from the Ningyuan mantle xenoliths has Mg# of 0.89–0.91, which shows reverse correlations with both TiO₂ and Al₂O₃ contents (Fig. 4b). Orthopyroxene contains 3.61–4.96 wt.% Al₂O₃ and 0.51–0.8 wt.% CaO. Clinopyroxene with Mg# of 0.90–0.92 contains 4.78–7.32 wt.% Al₂O₃, 18.74–21.23 wt.% CaO, 1.04–2.01 wt.% Na₂O and 0.12–0.59 wt.% TiO₂. Clinopyroxene in the harzburgite (TYS07) has lower contents of Al₂O₃ and TiO₂ but higher Cr₂O₃ contents than those in the lherzolites. The Mg# of clinopyroxene show reverse correlations with both Al₂O₃ (Fig. 4c) and TiO₂ contents (Fig. 4d). Sample TYS01-3 plots away from the correlation to remarkably low contents of TiO₂ and Na₂O. The spinel Cr# displays reverse relationships with the Na₂O contents of the clinopyroxene (Fig. 4a). The Na₂O contents of clinopyroxene in our samples are comparable to those reported for Daoxian.

![Microscopic photographs of Ningyuan mantle xenoliths.](image)
mantle xenoliths by Zheng et al. (2004), but distinctly higher than those of Ningyuan mantle xenoliths obtained by Xia et al. (2010).

### 4.2.2. Trace elements

Clinopyroxene from all lherzolites but TYS01-3 displays flat patterns from heavy rare earth elements (HREE) to middle rare earth elements (MREE), but shows variable depletion in light rare earth elements (LREE; Fig. 5a). Their (La/Yb)n (n: chondrite-normalized; Anders and Grevesse, 1989) ratios vary from 0.07 to 0.41. In contrast, clinopyroxene in sample TYS01-3 shows remarkable enrichment in both LREE and MREE, with a (La/Yb)n ratio of 3.67. Clinopyroxene in the harzburgite TYS07 displays a relatively flat REE pattern, with a slightly depletion in LREE. Its HREE contents are distinctly lower than those of the lherzolites (Fig. 5a).

Clinopyroxene in sample TYS01-3 shows an enriched pattern in trace elements (Fig. 5b), especially the large ion lithophile elements (LILE: Ba, Th and U). It also shows remarkable negative anomalies in Sr and the high strength field elements (HFSE: Zr, Hf, Nb, Ta and Ti). Clinopyroxene from other lherzolites and the harzburgite show depleted trace element patterns and negative Nb, Ta and Ti anomalies. However, they do not display negative Zr, Hf and Sr anomalies.

### 4.3. Equilibrium temperatures

Mineral chemistry indicates that equilibrium has been achieved in all Ningyuan mantle xenoliths, and thus the temperatures can be calculated using various geothermometers (Wood and Banno, 1973; Wells, 1977; Bertrand and Mercier, 1985; Brey and Kohler, 1990; Witt-Eickschen and Seck, 1991), which are listed in Table 4. When a single thermometer

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### Table 1

| Whole rock major elements of Ningyuan mantle xenoliths (in wt.%). |
|-----------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                       | SiO₂             | TiO₂             | Al₂O₃            | Fe₂O₃            | MnO             | MgO             | CaO             | Na₂O            | K₂O             | P₂O₅            | LOI             | Total           | Mg#             | CaO/Al₂O₃ |
| TYS01-3               | 43.90            | 0.02             | 2.06             | 9.19             | 0.11            | 37.41           | 2.03            | 0.05            | 0.01            | 0.01            | 4.81            | 99.60           | 0.89            | 0.99      |
| TYS02-2               | 44.07            | 0.09             | 3.10             | 8.81             | 0.11            | 36.03           | 3.30            | 0.08            | 0.01            | 0.02            | 3.94            | 99.56           | 0.89            | 1.06      |
| TYS02-3               | 43.96            | 0.10             | 3.26             | 8.81             | 0.11            | 34.89           | 3.91            | 0.09            | 0.02            | 0.02            | 4.29            | 99.46           | 0.89            | 1.20      |
| TYS03-2               | 45.38            | 0.07             | 2.80             | 8.87             | 0.11            | 35.31           | 2.78            | 0.07            | 0.02            | 0.02            | 4.26            | 99.69           | 0.89            | 0.99      |
| TYS03-8               | 44.16            | 0.13             | 3.10             | 10.17            | 0.13            | 35.02           | 2.45            | 0.08            | 0.03            | 0.03            | 4.19            | 99.49           | 0.87            | 0.79      |
| TYS03-16              | 44.48            | 0.11             | 3.33             | 9.18             | 0.11            | 34.27           | 3.30            | 0.09            | 0.04            | 0.03            | 5.01            | 99.95           | 0.88            | 0.99      |
| TYS03-16-R            | 44.45            | 0.10             | 3.33             | 9.15             | 0.11            | 34.19           | 3.29            | 0.09            | 0.03            | 0.03            | 4.86            | 99.63           | 0.88            | 0.99      |
| TYS03-19              | 44.70            | 0.11             | 4.01             | 8.70             | 0.11            | 33.61           | 3.40            | 0.10            | 0.01            | 0.02            | 4.34            | 99.11           | 0.89            | 0.85      |
| TYS03-23              | 44.22            | 0.12             | 3.60             | 9.84             | 0.12            | 32.72           | 3.82            | 0.11            | 0.04            | 0.03            | 5.29            | 99.90           | 0.87            | 1.06      |
| TYS04-4               | 44.66            | 0.07             | 3.45             | 8.58             | 0.10            | 34.82           | 2.89            | 0.07            | 0.01            | 0.02            | 4.91            | 99.48           | 0.89            | 0.84      |
| TYS05-2               | 43.77            | 0.14             | 3.00             | 8.58             | 0.11            | 34.38           | 3.49            | 0.08            | 0.09            | 0.06            | 5.89            | 99.59           | 0.89            | 1.16      |
| TYS05-2-R             | 43.65            | 0.14             | 2.96             | 8.56             | 0.11            | 34.39           | 3.48            | 0.08            | 0.09            | 0.06            | 5.89            | 99.41           | 0.89            | 1.18      |
| TYS06                 | 44.70            | 0.11             | 3.72             | 9.00             | 0.11            | 33.22           | 3.45            | 0.11            | 0.01            | 0.02            | 4.79            | 99.24           | 0.88            | 0.93      |
| TYS07                 | 45.42            | 0.02             | 1.72             | 8.69             | 0.10            | 38.01           | 1.17            | 0.03            | 0.01            | 0.02            | 4.28            | 99.47           | 0.90            | 0.68      |
| TYS08                 | 44.70            | 0.16             | 4.09             | 9.03             | 0.12            | 33.51           | 3.19            | 0.12            | 0.07            | 0.04            | 4.17            | 99.20           | 0.88            | 0.78      |
| TYS08-R               | 44.80            | 0.16             | 4.08             | 9.01             | 0.12            | 33.60           | 3.21            | 0.12            | 0.07            | 0.04            | 4.13            | 99.34           | 0.88            | 0.79      |

Mg# = Mg/(Mg + Fe); Fe₂O₃: total iron.
R: replicate analysis.

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**Fig. 3.** Diagrams of bulk-rock MgO versus bulk contents of Al₂O₃ (a), CaO (b), Na₂O (c) and TiO₂ (d).
is employed, equilibrium temperatures of Ningyuan mantle xenoliths show an overall uniform trend, although temperatures obtained by different thermometers for a given sample are variable. Applying the two-pyroxene geothermometer of Brey and Kohler (Brey and Kohler, 1990), temperatures of Ningyuan mantle xenoliths are calculated to vary from 994 to 1081 °C. Similar high temperatures (948–1135 °C) have been previously reported for Daoxian mantle xenoliths using the same geothermometer (Zheng et al., 2004). Garnet is absent in both Ningyuan and Daoxian mantle xenoliths, which makes it difficult to precisely estimate the pressures. Nevertheless, it is reasonable to conclude that they were derived from depths shallower than the spinel-garnet transition (e.g., ~65 km).

4.4. HSEs and Re–Os isotopes

The Ningyuan mantle xenoliths contain 2.09–4.27 ppb Os, 2.1–3.64 ppb Ir, 3.9–7.69 ppb Ru, 3.77–7.29 ppb Pt, 1.88–5.94 ppb Pd and 0.08–0.28 ppb Re (Table 5). The lherzolites display consistent HSE patterns (Fig. 6), similar to those of fertile abyssal peridotites (Liu et al., 2009) and those inferred for the primitive upper mantle
Table 3
Trace element compositions of clinopyroxene of Ningyuan mantle xenoliths (in ppm).

| Sample | Li   | Sc   | Ti   | V    | Cr   | Co   | Ni   | Zn   | Ga   | Sr   | Y   | Zr   | Nb   | Ba   | La   | Ce   | Pr   | Nd   | Sm   | Eu   | Gd   | Tb   | Dy   | Er   | Tm   | Yb   | Ho   | Er   | Hf   | Ta   | Pb   | Th   | U    |
|--------|------|------|------|------|------|------|------|------|------|------|-----|-----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| TYS01-3 | 4.20 | 56   | 2659 | 36    | 3368 | 14.7 | 369  | 18.7 | 5.7  | 100  | 16.3| 30.3| 1.424| 2.036| 5.889| 2.928| 5.100| 6.488 | 1.763| 4.750| 0.623 | 3.411| 6.050 | 1.612 | 0.226 | 1.489 | 0.496 | 0.077 | 0.223 | 0.082 | 0.203  |
| TYS02-2 | 1.76 | 53   | 2854 | 262  | 5406 | 10.2 | 343  | 15.4 | 5.0  | 42   | 15.4| 20.3| 0.036| 0.674| 3.364 | 2.228 | 0.516 | 3.423 | 1.525 | 0.667 | 1.835 | 0.408 | 2.731 | 0.317 | 0.645 | 0.040 | 0.031 | 0.212 | 1.023  |
| TYS03-2 | 1.80 | 53   | 2860 | 272  | 5445 | 10.1 | 352  | 14.9 | 4.8  | 55   | 14.9| 19.4| 0.023| 0.079| 0.317 | 2.151 | 0.486 | 3.294 | 1.432 | 0.645 | 1.718 | 0.391 | 2.703 | 0.372 | 0.665 | 0.039 | 0.034 | 0.213 | 1.012  |
| TYS03-3 | 1.42 | 53   | 2327 | 308 | 6618 | 1.3 | 407  | 13.6 | 3.7  | 45   | 13.6| 5.8 | 0.102 | 0.077 | 0.099 | 0.442 | 0.339 | 3.619 | 1.431 | 0.749 | 1.616 | 0.436 | 2.483 | 0.436 | 0.764 | 0.037 | 0.039 | 0.215 | 1.029  |
| TYS03-19 | 1.94 | 54  | 2543 | 236 | 5264 | 13.3 | 407 | 16.5 | 5.7  | 40   | 16.5| 8.0 | 0.749 | 0.078 | 0.099 | 0.442 | 0.339 | 3.619 | 1.431 | 0.749 | 1.616 | 0.436 | 2.483 | 0.436 | 0.764 | 0.037 | 0.039 | 0.215 | 1.029  |
| TYS03-16 | 2.56 | 57   | 2837 | 227 | 4865 | 11.4 | 359  | 15.7 | 5.7  | 46   | 15.7| 8.0 | 0.749 | 0.078 | 0.099 | 0.442 | 0.339 | 3.619 | 1.431 | 0.749 | 1.616 | 0.436 | 2.483 | 0.436 | 0.764 | 0.037 | 0.039 | 0.215 | 1.029  |
| TYS03-19 | 1.69 | 57   | 3229 | 257 | 5224 | 7.7 | 300  | 15.1 | 3.7  | 46   | 15.1| 5.5 | 0.749 | 0.078 | 0.099 | 0.442 | 0.339 | 3.619 | 1.431 | 0.749 | 1.616 | 0.436 | 2.483 | 0.436 | 0.764 | 0.037 | 0.039 | 0.215 | 1.029  |
| TYS03-23 | 2.78 | 55   | 3189 | 277 | 6477 | 11.4 | 332  | 16.0 | 4.5  | 46   | 16.0| 5.5 | 0.749 | 0.078 | 0.099 | 0.442 | 0.339 | 3.619 | 1.431 | 0.749 | 1.616 | 0.436 | 2.483 | 0.436 | 0.764 | 0.037 | 0.039 | 0.215 | 1.029  |
| TYS04-4 | 1.71 | 55   | 1952 | 258 | 5413 | 7.7 | 347  | 15.1 | 4.5  | 46 | 15.1| 5.5 | 0.749 | 0.078 | 0.099 | 0.442 | 0.339 | 3.619 | 1.431 | 0.749 | 1.616 | 0.436 | 2.483 | 0.436 | 0.764 | 0.037 | 0.039 | 0.215 | 1.029  |
| TYS05-2 | 2.01 | 56   | 2753 | 257 | 6373 | 9.7 | 311  | 16.1 | 4.5  | 46   | 16.1| 5.5 | 0.749 | 0.078 | 0.099 | 0.442 | 0.339 | 3.619 | 1.431 | 0.749 | 1.616 | 0.436 | 2.483 | 0.436 | 0.764 | 0.037 | 0.039 | 0.215 | 1.029  |
| TYS06 | 1.63 | 60   | 260 | 277 | 5099 | 9.7 | 371  | 15.9 | 5.5  | 46 | 15.9| 5.5 | 0.749 | 0.078 | 0.099 | 0.442 | 0.339 | 3.619 | 1.431 | 0.749 | 1.616 | 0.436 | 2.483 | 0.436 | 0.764 | 0.037 | 0.039 | 0.215 | 1.029  |
| TYS07 | 2.10 | 51   | 214 | 253 | 7896 | 9.7 | 316  | 15.9 | 5.5  | 57 | 15.9| 5.5 | 0.749 | 0.078 | 0.099 | 0.442 | 0.339 | 3.619 | 1.431 | 0.749 | 1.616 | 0.436 | 2.483 | 0.436 | 0.764 | 0.037 | 0.039 | 0.215 | 1.029  |
| TYS08 |     |     |     |     |      |     |      |      |      |     |      |     |     |      |     |      |     |      |      |      |      |     |      |      |      |     |      |     |     |      |     |      |     |      |      |      |     | 58.53 |

Fig. 4. Mineral compositions of the Ningyuan mantle xenoliths. (a) Spinel Cr# vs. Cpx Na2O content; (b) Opx Mg# vs. Al2O3 content; (c) Cpx Mg# vs. Al2O3 content; (d) Cpx Mg# vs. TiO2 content. Literature data of Daoxian (Zheng et al., 2004; Xia et al., 2010) and Ningyuan (Zheng et al., 2004; Xia et al., 2010) are also shown for comparison. Symbols are same as in Fig. 3.
Most lherzolites have subchondritic to roughly chondritic Re/Ir, Os/Ir and Pt/Ir ratios, but suprachondritic Ru/Ir and Pd/Ir ratios, suggesting that sulfides in these samples have not been significantly lost during late-stage processes. They have chondritic Os/ Ir and Pt/Ir ratios, but suprachondritic Ru/Ir and Pd/Ir ratios. Most lherzolites have subchondritic to roughly chondritic Re/Ir ratios, whereas three lherzolites (TYS02-3, TYS03-8 and TYS03-19) display suprachondritic Re/Ir ratios. The harzburgite (TYS07) shows a relative flat pattern from Os to Ru, but strong depletion in Pt, Pd and Re.

The 187Re/188Os and 187Os/188Os ratios of the Ningyuan lherzolite xenoliths vary from 0.18 to 0.51 and from 0.12116 to 0.12929, respectively (Table 5). Among the Ningyuan mantle xenoliths, the harzburgite has the lowest 187Re/188Os of 0.1 and the most unradiogenic 187Os/188Os ratio of 0.11681. The 187Os/188Os ratios of Ningyuan mantle xenoliths show positive correlations with both 187Re/188Os ratios and bulk-rock Al2O3 contents (Fig. 7a, b). Both TYS02-3 and TYS03-8 have model ages (TMA) calculated relative to the primitive upper mantle (PUM; Meisel et al., 2001) older than the Earth’s age, whereas TYS03-19 gives a future model age. The TMA ages of other samples vary from ~1.58 to ~3.24 Ga. The Re-depletion age (TRD) relative to the PUM is calculated assuming a Re/Os ratio of zero in the sample. Therefore, the TRD represents minimum ages and provide few age constraints on lherzolites, in which substantial amounts of Re are still left after melt extraction. The lherzolites have TRD ages varying from ~0.25 to ~1.25 Ga, which are, unsurprisingly, younger than that of the harzburgite (~1.82 Ga). It should be noted that the harzburgite is unusually fertile, and probably contains some Re after melt extraction. Therefore, its TRD age (~1.82 Ga) may be much younger than the true extraction age.

### 5. Discussion

#### 5.1. Melt depletion and enrichment processes

The Mesozoic mantle xenoliths entrained in both Daoxian and Ningyuan basalts are mainly composed of fertile lherzolites, with a few harzburgites and dunites (Wang et al., 1997; Zheng et al., 2004; Zhang et al., 2008; Xia et al., 2010). All Ningyuan lherzolites reported in the present study have fertile bulk-rock compositions, i.e., high Al2O3 and CaO contents, whereas the harzburgite has only a slightly refractory composition. The fertile nature of these rocks is also shown by the mineral compositions. Olivines in the Ningyuan mantle xenoliths have low Fo contents (88–91), which are distinctly lower than those of refractory Archean and Proterozoic cratonic mantle xenoliths (Boyd, 1989; Griffin et al., 1998). Both clinopyroxene and orthopyroxene have high Al2O3 contents. Furthermore, clinopyroxene contains high Na2O contents. All these geochemical characteristics support the suggestion that the Ningyuan mantle xenoliths have been subjected to only low degrees of partial melting.

Degrees of partial melting experienced by mantle peridotites can be constrained by spinel composition. Spinels become Cr-rich with progressive melt extraction, resulting in a positive relationship between degree of fractional partial melting (F) and spinel Cr# (Dick and Bullen, 1984; Hellebrand et al., 2001). Hellebrand et al. (2001) formulated a function, F = 10ln(Cr#) + 24, suitable for Cr# of 0.1–0.6, to calculate the degree of partial melting suffered by residual peridotites from the depleted MORB mantle (DMM) source. Degrees of partial melting are estimated by this method to be ~1–5% for most Ningyuan lherzolites, and ~10% for the harzburgite (Fig. 8a). This substantiates the hypothesis that the Ningyuan mantle xenoliths have experienced low to moderate degrees of melt extraction. Degrees of partial melting of three Ningyuan lherzolites cannot be inferred by this function because of their low Cr# (~0.1–0.5). A possible explanation is that their compositions are more fertile than the inferred compositions of the DMM. In other words, little melt has been extracted from these three samples.

Degrees of partial melting experienced by mantle peridotites can also be inferred from some trace elements (e.g., Y and Yb) in clinopyroxene (Norman, 1998; Xu et al., 2000). Comparison of Y and Yb contents in clinopyroxene and the modeled melting trend suggest that the Ningyuan lherzolites represent residues after ~3–6% fractional melting of the primitive mantle, whereas the harzburgite has experienced ~13% degrees of
fractional melting (Fig. 8b). It should be noted that degrees of partial melting estimated using clinopyroxene trace elements are slightly higher than the values obtained using spinel Cr#. The difference probably lies in the different compositions of mantle sources assumed in the two methods, i.e., the DMM is more depleted than the primitive mantle. Therefore, both whole rock and mineral compositions of the Ningyuan mantle xenoliths have been subjected to very low to moderate degrees of partial melting. On the other hand, the Mesozoic mantle lithosphere has experienced limited or negligible enrichment after melting, because clinopyroxenes in most Ningyuan mantle xenoliths show variable degrees of partial melting. On the other hand, it is also plausible that the mantle peridotites, and thus, can be used as proxies for the extent of melt extraction. More importantly, these elements are more resistant than Re to disturbance by secondary processes (e.g., metasomatism and refertilization) (Büchl et al., 2000; Becker et al., 2006; van Acken et al., 2008). Other immobile elements, such as aluminum and heavy rare earth elements (HREE; Yb or Lu), are sometimes plotted against 187Os/188Os to determine model ages of peridotites that are assumed to share a common origin through melt extraction (Reisberg and Lorand, 1995; Peslier et al., 2000a; Peslier et al., 2000b). These elements have bulk partition coefficients similar to that of Re during melting of mantle peridotites, and thus, can be used as proxies for the extent of melt extraction. More importantly, these elements are more resistant than Re to disturbance by secondary processes (e.g., metasomatism and refertilization), the most commonly employed element in this regard.

5.2. Age of the Mesozoic lithospheric mantle beneath southern Hunan Province

There are multiple methods that can be used to determine ages of peridotites using the Re–Os isotope system. As for most chronometers, the most robust ages are derived from isochrons. A positive correlation on a Re–Os isochron diagram is found for the Ningyuan mantle xenoliths (Fig. 7a), which if interpreted chronologically would yield a young age of 1571 ± 370 Ma. However, true Re–Os isochrons have been rarely reported for mantle peridotites. This may, on one hand, reflect the fact that mantle peridotites represent residues after variable degrees of partial melting of a mantle precursor whose 187Os/188Os ratio was not perfectly uniform at the time of melting. On the other hand, it is also plausible that the mantle peridotites were not genetically related. More possible reasons include the mobility of Re, which can be fluid-mobile under oxidizing conditions (Xiong and Wood, 1999; Becker, 2000), and addition of Re during late magmatic processes, i.e., metasomatism and refertilization (Büchl et al., 2002; Becker et al., 2006; van Acken et al., 2008).

<table>
<thead>
<tr>
<th>Table 5</th>
<th>HSE and Re–Os isotope compositions of Ningyuan mantle xenoliths.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Os</td>
<td>Ir</td>
</tr>
<tr>
<td>TYS01-3</td>
<td>4.27</td>
</tr>
<tr>
<td>TYS02-2</td>
<td>3.88</td>
</tr>
<tr>
<td>TYS03-3</td>
<td>3.63</td>
</tr>
<tr>
<td>TYS03-2</td>
<td>2.56</td>
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<tr>
<td>TYS03-8</td>
<td>3.40</td>
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<tr>
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<td>2.63</td>
</tr>
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<tr>
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<td>TYS07</td>
<td>3.76</td>
</tr>
<tr>
<td>TYS08</td>
<td>2.89</td>
</tr>
</tbody>
</table>

HSE concentrations are in ppb. Both TMA and TRD are calculated relative to the primitive upper mantle (PUM), using C.-Z. Liu et al. / Chemical Geology 291 (2012) 186–198.
...is aluminum (Reisberg and Lorand, 1995), leading some authors to coin the term “alumina-chron”. A good correlation can be found for the Ningyuan mantle xenoliths on the $^{187}\text{Os}/^{188}\text{Os}$ vs. $\text{Al}_2\text{O}_3$ diagram (Fig. 7b). The alumina-chron gives an initial $^{187}\text{Os}/^{188}\text{Os}$ ratio of 0.111, assuming a zero $\text{Al}_2\text{O}_3$ content, which corresponds to an age of Late Archean (~2.6 Ga) relative to the primitive upper mantle (PUM; Meisel et al., 2001). However, it has been argued that about 0.7 wt.% $\text{Al}_2\text{O}_3$ still remains in mantle residues after Re is completely consumed during melting (Handler and Bennett, 1999). Extrapolation of the alumina-chron of the Ningyuan xenoliths to 0.7 wt.% $\text{Al}_2\text{O}_3$ yields an $^{187}\text{Os}/^{188}\text{Os}$ ratio of ~0.1138, giving a model age of ~2.2 Ga. It should be noted that the alumina-chron age is older than the Re-depletion age ($T_{\text{Re}}$) of the most refractory sample (TYS07; ~1.8 Ga). The latter ignores the in-growth of $^{188}\text{Os}$ due to Re in the sample, and thus represents a minimum estimate of the true melt depletion age (Walker et al., 1989).

The whole-rock Re–Os isotopes thus suggest that the Ningyuan mantle xenoliths might have experienced a melt extraction event during the Paleoproterozoic (~1.8–2.2 Ga). It is generally assumed that melt extraction occurred during creation of the subcontinental lithospheric mantle. If this assumption is accepted, the Mesozoic subcontinental lithospheric mantle beneath southern Hunan Province was probably formed during the Paleoproterozoic. In this case, the melting process produced residues with Re/Os ratios that varied systematically with the degree of fertility of the peridotites (Reisberg and Lorand, 1995). Ancient mantle, coexisting with juvenile mantle, has been found in previous studies of Cenozoic mantle xenoliths from the coastal areas of South China (Xu et al., 2000; Xu et al., 2002; Zheng et al., 2004). However, interpretation of Os isotope ages of mantle xenoliths has to consider the Os isotope heterogeneity of the convecting upper mantle (Rudnick and Walker, 2009). There is growing evidence that Os isotopic heterogeneities caused by ancient melting can be preserved for over a billion year in the asthenosphere (Brandon et al., 2000; Harvey et al., 2006; Liu et al., 2008). For example, some abyssal peridotites from Gakkel ridge, Arctic Ocean, have Os model ages up to 2 Ga (Liu et al., 2008). In particular, a positive $^{187}\text{Os}/^{188}\text{Os}$–$\text{Al}_2\text{O}_3$ correlation was also found for abyssal peridotites from the same dredge site on Gakkel ridge, Arctic Ocean (Liu et al., 2008). Such a correlation has been explained as a mixture of different mantle domains in the asthenosphere, in which the refractory mantle domains preserve ancient melting ages during convecting stirring processes (Liu et al., 2008). If such ancient depleted materials were accreted to the lithospheric mantle, the apparent model ages would be unrelated to the time of lithospheric formation (Reisberg et al., 2005).

While the tectonic interpretation of the ancient Os ages is ambiguous, for the following reasons our preferred model is that the Ningyuan mantle xenoliths were more likely derived from a juvenile lithospheric mantle rather than representing a Paleoproterozoic lithosphere relic. First, the Mesozoic mantle xenoliths entrained in both Ningyuan and Daoxian basalts consist dominantly of fertile lherzolites, with minor harzburgites (Wang et al., 1997; Zheng et al., 2004; Zhang et al., 2008; Xia et al., 2010). Their compositions are significantly different from the Proterozoic mantle xenoliths, but follow the oceanic trend (see Fig. 13 in Zheng et al., 2004). The studied lherzolites have slightly variable $^{187}\text{Os}/^{188}\text{Os}$ ratios of 0.12116–0.12929, which plot within the range of the abyssal peridotites (Fig. 7b). Secondly, previous studies have shown that both Ningyuan and Daoxian mantle xenoliths have depleted Nd isotope compositions (Guo et al., 1999; Chen et al., 2004; Zhang et al., 2008). Zhang et al. (2008) have reported that the Ningyuan mantle xenoliths have depleted $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of 0.513188–0.513341 and $\varepsilon_{160}$ of $+11$–$+13.5$. Thirdly, if the peridotites represented a Paleoproterozoic lithospheric relic they should have been metasomatized by slab-released fluids/melts during the subduction of the Paleo-Pacific plate, which was initiated as early as the mid-Permain (Li and Li, 2007). However, no hydrous phases have been reported in the Ningyuan mantle xenoliths (Wang et al., 1997; Zheng et al., 2004; Zhang et al., 2008; Xia et al., 2010). Clinopyroxene trace element compositions of samples in this study indicate that the lithospheric mantle has been only weakly metasomatized.

5.3. The Mesozoic mantle replacement in the South China Block

Generally, the sub-continental lithospheric mantle (SCLM) is both temporally and mechanically coupled with the overlying crust (Pearson, 1999; Carlson et al., 2005). The Yangtze block consists of an Archean to Paleoproterozoic basement (Chen and Jahn, 1998; Zheng et al., 2006), whereas the basement of the Cathaysia block exhibits Paleoproterozoic to Mesoproterozoic ages and possibly Neoarchean ages (Li et al., 1989; Yu et al., 2007). This implies the existence of ancient lithospheric mantle beneath the South China Block. Compositions of the garnet lherzolite xenoliths in the Yangtze block (Dahongshan lamproites) suggest that the subcontinental lithospheric mantle (SCLM) beneath the South China Block is the Harzburgite block (Dahongshan lamproites) suggest that the subcontinental lithospheric mantle (SCLM) beneath the South China Block is the...
beneath the SCB must have been significantly thinned and replaced by juvenile asthenospheric mantle. Heat from the asthenosphere would have produced a hot geotherm for the lithosphere relic. On the other hand, it is also possible that the ancient SCLM has been completely removed and replaced by asthenospheric mantle. Therefore, juvenile mantle has been accreted from the asthenosphere beneath the Ningyuan region, no matter how we interpret the Re–Os isotope of the Ningyuan mantle xenoliths.

In addition to the modification of the geotherm, the composition of the lithospheric mantle was also transformed as a result of accretion of juvenile mantle during the Mesozoic. The Paleozoic (ca. 480–500 Ma) lamproites emplaced at Daohongshan in Hubei Province and Zhengyuan in Guizhou Province show enriched Sr–Nd isotopic characteristics, with εNd of −3 to −12 (Li et al., 1993; Fang et al., 2002), which suggests that they were derived from an enriched lithospheric mantle. In contrast, the Mesozoic mantle xenoliths have depleted Nd isotope compositions (Guo et al., 1999; Chen et al., 2004; Zhang et al., 2008). Furthermore, compositions of the Cenozoic tholeiitic basalts in the Jianghan Basin indicate that they originated from a juvenile and depleted asthenospheric mantle (Peng et al., 2006).

Mantle thinning and accretion would lead to lithospheric extension in the South China Block. Therefore, the age of SLM thinning and accretion can be constrained through evidence for lithospheric extension. The following geological observations support the suggestion that the South China Block was in an extensional setting during the Mesozoic. First, rift basins and faulted depression basins were widely distributed in South China during the Mesozoic (Gilder et al., 1991; Zhou et al., 2006). Sedimentary settings in South China changed from stable shallow-sea facies during the Paleozoic to lake facies during the Mesozoic (Li and Li, 2007; Shu et al., 2009). Second, both alkaline and tholeiitic basalts were erupted during the Jurassic in an east–west trending array in the interior of the Cathaysia block (Fan et al., 2003; Wang et al., 2003; Xie et al., 2005; Zhou et al., 2006; Chen et al., 2008; Xu, 2008). Furthermore, emplacement of gabbros, A-type granites and syenitic rocks also points to an extensional setting in South China during the Mesozoic (Li et al., 2003; Li et al., 2004; Zhu et al., 2006; Li and Li, 2007). The pyroxenite and gabbro xenoliths entrained in the Daoxian basalts show depleted isotopic compositions (i.e., εNd of 0–8), which have been explained as cumulates of asthenosphere-derived magmas under extensional settings (Guo et al., 1997; Dai et al., 2008). Zircons from the gabbroic xenoliths give U–Pb ages of ~225 Ma (Fan et al., 2003; Dai et al., 2008). This suggests that lithospheric extension and thus mantle accretion in South China commenced as early as the Late Triassic (Fan et al., 2003).

We suggest that the lithospheric thinning and accretion in South China was probably caused by mantle delamination according to the following scenario. The lithospheric mantle beneath the SCB was metasomatized by the fluids/melts released from the subducted pacific-Pacific plate. Metametamorphism reduced the viscosity of the lithospheric mantle through formation of hydrous minerals (Pollack, 1986), thus favoring mantle delamination. Delamination led to the upwelling of the hot asthenosphere. Decompressional melting of the asthenosphere gave rise to not only the mafic volcanic rocks but also underplating of basaltic magmas (Guo et al., 1997; Guo et al., 1998; Guo et al., 1999; Li et al., 2003; Wang et al., 2003; Li et al., 2004; Wang et al., 2005). Underplating of high temperature basaltic magmas led to the anatexis of the crustal rocks, which produced the A-type granites, syenitic rocks and the widespread granitoids during the Jurassic in South China (Li et al., 2003; Li et al., 2004; Zhou et al., 2006; Li and Li, 2007).

6. Conclusion

Both whole rock and mineral compositions of mantle xenoliths entrained in the Mesozoic Ningyuan basalts suggest that they have been subjected to low degrees of partial melting, after which they have been only weakly metasomatized. The estimated temperatures indicate that the Mesozoic lithosphere beneath southern Hunan Province has a hot geotherm. Absence of garnet in the Ningyuan mantle xenoliths implies a thin lithosphere (<80 km) during the Mesozoic. The Os isotopic composition of the harzburgite gives a TDM age of ~1.8 Ga, which is slightly younger than the alumina-chron age of the Ningyuan mantle xenoliths (~2.2 Ga). Although the tectonic implications of the old ages is uncertain, the Ningyuan mantle xenoliths provide further evidence of thinning of ancient lithospheric mantle and accretion of juvenile mantle beneath South China during the Mesozoic. Mantle thinning and accretion was probably caused by mantle delamination, which led to lithospheric extension. Upwelling of hot asthenosphere in response to the lithospheric extension not only gave rise to the mafic rocks but may also have led to the extensive granitic magmatism in South China during the Jurassic.

Acknowledgments

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House, Bejing.


